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Ollscoil na hÉireann Má Nuad

THE DETECTION AND PREDICTION OF CLIMATE CHANGE IN IRELAND USING AN AUTOMATED CLASSIFICATION OF ATMOSPHERIC CIRCULATION PATTERNS

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Abstract

The primary objective of this thesis is to investigate whether Irish climate is changing, and if so, what are the possible driving forces of this change. Analyses of surface climate records appear to support global trends. Annual temperature records indicate an increase of 0.5°C since the beginning of the 20th century, with more rapid warming in the past three decades. Irish precipitation changes are also consistent with the predictions of Global Climate Models (GCMs), with evidence of a shift towards winter increases. Other important trends include a decrease in frequency of frost days and an increase in frequency of wet and rain days in certain months of the year. An important element of the research, therefore, is to investigate what is steering this change in climate. A circulation-type catalogue for Ireland has been constructed from National Centers for Environmental Prediction (NCEP) Reanalysis data, to objectively classify atmospheric circulation patterns. It is thus possible to determine to what extent the changing frequency of circulation types is influencing the spatial and temporal variability of the local climate. As a further step, by using the HadCM3 GCM data for the 2041-2070 period, it is possible to outline what changes in frequency of circulation types may be expected to occur with respect to the emission scenarios. Based on the relationships derived in the present, between CTs and precipitation, these can be applied to future CT frequencies to derive precipitation scenarios. The seasonal precipitation changes found are most likely attributed to changes in the westerly and southwesterly flow, associated with a shift in the North Atlantic Oscillation Index.

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List of Abbreviations

ACCORD	Atmospheric Circulation Classification and Regional Downscaling
CA	Cluster Analysis
CCA	Canonical Correlation Analysis
CCCma	Canadian Centre for Climate Modelling and Analysis
CET	Central England Temperature
CLIVAR	Climate Variability and Predictability
CRU	Climate Research Unit
CSIRO	The Commonwealth Scientific and Industrial Research Organisation
CT	Circulation Type
DTR	Diurnal Temperature Range
ECA&D	European Climate Assessment and Dataset
ECHAM/OPYC3	ECMWF model developed at Hamburg (ECHAM)/ Ocean Isopycnal model (OPYC)
ECMWF	European Centre for Medium-Range Weather Forecasts
ECMWF ERA-40	ECMWF Reanalysis data
EOF	Empirical Orthogonal Functions
EPA	Environmental Protection Agency
GCM	Global Climate Model
GRIAN	Greenhouse Ireland Action Network
HadCM2/3	The Hadley Centre for Climate Prediction and Research Model 2/3
h-Pa	hecto-pascal
IPCC	Intergovernmental Panel on Climate Change
LWT	Lamb Weather Types
MSLP	Mean Sea Level Pressure
NAO	North Atlantic Oscillation
NCAR	National Centers for Atmospheric Research
NCEP	National Centers for Environmental Protection
PCA	Principal Component Analysis
RCM	Regional Climate Model
SAR	Second Assessment Report
SRES	Special Report on Emission Scenarios
SST	Sea Surface Temperatures
TAR	Third Assessment Report
UKCIP	United Kingdom Climate Impacts Programme
WMO	World Meteorological Organisation

Circulation Types

U	Unclassified
A	Anticyclonic
ANE	Anticyclonic Northeasterly
AE	Anticyclonic Easterly

ASE	Anticyclonic Southeasterly
AS	Anticyclonic Southerly
ASW	Anticyclonic Southwesterly
AW	Anticyclonic Westerly
ANW	Anticyclonic Northwesterly
AN	Anticyclonic Northerly
NE	Northeasterly
E	Easterly
SE	Southeasterly
S	Southerly
SW	Southwesterly
W	Westerly
NW	Northwesterly
N	Northerly
C	Cyclonic
CNE	Cyclonic Northeasterly
CE	Cyclonic Easterly
CSE	Cyclonic Southeasterly
CS	Cyclonic Southerly
CSW	Cyclonic Southwesterly
CW	Cyclonic Westerly
CNW	Cyclonic Northwesterly
CN	Cyclonic Northerly

Chapter 1

Climate Change and an Overview of Circulation Classification Methods

1.1 An Introduction to Global Climate Change

The current definition of climate change, as denoted by the Intergovernmental Panel on Climate Change (IPCC, 2001), is 'any change in climate over time, whether due to natural variability or as a result of human activity'. The IPCC First Assessment Report in 1990 advised that human induced climate change was a real threat. By the time of the Second Assessment Report (IPCC, 1995) the IPCC concluded that '…the balance of evidence suggests…a discernible human influence on global climate'. Now, however, the evidence for an anthropogenic influence on climate change is stronger than previously claimed. The extent of uncertainty has decreased in the past 15 years, such that, in the most recent IPCC report (IPCC, 2001) the assertion had changed to 'Anthropogenic greenhouse gases are likely to have made a significant and substantial contribution to the warming observed over the second half of the 20th century' (2001: 728).

Global mean temperature is a key indicator of climate change, and has increased by $0.6^{\circ} \pm 0.2^{\circ}$C since the beginning of the 20th century (IPCC, 2001). This warming has occurred in 2 main phases, 1910-1945 and from the mid-1970s to the present. The 1990s has been the warmest decade in the long-term record (since 1856) with 10 of the warmest years globally having occurred between 1990 and 2003 (Palutikof, 2004). Nighttime daily minimum temperatures over land have increased at about twice the rate of increase of daytime daily maximum temperatures between the period 1950 and 1993. This has resulted in a lengthening of the freeze-free season in many mid- to high-latitude regions. Changes in other climate elements include a likely increase in precipitation of 0.5 to 1% per decade in the 20th century over the mid- and high-latitudes of Northern Hemisphere continents, and in the latter half of the century, a 2 to 4% increase in the frequency of heavy precipitation events. An increase in cloud cover of 2% is also likely to have occurred in these latitudes in the 20th century (IPCC, 2001).

Both natural and human influences can cause global, regional and local climate variations. There is a general consensus among atmospheric scientists that climate is changing and that humans have played a more active part in this change in recent decades (IPCC, 2001). Increasing concentrations of greenhouse gases since the middle of the 19th century are largely attributed to anthropogenic activities, primarily from energy, agriculture and industrial sources. Ireland had the fourth highest level of per capita greenhouse gas emissions in the industrialised world in 1999, and within the EU, had the highest per capita emissions at 15.6 tonnes of CO_2 per person (Turton and Hamilton, 2002). Figures calculated by Greenhouse Ireland Action Network (GRIAN) reveal that emissions are approaching double the EU average, and are increasing at the fastest rate in the EU (Finnegan, 2003).

As well as increasing levels of greenhouse gases through anthropogenic activity, natural variations in external forcing (such as changes in solar energy output, variations in the Earth's orbital characteristics and volcanicity) or variations in dominating atmospheric circulation can have an impact on climate change. Natural oscillations within the climate system, such as the El-Niño Southern Oscillation (ENSO) or the North Atlantic Oscillation (NAO) are also important factors. Anthropogenic climate change will manifest itself against the background of natural climate variability. Therefore, in order to be able to detect and predict the influence of anthropogenic climate change, it is also necessary to understand the natural variability of climate (Slonosky *et al.*, 2000).

1.2 Classifying the Atmospheric Circulation

Large-scale circulation of the atmosphere, particularly in the mid-latitudes, has been recognised as one of the primary determinants of regional climate variation (Hurrell, 1995; Hurrell and van Loon, 1997; Slonosky *et al.*, 2000; Slonosky *et al.*, 2001). Changes in atmospheric circulation are potentially very important, even if they do not have as direct an impact on human activity. The atmospheric circulation forms the main link between regional changes in wind, temperature and precipitation in the troposphere, and other climatic variables such as ocean currents and sea surface temperatures (SSTs) (Trenberth, 1995). While local and regional climates are influenced by both large-scale atmospheric circulation and surface features such as orography, altitude, latitude and land-ocean interactions, it is generally the changing circulation which plays a bigger role than the relatively static orography, altitude and latitude.

There are a variety of approaches for classifying atmospheric circulation in order to relate it to local surface weather. These include manual (subjective) methods such as the Lamb Weather Types (LWTs) for the British Isles and the Grosswetterlagen for Germany and central Europe. Manual schemes involve the subjective classification by the researcher of the circulation patterns by visual analysis of daily pressure maps. This method is based on the researcher's experience and its straightforwardness makes it easy to interpret. However, it is a labour intensive method and there are difficulties in applying the method to a different area or use by another researcher. Classification of circulation can also be carried out by automated (objective) methods, such as the use of indices. Examples include the Jenkinson-Collison automated version of the Lamb catalogue for Britain (Jenkinson and Collison, 1977). This scheme is based on grid point values of mean sea level pressure (MSLP) and can be applied to other regions in the mid-latitudes. Eigenvector-based methods have also been used, such as Principal Components Analysis (PCA) and Canonical Correlation Analysis (CCA). While these circulation classifications are generally easier to compute, they may be more difficult to interpret and compare across spatial and temporal scales. Some of the identified patterns may not have any climatic significance, while others that occur infrequently may be missed entirely.

After an analysis of the many methodologies suitable for classifying the atmospheric circulation of Ireland, this study utilises a variation of the Jenkinson-Collison version of the LWT catalogue. Each day is assigned to one of 27 circulation types based on indices of airflow direction, vorticity and geostrophic flow: 8 directional types (E, SE, S, SW, W, NW and N), 2 rotational types (cyclonic and anticyclonic) or 16 hybrid types (AE, CNE, ASW etc). There is also an unclassified (U) category. Relationships between large-scale atmospheric circulation can be related to local surface weather, to determine the climate characteristics and variability for Ireland, using this classification scheme.

The development of future climate scenarios is restricted by the ability of Global Climate Models (GCMs) to predict accurately at local and regional scales. Information is usually required at levels smaller than that of a typical GCM grid-cell. GCMs are generally more successful at reproducing the main modes of sea level pressure or atmospheric circulation at the global and hemispheric scale than surface climate elements, such as temperature or precipitation, at the local level. There is also a scale mismatch between what climate modellers provide and what impact analysts require. Changing climate will have impacts on a wide variety of sectors including health (mortality, air quality); agriculture (crop yields, irrigation demands); water resource issues (supply, quality, increased demand and competition for water); coastal areas (erosion of beaches, inundation of coastal lands) and species and ecological sectors (loss of habitats). This scale mismatch has led researchers to develop techniques to establish statistical links between the large-scale circulation and surface climate variables at local stations which can then be applied in a downscaling methodology to GCM output (Trigo and Palutikof, 2001). However, future climate scenarios are usually based on a variety of assumptions and, with inherent difficulties in model building, they are purely 'projections' and not 'predictions'.

1.3 Aims and Objectives

The level of climate research in Ireland has been developing recently and this thesis aims to add to this research. The main aims of the thesis are:

- to determine if Irish climate has changed, and if so, what are the possible drivers of this change, and
- to outline possible future trends in Irish climate.

Spatial and temporal variations in the observational surface climate record, such as temperature and precipitation, will be examined. Following from this, a daily, objective, automated atmospheric circulation classification system for Ireland will be constructed. This classification scheme can be used in order to determine if the changes identified in Irish climate in the past can be related to large-scale changes in atmospheric circulation. Circulation is the fundamental control for surface weather, and by examining the frequency of circulation types over Ireland, the extent to which the observed trends in climatic elements are caused by long-term changes in circulation can be investigated. The establishment of the links between circulation patterns and local scale weather variables is also important in the development of circulation-based methods of downscaling, from coarse scale GCMs to finer resolution regional and local levels. By downscaling for the future, possible scenarios based upon the physical relationships established will be projected.

1.4 Thesis Structure

Chapter 2 begins with an outline of changes which have already occurred in Irish climate in the context of global change outlined in the IPCC (2001) Third Assessment Report. Long-term trends over the past century are examined as well as a detailed study of the changes in the period 1960 to 2000. This is to determine whether changes have occurred in Irish climate and, if so, what has been the magnitude of these changes. As atmospheric circulation is a fundamental control for surface weather, Chapter 3 reviews various methods of classifying atmospheric circulation patterns, the strengths and weaknesses of each method along with a review of their application in the literature. Chapter 4 details a method for the construction of a circulation type catalogue for Ireland based on the Lamb/Jenkinson-Collison circulation weather type approach. Calculation of the indices for Ireland as well as an examination of the changes in the occurrence frequency of the major weather types is outlined. In Chapter 5 the relationship between surface climate variables – temperature and precipitation – and the circulation types are analysed. This identification of a relationship between circulation types and temperature and precipitation variables is particularly important in the study of past and future climate variability. It is also important for the development of downscaling techniques which aim at the generation of regional scale scenarios of future climate from coarse scale GCMs. Chapter 6 outlines a selection of downscaling methodologies, from conventional and composite downscaling to dynamical and statistical methods. Dynamical downscaling involves the development of finer resolution Regional Climate Models (RCMs) which are based on smaller temporal and spatial scales than GCMs. However a major drawback is their computational expense. There are a number of statistical methods which are sometimes preferred due to their ease of use. They can be subdivided into transfer functions, weather generators and weather typing techniques. It is the weather type approach which is utilised here, where a change in climate is determined primarily by the changing frequency of the weather classes. The frequencies of the circulation types obtained from the observed and the control run of the GCM (for the baseline period – 1961-1990) have to be compared so as to determine the validity of the GCM in classifying the circulation patterns. This is provided in Chapter 7. Finally, future changes in circulation type frequencies and modelled seasonal scenarios for Ireland are presented.

Chapter 2

Observed Trends in Irish Climate

2.1 Introduction

Ireland's position on the western edge of Europe ensures that its moist temperate climate experiences relatively small year to year variations. There are two major factors which shape the Irish climate: the westerly circulation, a feature of the mid-latitudes, and the proximity of the North Atlantic Ocean (Rohan, 1986). It is the moderating influence of the North Atlantic Drift, however, which ensures that Ireland does not experience those extremes found at other locations on the same latitude e.g. Moscow or Churchill in Hudson Bay (Barrow and Hulme, 1997).

Mean annual temperatures are higher on the south and southwest coast with lower temperatures in the midlands and north of the country. However, the difference in mean annual temperatures between stations is only 1-2°C throughout the country. Local temperature differences at individual stations are larger, with more extreme values and wider temperature ranges at stations on the east and midlands, and narrower ranges at coastal locations. This is primarily due to the regulatory influence of the North Atlantic. Precipitation is highest on the northwest, west and southwest coasts. While the east coast receives approximately 750 - 1000mm per year, this increases to between 1000 - 1250mm on the west coast and up to 3000mm in mountainous regions (Met Éireann, 2004).

Climate change as a consequence of global warming is expected to alter these climatic norms. For mid- to high-latitude land areas such as Europe, the temperature rise is predicted to be substantially greater than the increase predicted for the global mean temperature (Cubasch *et al.*, 1996; Jones *et al.*, 1997; Balling *et al.*, 1998; Déqué *et al.*, 1998). Annual precipitation increases would also be likely for Ireland as a consequence of a warmer atmosphere maintaining more moisture. It would be interesting to determine how these changes may become apparent, especially on a local and regional level. For example, will the temperature rise be more evident in maximum daytime temperatures rather than minimum temperatures, or on a regional basis, will there be greater precipitation increases in the north or south of the country?

In recent years, there has been an increased awareness of the potential impacts of climate change on a variety of sectors in society. Policy decisions need to be based on an understanding of trends in climate and changing frequencies and intensities of extreme events. It is therefore useful, and necessary, to examine the observed trends in Irish climate to discover whether the trends already established in global climate can already be seen in the observational record.

Within this context, the following chapter will initially review the observed trends in global climate, following the publication of the comprehensive Intergovernmental Panel on Climate Change Third Assessment Report (TAR) (IPCC, 2001). This is followed by a review of the Irish climate monitoring network and an outline of the data available for use in this research. Subsequently, a detailed examination of Irish temperature and precipitation data - daily, monthly, seasonally and annually - is conducted. Temporal and spatial variability of these climatic indicators is studied to determine whether the trends in the latest IPCC report can already be seen in the Irish observational record.

2.2 Observed Trends in Global Climate

The IPCC TAR (2001) concluded that there has been an increase in mean global temperatures of $0.6 \pm 0.2^{\circ}C$ since the late 19th century. The warming has not occurred in a linear fashion, but in two main periods: 1910-1945 and 1976 to the present (Jones, 2001). The combined global land and marine surface temperature record compiled by the Climate Research Unit (CRU) and the UK Meteorological Office reveal that the 1990s was the warmest decade in the series, which extended from 1856 to 2003, with the ten warmest years globally having occurred since 1990 (Palutikof, 2004). The bulk of this recent warming has occurred at night, with daily minimum temperatures increasing at a greater rate than daily maxima. There has also been a reduction in the frequency of low temperatures, with a smaller increase in extreme high temperatures. Because of this, the freeze-free season in many mid-

/high-latitude regions has lengthened. There have also been related increases in cloud cover, at the rate of 2% during the 20th century, especially over the mid-/high-latitudes (IPCC, 2001). Warming since 1850 over the Northern Hemisphere has been strongest in the non-summer seasons, especially the winter and spring seasons in both of the warming phases. (Jones, 2001).

Analyses of yearly and seasonal precipitation trends over the past century have also been conducted. Small positive increases in precipitation of the order of 0.5-1% per decade in the mid-/high-latitudes of the Northern Hemisphere have been observed. This pattern is not consistent throughout the globe, however, as large areas are characterised by negative trends (IPCC, 2001). The data for Europe reveal an increase in precipitation in northern areas and a decrease in the south (Schönwiese and Rapp, 1997). Analysis of the frequency of heavy rainfall events indicates a probability of over 90% that a 2-4% increase in frequency has occurred during the past 50 years in the Northern Hemisphere (IPCC, 2001).

Global Climate Model (GCM) results generally indicate that the frequency and intensity of heavy rainfall are expected to increase under enhanced greenhouse conditions, particularly during the non-summer seasons (Hennessy *et al.*, 1997; McGuffie *et al.*, 1999; Jones and Reid, 2001). Results from Osborn *et al.* (2000) for the United Kingdom indicate that, for the period 1961 to 1995, there have been increases in the number of heavy rainfall events, and also rainfall amounts on these days, especially in winter.

2.3 The Irish Climate Monitoring Network

The Irish climate monitoring network consists of fifteen synoptic stations and over 100 climatological stations. The synoptic stations provide hourly measurements of temperature, precipitation, wind speed, direction, sunshine, cloud cover, pressure, humidity, soil and grass temperatures. At some stations, evapotranspiration and solar radiation are also measured. At the climatological stations, daily measurements of temperature and rainfall are recorded, with sunshine, soil and earth temperatures measured at some of these (Fitzgerald and Fitzgerald, 2004). There are a further 550 stations which measure daily rainfall, which are operated by public bodies or volunteers. All data are quality controlled by Met Éireann.

Long term observations began in the 19th century in Ireland at a number of stations, some of which are still in existence today e.g. Valentia Observatory, Malin Head and Birr. From about 1880 onwards the records at these sites would be considered fairly reliable. The oldest station in the country is the climatological station at Armagh Observatory, where records have been continued without interruption since 1795 (Butler *et al.*, 1998).

Station Number	Station Name	Latitude/ Longitude	Height (m) above sea level	Open date	Close Date
305	Valentia	51°56'N 10°14'W	11m	1866	To present
518	Shannon	52°41'N 8°55'W	6m	1937	To present
532	Dublin Airport	53°25'N 6°14'W	71m	1939	To present
545	Malin Head	55°22'N 7°20'W	22m	1885	To present
1004*	Roche's Point	51°46'N 8°15'W	41m	1877	To present
1034	Belmullet	54°13'N 10°00'W	11m	1956	To present
2437	Clones	54°11'N 7°14'W	89m	1950	To present
2615	Rosslare	52°15'N 6°20'W	26m	1956	To present
2727	Claremorris	53°42'N 8°59'W	71m	1943	To present
2222	Mullingar I	53°31'N 7°21'W	111m	1943	1974
2922	Mullingar II	53°14'N 7°21'W	104m	1973	To present
3613	Kilkenny	52°39'N 7°16'W	66m	1957	To present
3723	Casement Aerodrome	53°18'N 6°26'W	94m	1944	To present
3904	Cork Airport	51°50'N 8°29'W	154m	1961	To present
4919	Birr	53°05'N 7°53'W	73m	1873	To present
9336	Armagh	54°21'N 6°39'W	64m	1795	To present

Table 2.1 Synoptic stations in Ireland, their station number, grid coordinates, height above sea level and open and close date. (* denotes fully automated station)

Of the fifteen synoptic stations, eleven stations were open for the period 1960 to 2000. Of these, nine stations had temperature and precipitation records which were 100% complete and continuous. Table 2.1 lists the fifteen stations, their grid co-ordinates, mean height (in metres) above sea level, and open and close date. The locations of these stations are illustrated in Figure 2.1.

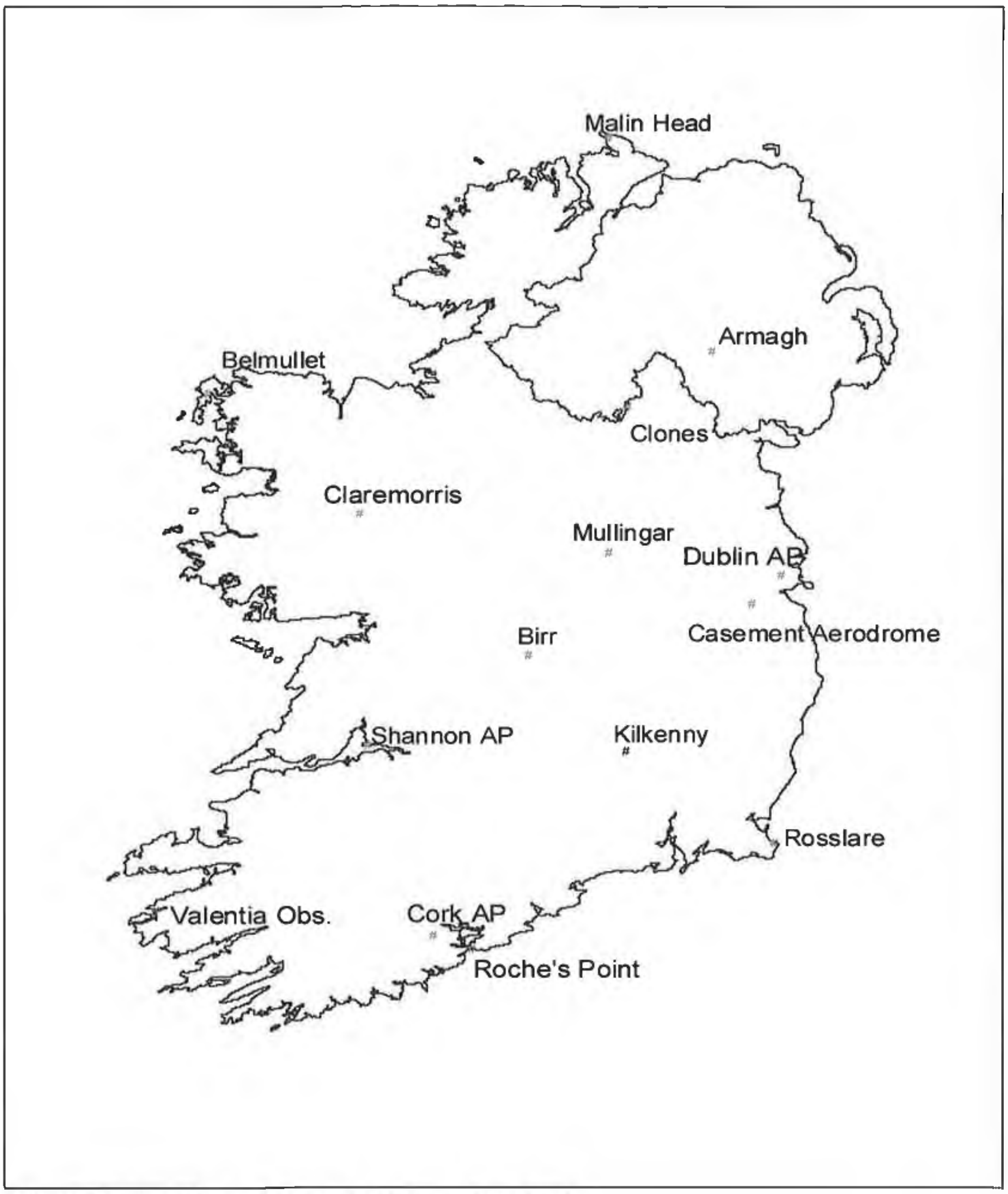


Figure 2.1 Location of synoptic stations in Ireland

2.4 Annual and Seasonal Trends in Irish Temperature

2.4.1 Global and Irish long-term temperature anomaly

It is necessary to examine the Irish meteorological record to determine to what extent the trends identified by the IPCC and others on a global level are being replicated in Ireland. For each of the long-term stations - Armagh, Birr, Malin Head and Valentia - monthly data from 1890 to 2000 were analysed. For each station a monthly temperature anomaly using the 1961-1990 period as baseline was created. Anomalies are utilised as they offer a more accurate description of climatic variability than absolute temperatures and facilitate comparison between different areas (Ventura *et al.*, 2002). The World Meteorological Organisation (WMO) recommends 30 years as the standard period for calculating the average when using anomalies (Ventura *et al.*, 2002). Annual averages were produced from the aggregation of these station data. This approach was similar to that employed by researchers at the Climate Research Unit (CRU) at East Anglia in the UK in deriving the global surface air temperature anomaly. Both of these time series are shown in Figure 2.2.

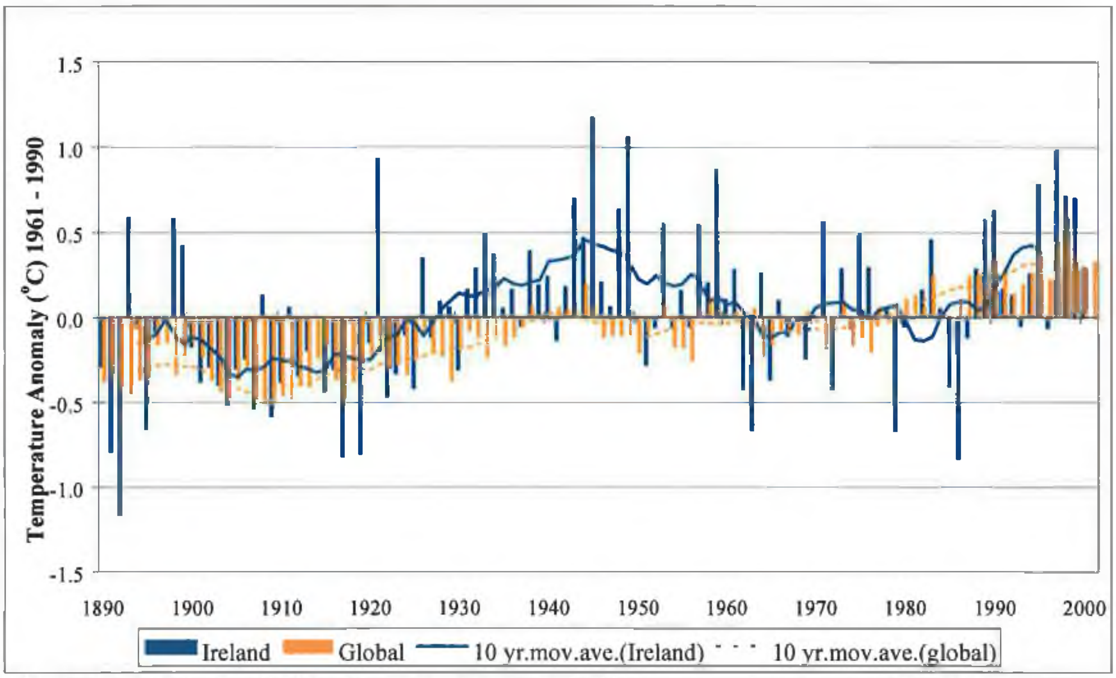


Figure 2.2 Global and Irish air temperature anomaly

The global temperature series shows an increasing trend from 1910 to 1940 followed by a decrease until the mid-1970s. This is followed by above average warming which continues to the end of the series. The Irish series reveals much greater variation, with departures of over 1°C from the mean observed. However, a similar pattern to the global one is followed, with warming not occurring as a linear process, but in two distinct and separate phases. Warming is evident from 1910 to the 1950s, during which the warmest year of the 20th century in Ireland occurred – 1945. A cooler phase followed, lasting up to the beginning of the 1980s. Finally, a period of abrupt and significant warming occurred which has continued to the present. The warmest year of the record globally was 1998, which has an anomaly of 0.58°C from the 1961-90 average. Ireland's warmest year – 1945 – was 1.18°C greater than normal based on this index. There are a number of years in the period 1950-1980 when temperatures were both above and below normal for Ireland, but the trend is generally decreasing for the period. Globally, temperatures have increased by 0.6°C since the beginning of the 20th century. Irish temperatures have been in agreement with this, recording an increase of 0.5°C over the period.

2.4.2 Long-term Irish temperature record

Figure 2.3 illustrates the average of the mean annual temperatures for the four long-term stations of Armagh, Birr, Malin Head and Valentia, along with a 10-year moving average which has been plotted to give a clearer picture of decadal trends.

Warming in Ireland in the past two decades has occurred at a more rapid rate than warming globally. Five of the ten warmest years in the long-term record have occurred since 1990, with 1997 being the warmest year. (Globally, the nine warmest years have occurred in the 1990s and 2000s, with 1998, 2002 and 2003 (joint second) and 2001 being the four warmest years respectively (Palutikof, 2004)). UK temperature trends are also in agreement with this, where the 1990s have been the warmest decade in records extending back over 240 years based on the Central England Temperature (CET) record (Hulme and Jenkins, 1998). There does appear to be a tendency for Irish temperatures to have greater variability than global and CET temperatures. This may be due to the influence of the North Atlantic Ocean. According to Rodwell *et al.* (1999), '...sea surface temperatures are 'communicated' to the atmosphere through evaporation, precipitation and atmospheric-heating processes, leading to changes in temperature, precipitation and storminess over Europe'.

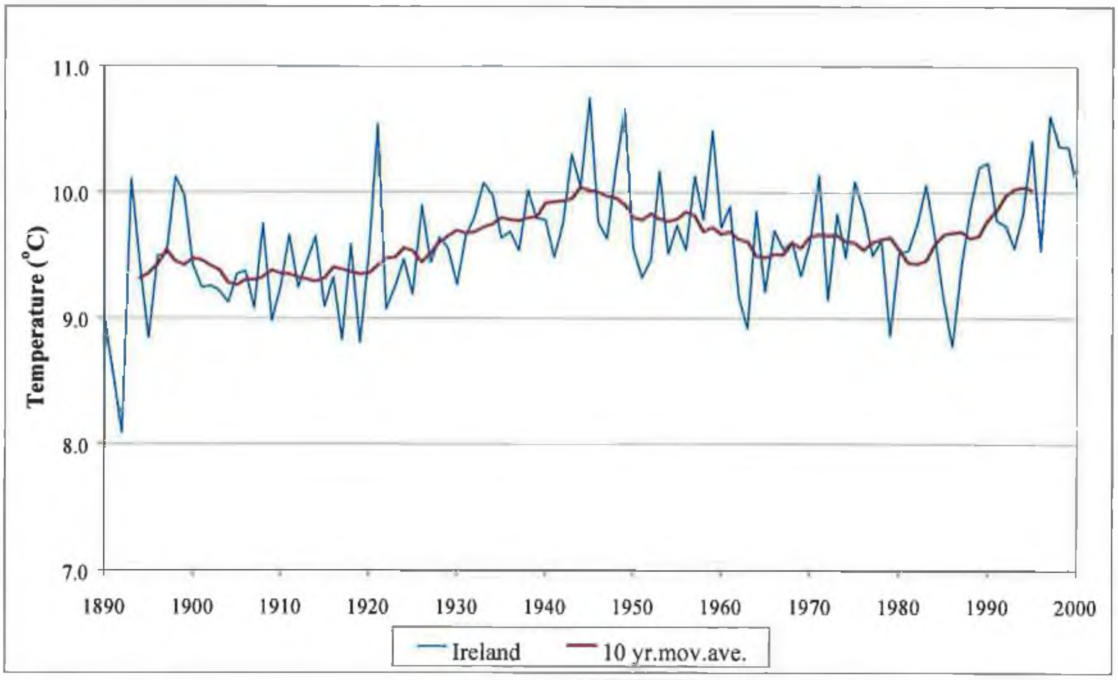


Figure 2.3 Irish long-term annual air temperature record

2.4.3 *Seasonal maximum and minimum temperatures*

One of the expectations from greenhouse warming is a somewhat greater increase in minimum relative to maximum temperature (Folland *et al.*, 1999). Thus, there is an added importance to exploring maximum and minimum temperatures, rather than simply the mean. Easterling *et al.* (1997), in their analysis of global mean surface air temperature covering 54% of the total global land area, have observed that its increase is partly due to asymmetrical changes in daily maximum and minimum temperatures. In most cases, daily minimum temperatures were increasing at a faster rate or decreasing at a slower rate than the daily maximum (Easterling *et al.*, 1997). This results in a narrowing of the diurnal temperature range (DTR). The DTR is defined as the difference between the mean monthly maximum and minimum temperatures. While not all regions show a greater warming at night, it does appear to be the dominant signal in many regions. Karl *et al.* (1993) showed that minimum temperatures have increased two to three times more than maximum temperatures over 37% of the global landmass during the period 1951 - 1990. They also indicated a decrease in the DTR over many areas of the globe. An increase in mean temperature has been replicated in maximum and minimum temperatures, with both increasing, in Northern and Central Europe. However, minimum temperatures have increased slightly more (Heino *et al.*, 1999). Jones *et al.* (1999) in their analysis of the 240-year CET record 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. Warming since 1850 over the Northern Hemisphere has been strongest in the non-summer seasons, especially the winter and spring seasons in the two warming phases (Jones, 2001).

A least squares linear regression line was fitted to maximum and minimum temperature data for each of nine synoptic stations in Ireland, for each season to establish a generalised trend over the period of record, 1960-2000. Each of the seasons are regarded as 3-month periods: March-April-May for spring, June-July-August for summer, September-October-November for autumn and December-January-February for winter. For each station, daily maximum and minimum temperatures were averaged for the 3-month period and their 5-year moving averages plotted (see Figures 2.4 to 2.12). Table 2.2 shows the change in temperature at each station for the period 1960-2000.

	Spring Max	Spring Min	Summer Max	Summer Min	Autumn Max	Autumn Min	Winter Max	Winter Min
Valentia	+0.37	+0.75	+0.62	+1.16**	+0.37	+0.72	+1.01*	+1.28*
Shannon	+0.87**	+1.66**	+1.22*	+1.85**	+0.69	+1.36**	+1.39**	+1.86**
Dublin AP	+1.03*	-0.18	+1.17**	-0.04	+0.46	-0.27	+1.40*	+0.46
Malin Head	+0.25	+0.73	+0.39	+0.89**	+0.34	+0.57	+1.00*	+0.75
Belmullet	+0.84*	+0.84	+1.20*	+1.32**	+0.82	+0.42	+1.25*	+1.12
Birr	+0.69*	+0.79	+0.97	+1.14**	+0.45	+0.60	+1.34*	+1.15
Kilkenny	+0.96**	+1.00*	+1.23*	+1.34**	+0.67	+1.21*	+1.46*	+1.22*
Mullingar	+0.11	+0.74	+0.12	+0.81**	+0.25	+0.27	+1.34**	+1.09
Rosslare	+0.67*	+0.90**	+0.81*	+1.07**	+0.57	+0.76*	+1.36*	+1.08

** Significant at the 99% level

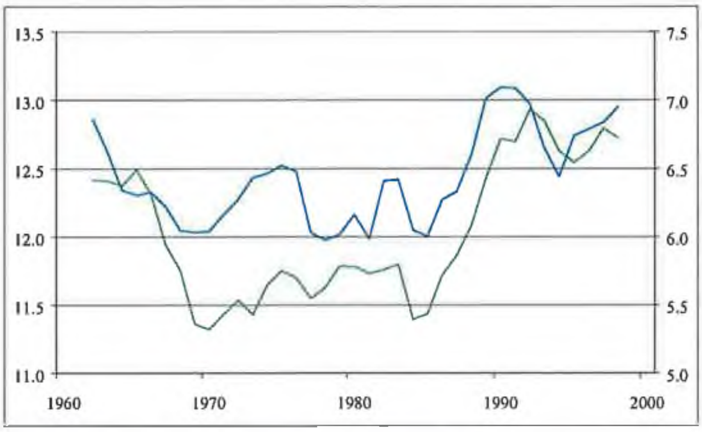
* Significant at the 95% level

Table 2.2 1960-2000 seasonal maximum and minimum temperature change.

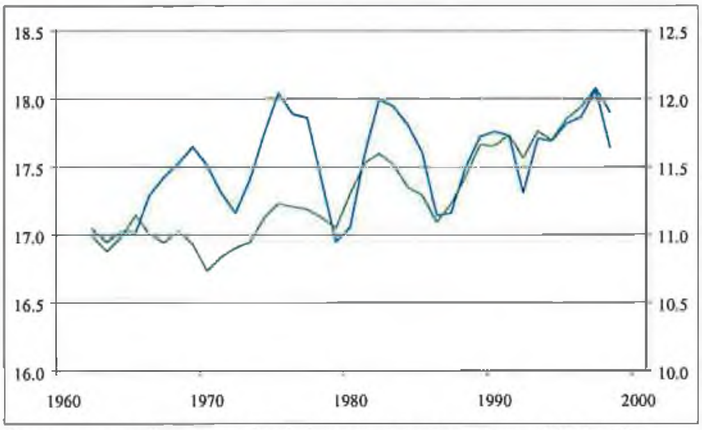
Maximum and minimum temperatures increase in all seasons at all stations, with the exception of spring, summer and autumn minimum temperatures at Dublin Airport. During these seasons at this station, minimum temperatures decrease slightly, although not significantly. At the remainder of stations in spring and summer, minimum temperatures increase more than maximum temperatures. Autumn temperatures also follow a similar pattern, with the exception of Belmullet, where the maximum temperature increase is greater than the minimum. Winter maximum temperatures increase more than winter minimum temperatures at seven of the nine stations analysed, with only Valentia and Shannon having greater minimum temperature increases. It is also interesting to note that all increasing summer minimum temperatures are significant at the 99% level (Kendall's non-parametric significance test), while all increasing winter maximum temperatures are significant at either the 99% or 95% significance level.

In summary, it is evident that minimum temperatures are warming more than maximum temperatures in spring, summer and autumn, with maximum temperatures in winter warming more than minimum temperatures. The only evidence of decreasing seasonal temperatures is in spring, summer and autumn minimum temperatures at Dublin Airport.

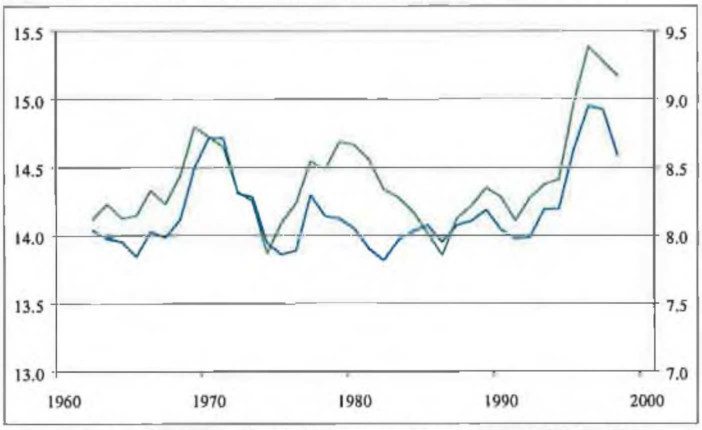
At a global level, the greatest seasonal warming has occurred during the Northern Hemisphere winter and spring. As a result, the difference between summer and winter temperatures has decreased (IPCC, 2001). Winter warming contributes most to the recent warming trend in Irish climate, with winter maximum temperatures accounting for the greatest proportion of this. The greatest warming occurs in the November to March period and also July and August, with least warming in April, May, June, September and October.



Spring maximum and minimum temperatures at Valentia



Summer maximum and minimum temperatures at Valentia



Autumn maximum and minimum temperatures at Valentia

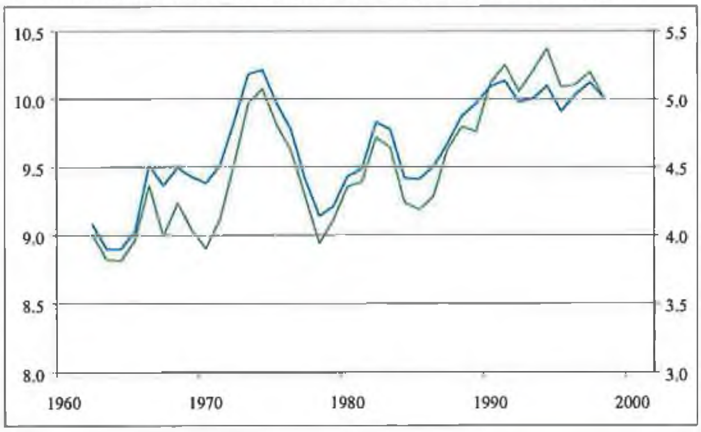
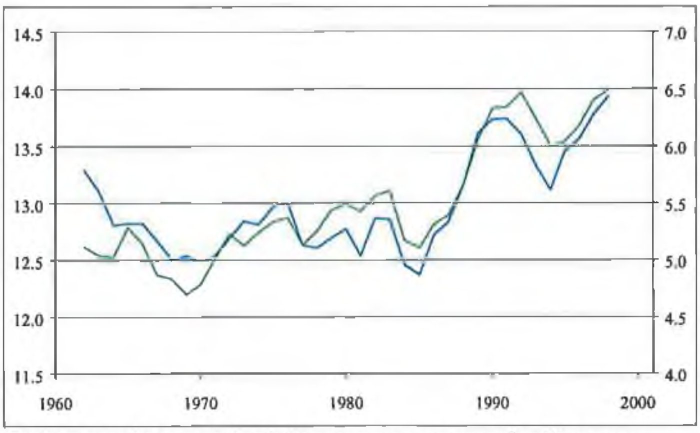
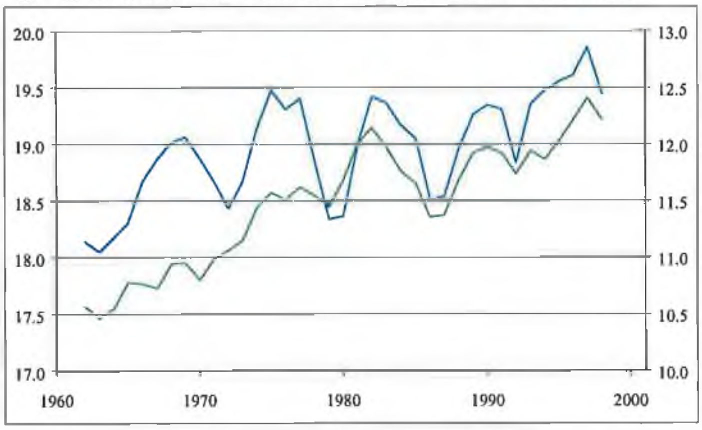


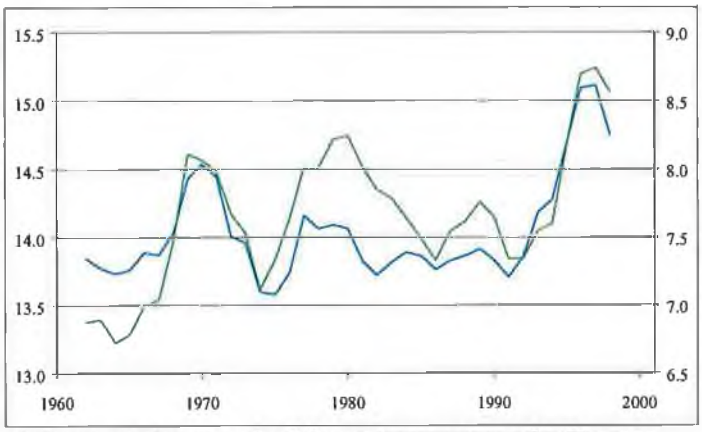
Figure 2.4 Winter maximum and minimum temperatures at Valentia
5 year moving averages, blue line = maximum temperature, green line = minimum temperature



Spring maximum and minimum temperatures for Shannon



Summer maximum and minimum temperatures for Shannon



Autumn maximum and minimum temperatures for Shannon

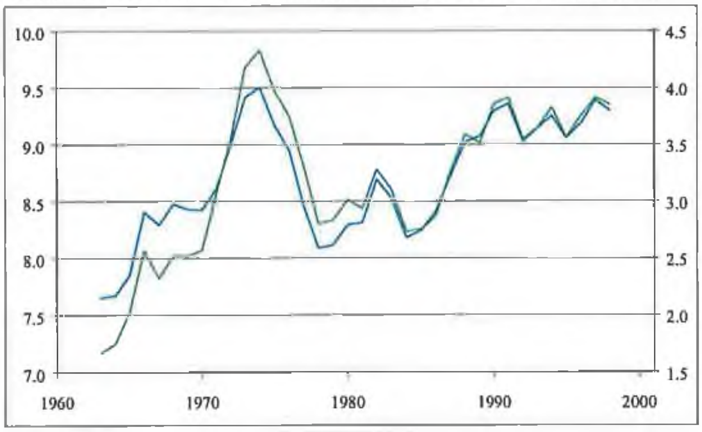
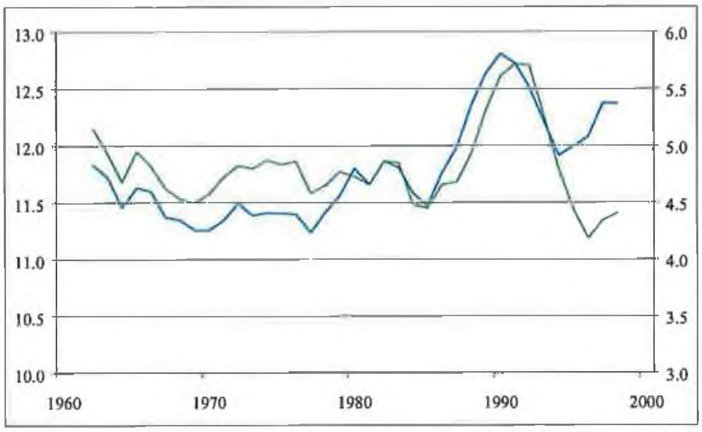
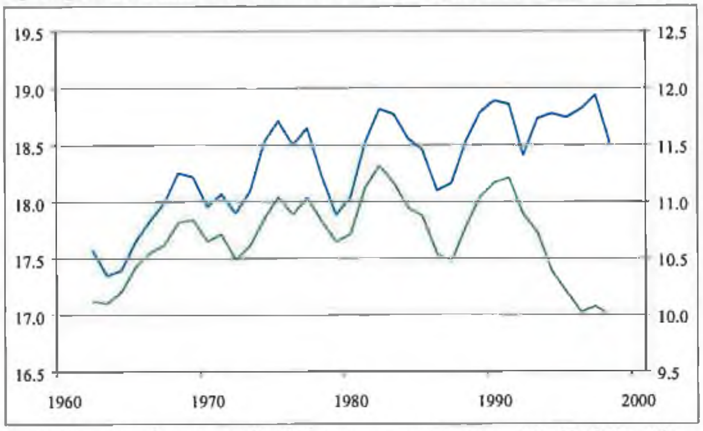


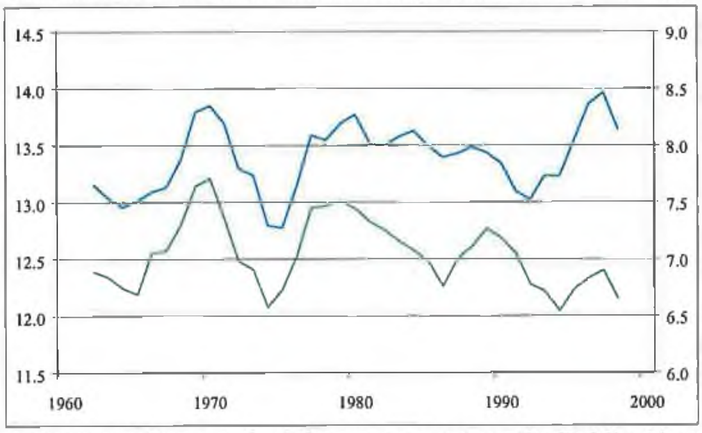
Figure 2.5 Winter maximum and minimum temperatures for Shannon
5 year moving averages, blue line = maximum temperature, green line = minimum temperature



Spring maximum and minimum temperatures for Dublin Airport



Summer maximum and minimum temperatures for Dublin Airport



Autumn maximum and minimum temperatures for Dublin Airport

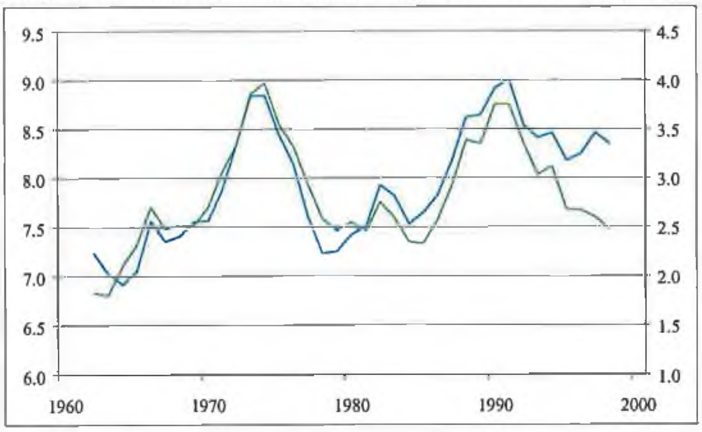
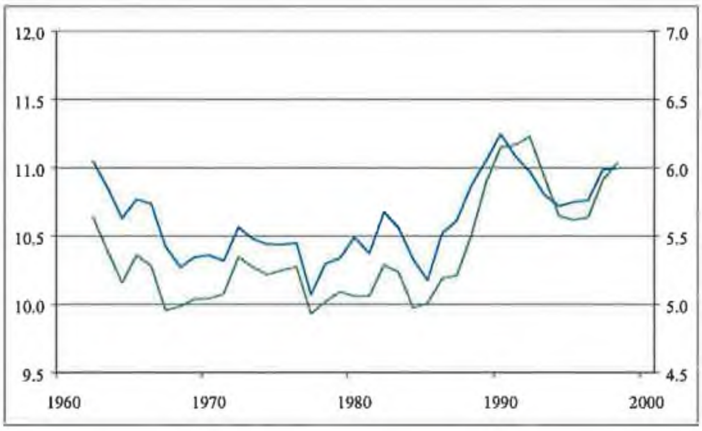
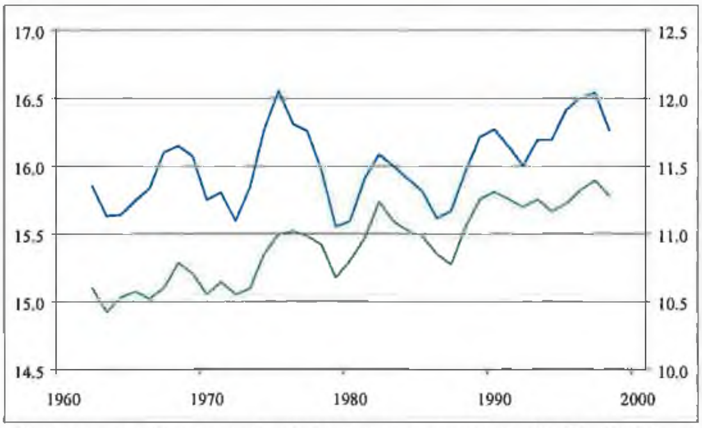


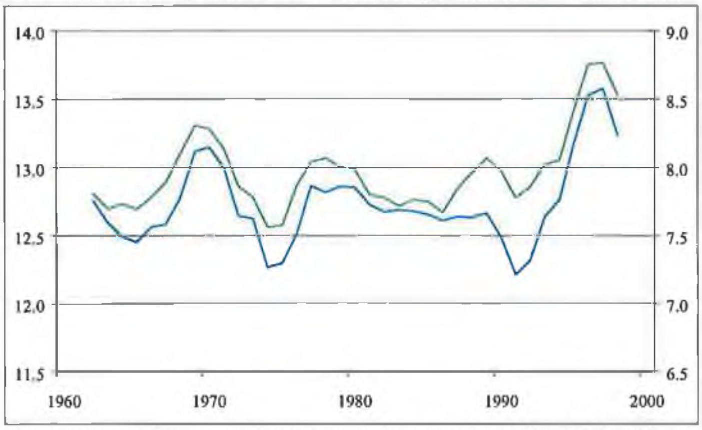
Figure 2.6 Winter maximum and minimum temperatures for Dublin Airport
5 year moving averages, blue line = maximum temperature, green line = minimum temperature



Spring maximum and minimum temperatures for Malin Head



Summer maximum and minimum temperatures for Malin Head



Autumn maximum and minimum temperatures for Malin Head

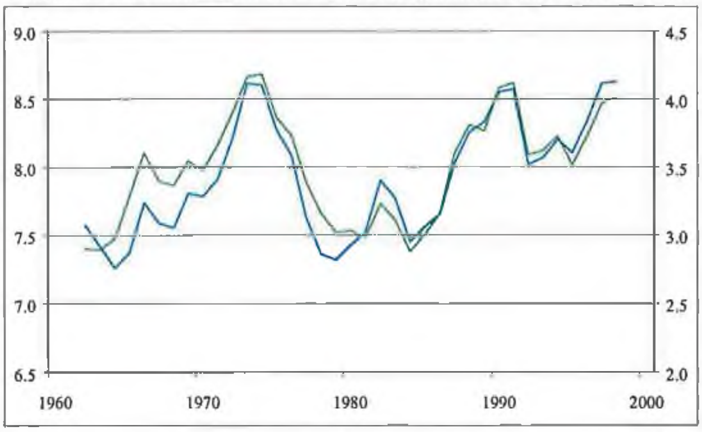
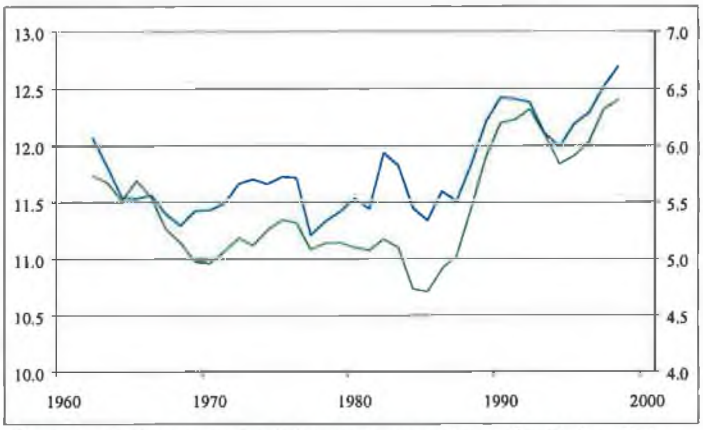
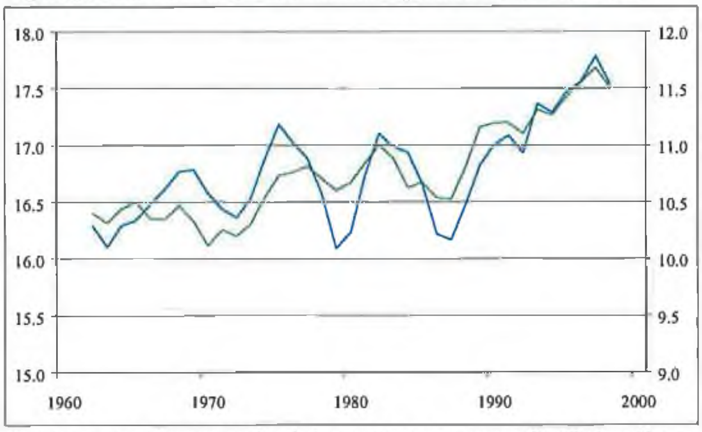


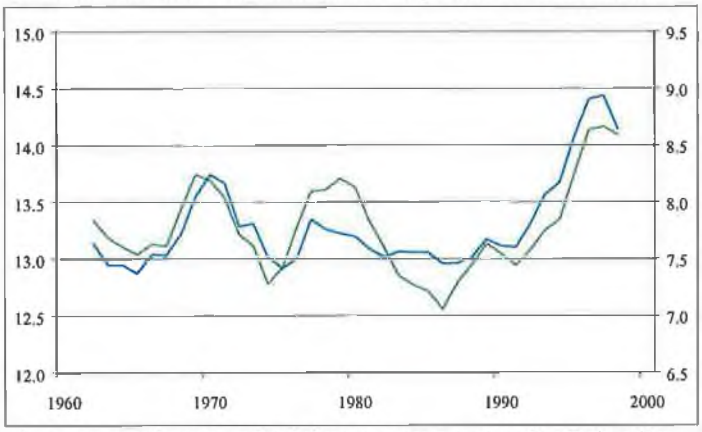
Figure 2.7 Winter maximum and minimum temperatures for Malin Head
5 year moving averages, blue line = maximum temperature, green line = minimum temperature



Spring maximum and minimum temperatures for Belmullet



Summer maximum and minimum temperatures for Belmullet



Autumn maximum and minimum temperatures for Belmullet

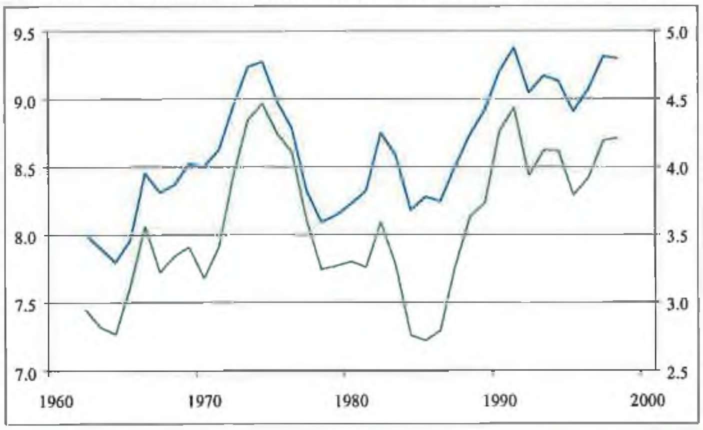
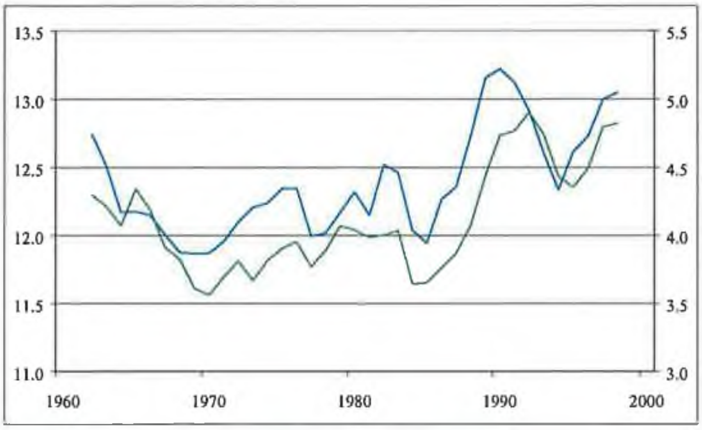
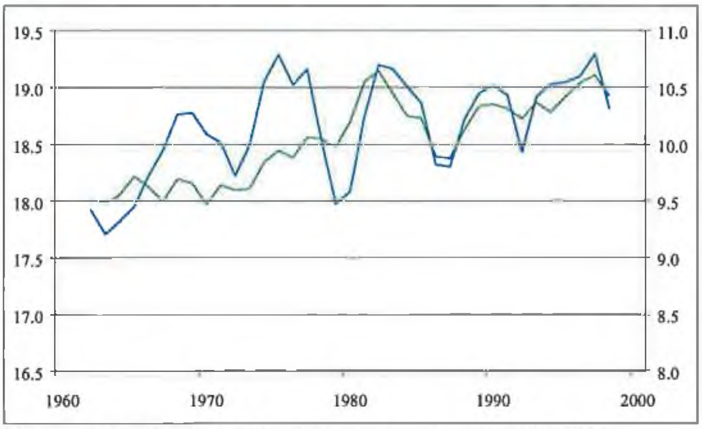


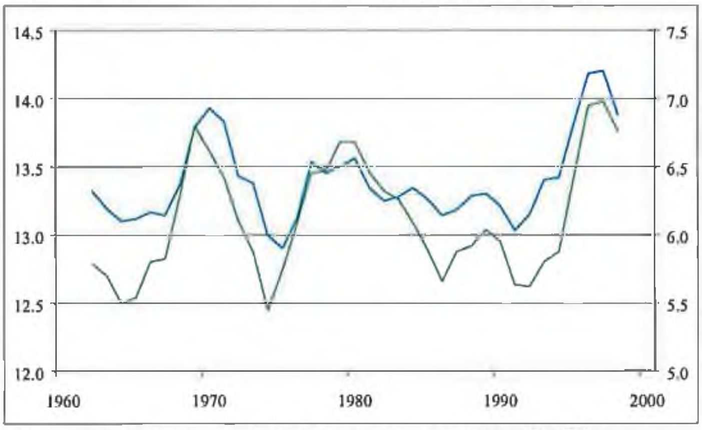
Figure 2.8 Winter maximum and minimum temperatures for Belmullet
5 year moving averages, blue line = maximum temperature, green line = minimum temperature



Spring maximum and minimum temperatures for Birr



Summer maximum and minimum temperatures for Birr



Autumn maximum and minimum temperatures for Birr

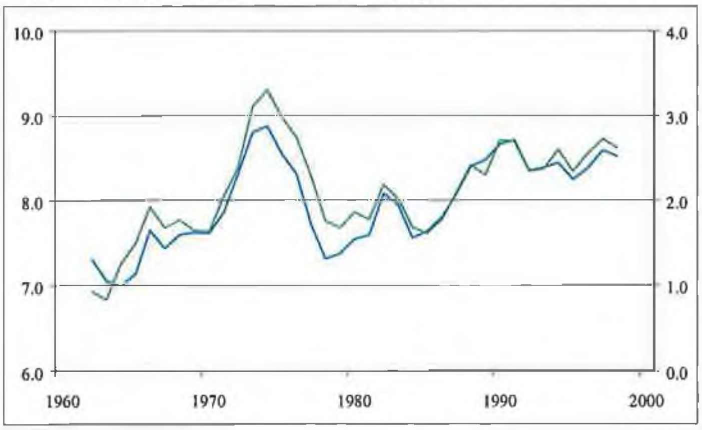
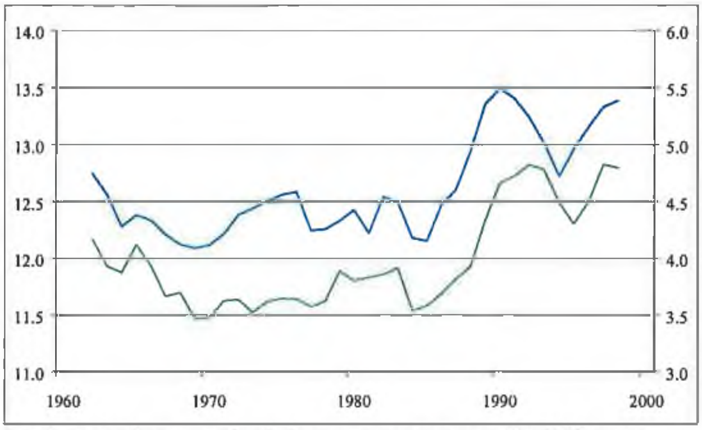
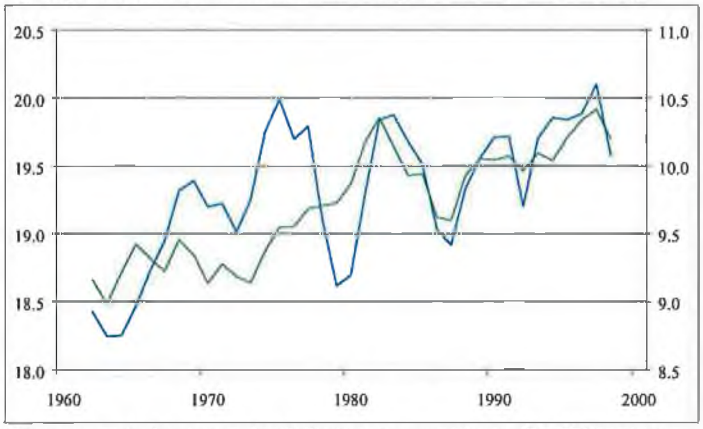


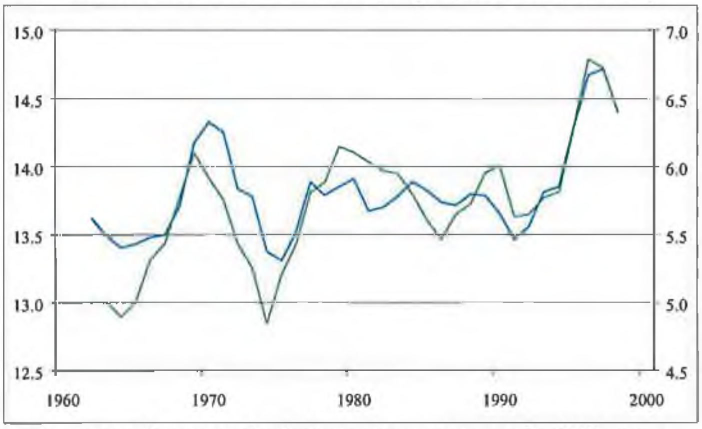
Figure 2.9 Winter maximum and minimum temperatures for Birr
5 year moving averages, blue line = maximum temperature, green line = minimum temperature



Spring maximum and minimum temperatures for Kilkenny



Summer maximum and minimum temperatures for Kilkenny



Autumn maximum and minimum temperatures for Kilkenny

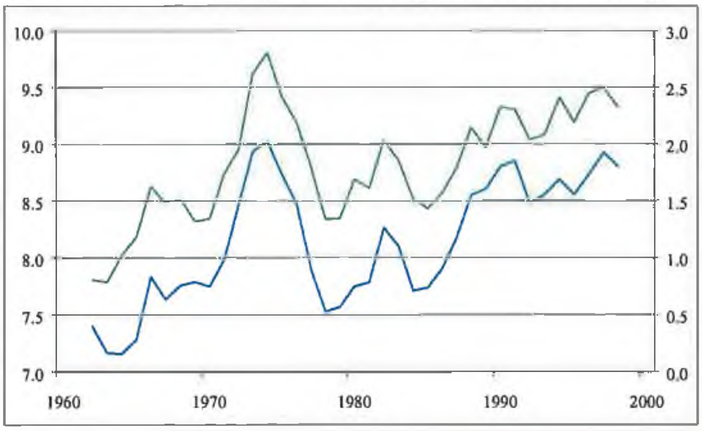
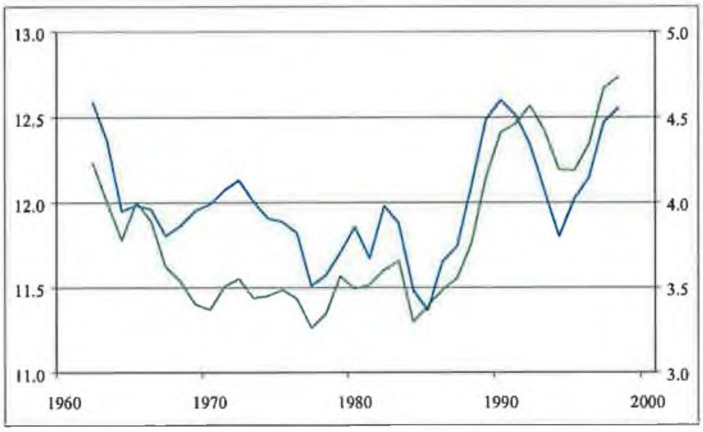
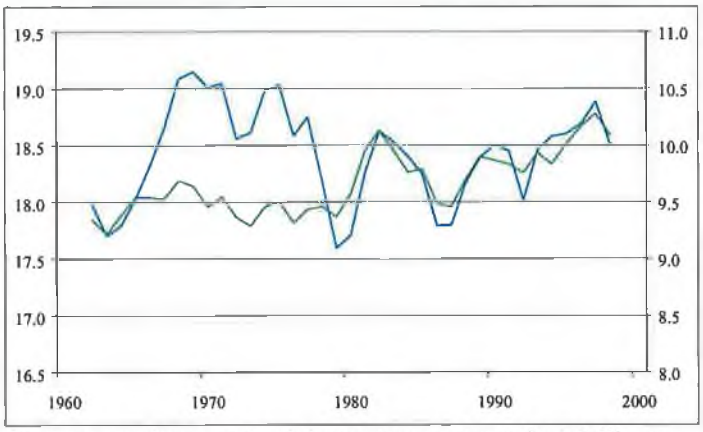


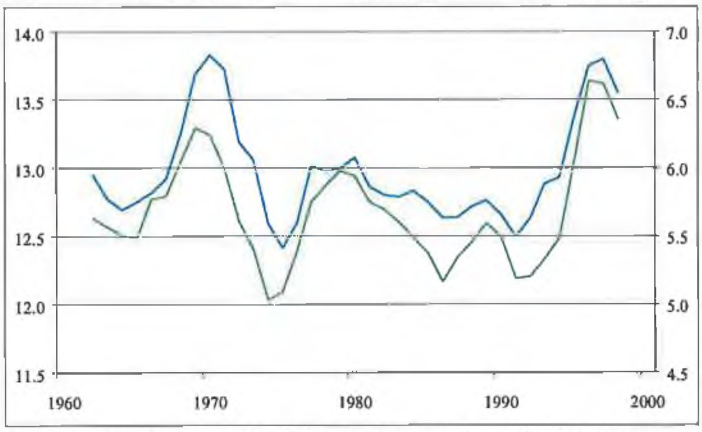
Figure 2.10 Winter maximum and minimum temperatures for Kilkenny
5 year moving averages, blue line = maximum temperature, green line = minimum temperature



Spring maximum and minimum temperatures for Mullingar



Summer maximum and minimum temperatures for Mullingar



Autumn maximum and minimum temperatures for Mullingar

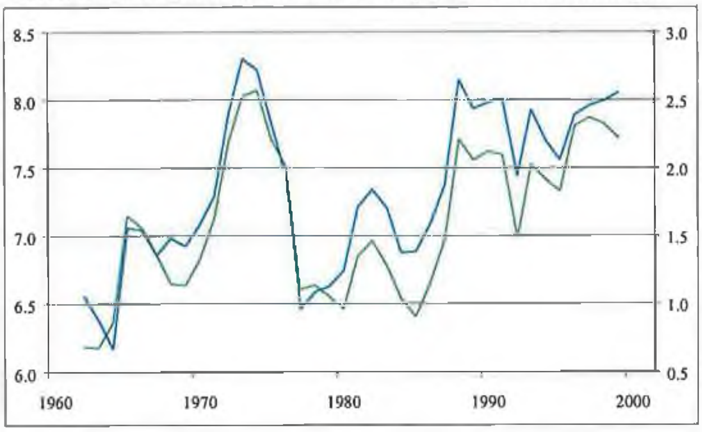
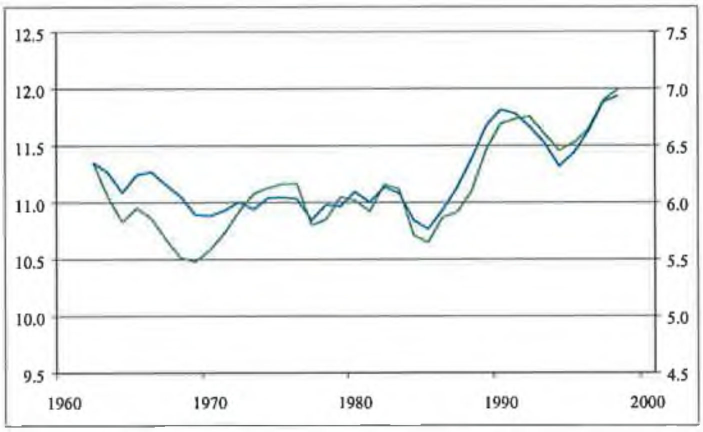
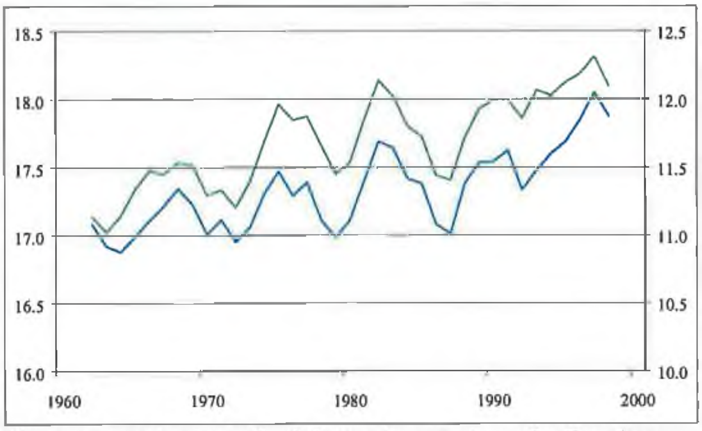


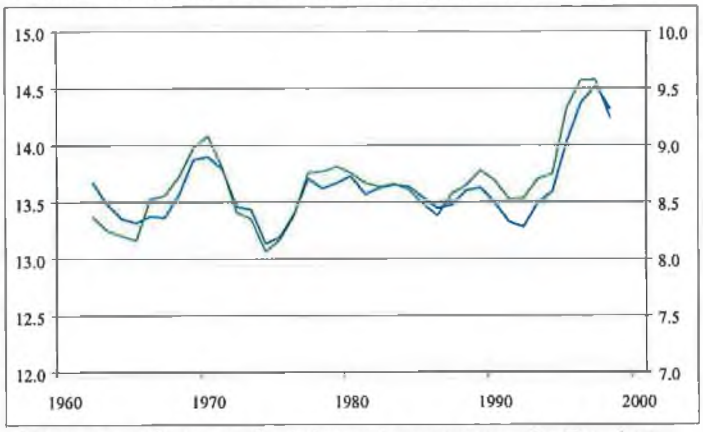
Figure 2.11 Winter maximum and minimum temperatures for Mullingar
5 year moving averages, blue line = maximum temperature, green line = minimum temperature



Spring maximum and minimum temperatures for Rosslare



Summer maximum and minimum temperatures for Rosslare



Autumn maximum and minimum temperatures for Rosslare

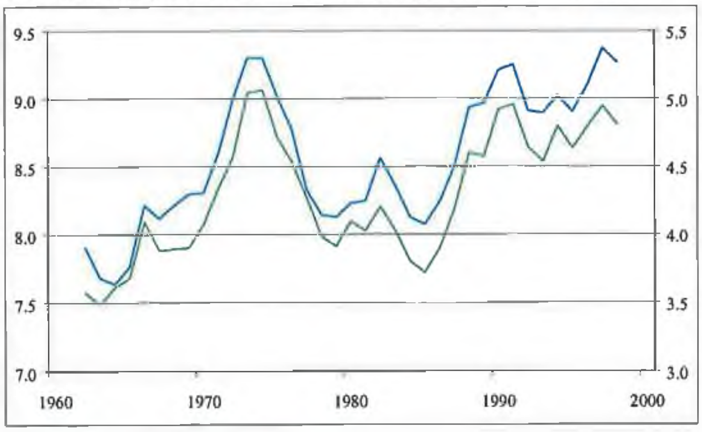


Figure 2.12 Winter maximum and minimum temperatures for Rosslare
5 year moving averages, blue line = maximum temperature, green line = minimum temperature

2.5 Secondary Temperature Indices

Important information regarding climate change detection is lost in some investigations, when monthly or longer averages are used (Przybylak, 2000). Analysing daily data and changes in the frequency of days above and below certain thresholds may identify more revealing trends. A relatively small change in mean can lead to large changes in the frequency of extremes (Katz and Brown, 1992; Salinger and Griffiths, 2001). Given that there are increases in annual and seasonal mean temperatures, it is expected that there may also be increases in what are considered extreme events (Easterling *et al.*, 2000). Until recently, trends in climate extremes had received little attention, largely as a result of issues concerned with data quality and quantity. Even a relatively small amount of missing data, which may not necessarily affect the mean significantly, raise the possibility that an extreme distribution has been missed (Manton *et al.*, 2001). According to Easterling *et al.* (2000) lack of long-term data suitable for the analysis of extremes is one of the single biggest obstacles to assessing whether extreme climate events have changed.

2.5.1 Frequency of 'hot' days

Globally, there has been a trend towards reduced numbers of extremely cold days, with fewer frosts and freezes, and also an increase in the number of extremely hot days, during the past century (Karl and Easterling, 1999). Ireland's oceanic climate however, means that temperature extremes are rare and the mean temperature fluctuates within narrow limits. There have been attempts at standardising climate indicators, such as those defined by the World Meteorological Organisation (WMO), Climate Variability and Predictability (CLIVAR) and the European Climate Assessment and Dataset (ECA&D). The ECA&D defines a frost day as a day when minimum temperatures are less than 0°C, while warm summer days are those with maximum temperatures greater than 25°C. While temperatures such as these would be frequent in continental Europe, the moderating influence of the North Atlantic Ocean ensures that maximum temperatures in Ireland reaching 25°C are relatively infrequent. For example, in 2002 a temperature above 25°C was only recorded at 2 synoptic stations, 25.6°C at Clones and 25.0°C at Mullingar (Met Éireann, 2002). For the purposes of this study, a 'hot' day is defined as any day

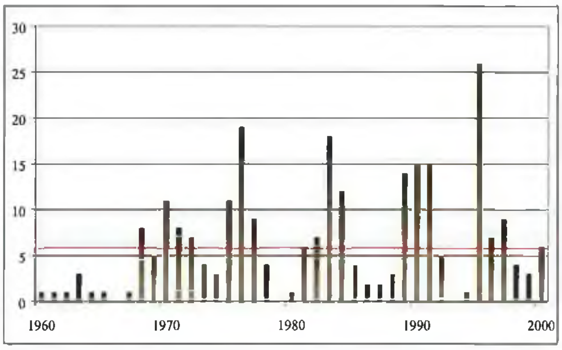


Figure 2.13 Valentia

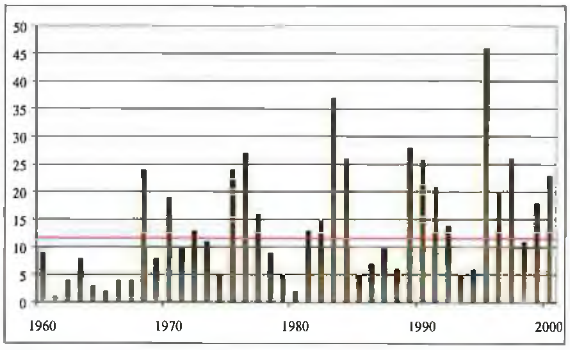


Figure 2.14 Shannon

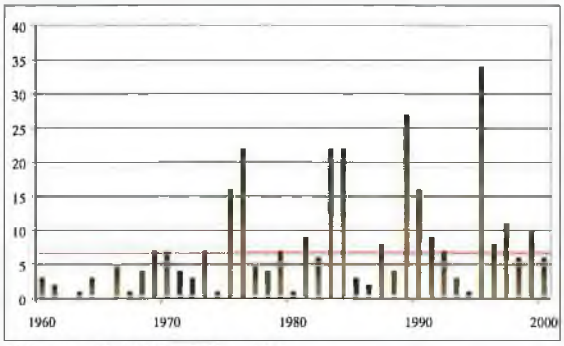


Figure 2.15 Dublin AP

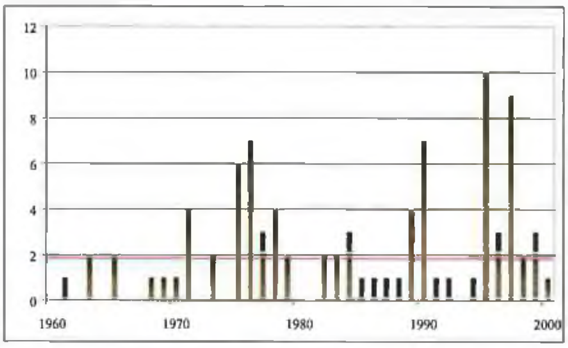


Figure 2.16 Malin Head

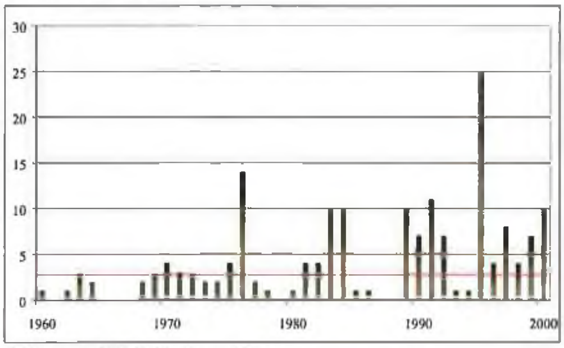


Figure 2.17 Belmullet

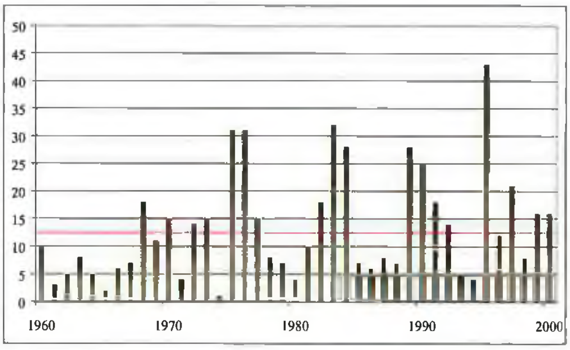


Figure 2.18 Birr

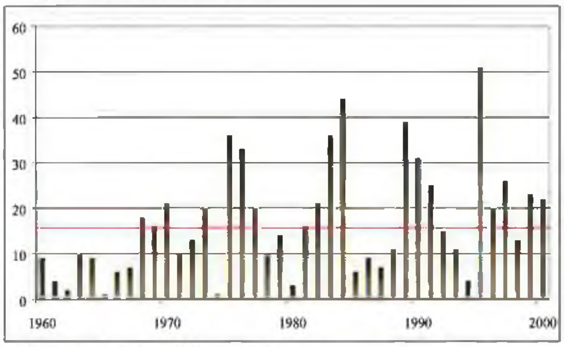


Figure 2.19 Kilkenny

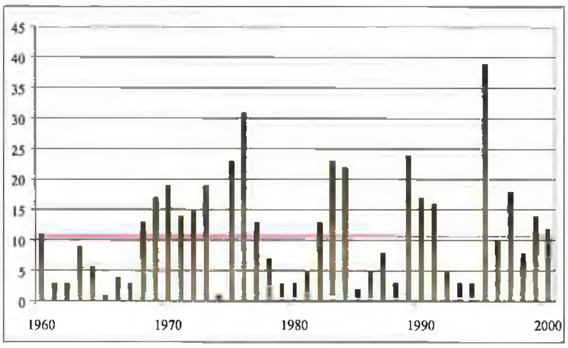


Figure 2.20 Mullingar

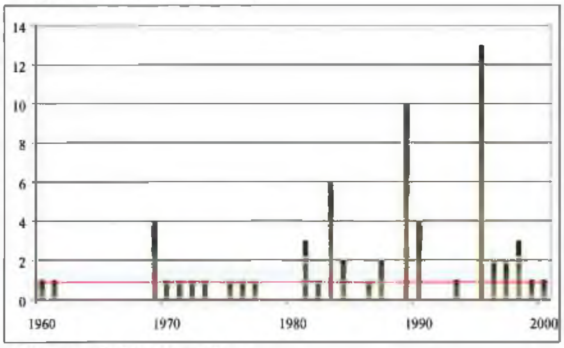


Figure 2.21 Rosslare
Frequency of 'hot' summer days per year at each station

when the maximum temperature is greater than 22°C. The frequencies of days reaching this threshold are illustrated in Figures 2.13 to 2.21. (The red horizontal line in each graph represents the 1961-1990 mean frequency of hot days). The number of hot days can be quite rare at the coasts with consecutive years at a number of stations recording zero or one day only. For example, at Rosslare (Figure 2.21), there were seven years in the 1960s which had zero hot days. In addition, in the 1980s at Malin Head (Figure 2.16) there were four years which measured only one hot day. Significantly, at all nine stations, 1995 emerges as the year with most hot days, ranging from 51 at Kilkenny to 10 at Malin Head. This represents an increase of three times the 1961-1990 average number of days at Kilkenny (on average sixteen warm days in '61-90), while there was a five-fold increase on the 1961-1990 average at Malin Head (61-90 average equals two). Seven stations have statistically significant increases in frequency of hot days over the period 1960 to 2000, at the 95% level for Malin Head, Rosslare and Birr, while at the 99% level for Kilkenny, Shannon, Dublin Airport and Belmullet.

Hulme's study on the Central England Temperature record over the period of the 20th century showed an increase in recent years in the number of summers with mean temperatures above 20°C, with the summer of 1995 measuring record numbers of days (Hulme, 1999a). In the longer term, the 240-year long daily CET shows no significant increase in very warm days in recent years but there is a marked decrease in the frequency of very cold days. Thus the rise in temperature in the last two decades is principally associated with a reduction in very cold days (Jones *et al.*, 1999).

2.5.2 First and last day of frost season

Due to an increase in minimum temperatures in spring and autumn, it might be expected that the length of the frost season would shorten, with a reduced number of frost days annually. The increase in the mean minimum temperature has been demonstrated to have affected the length of the frost-free period, which has potential impacts for a number of sectors such as agriculture, power generation and consumption (Karl and Easterling, 1999). The frost season extends from August 1st to July 31st in the northern latitudes, and is measured when the minimum temperature drops below 0°C (Folland *et al.*, 1999). A basic index to represent the date of first and last frost has been examined for four representative stations in Ireland. These were Dublin Airport (Figure 2.22), Valentia (Figure 2.23), Birr (Figure 2.24) and Malin Head (Figure 2.25). Different trends were found at each of the stations, and none of these were statistically significant. The frost season appears to be shorter in recent years at Birr and Malin Head, due primarily to an earlier last frost. The last frost at Birr seems to have shifted from the first week in May to the last week in April. The last frost is approximately two weeks earlier at Malin Head, shifting from mid-March to the beginning of the month. Valentia and Dublin Airport both appear to have a longer frost season, with Valentia's last frost day 9-10 days later, and Dublin's first frost date occurring earlier while the last frost is a number of days later.

The occurrence of frost has a considerable impact on many human activities, including the agricultural and construction industries (Heino *et al.*, 1999). Clearly this indicator would have important consequences for farmers, especially those growing frost-sensitive crops. The date of first and last frost occurrence for Ireland appears to be irregular and as such, not a very consistent climate change indicator.

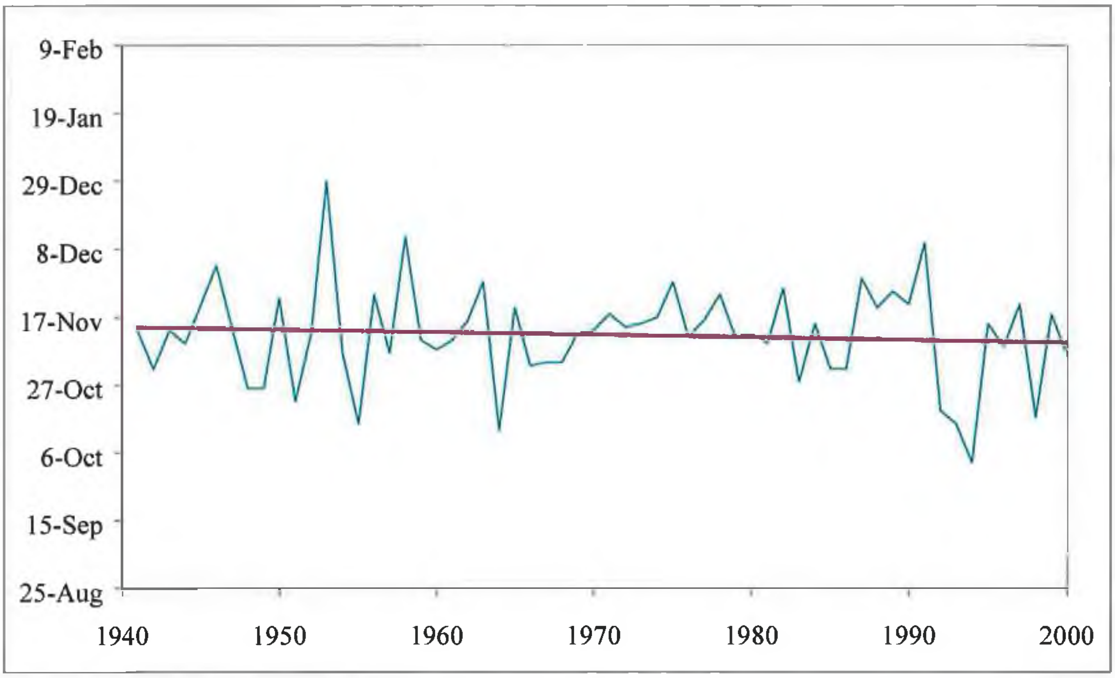


Figure 2.22a First date of frost at Dublin Airport

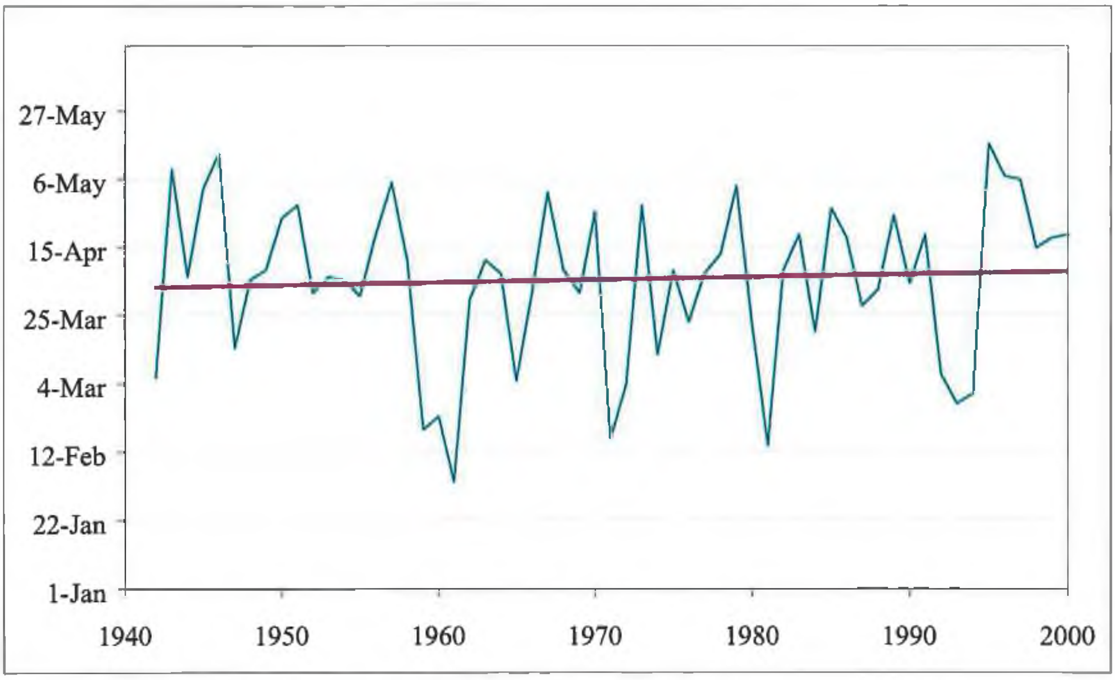


Figure 2.22b Last date of frost at Dublin Airport

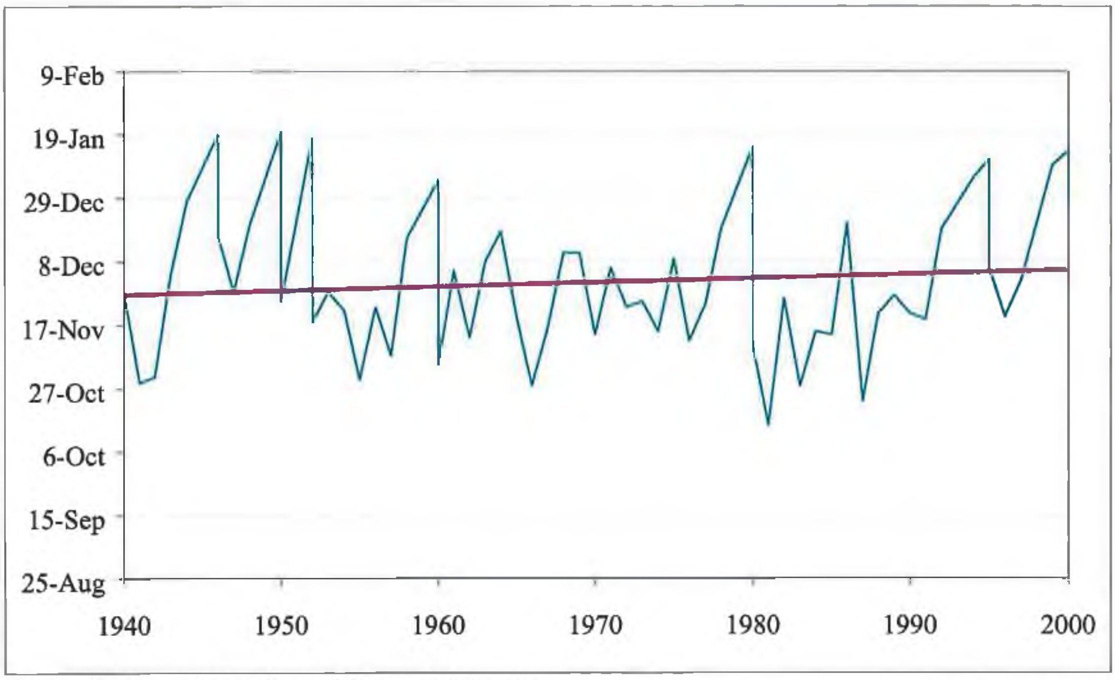


Figure 2.23a First date of frost at Valentia

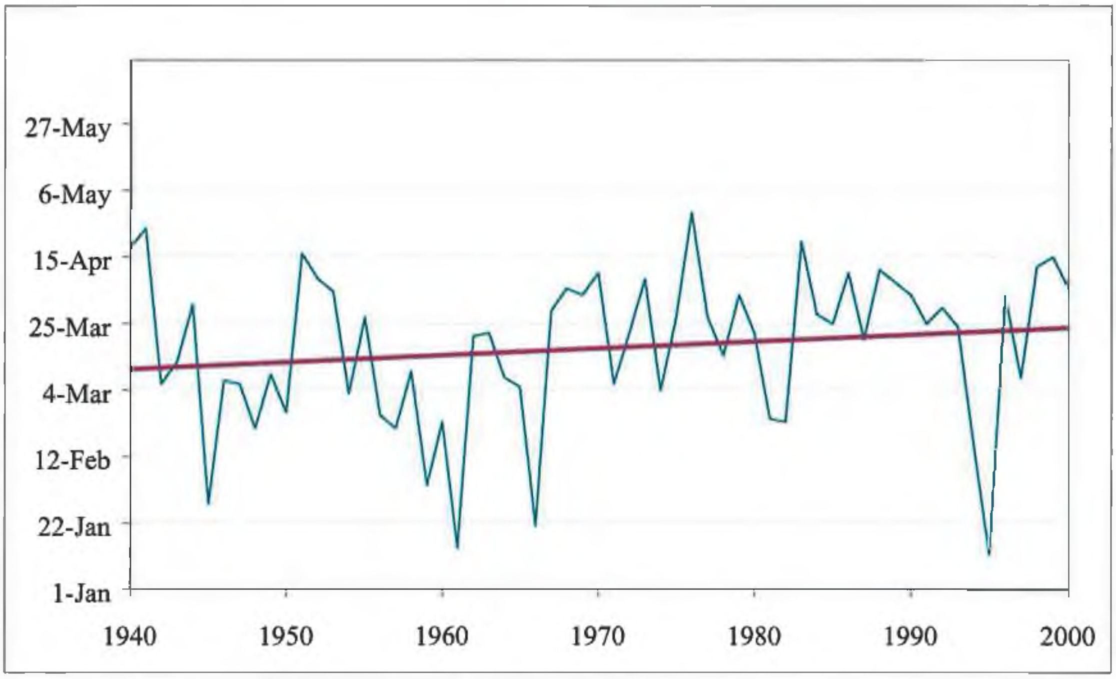


Figure 2.23b Last date of frost at Valentia

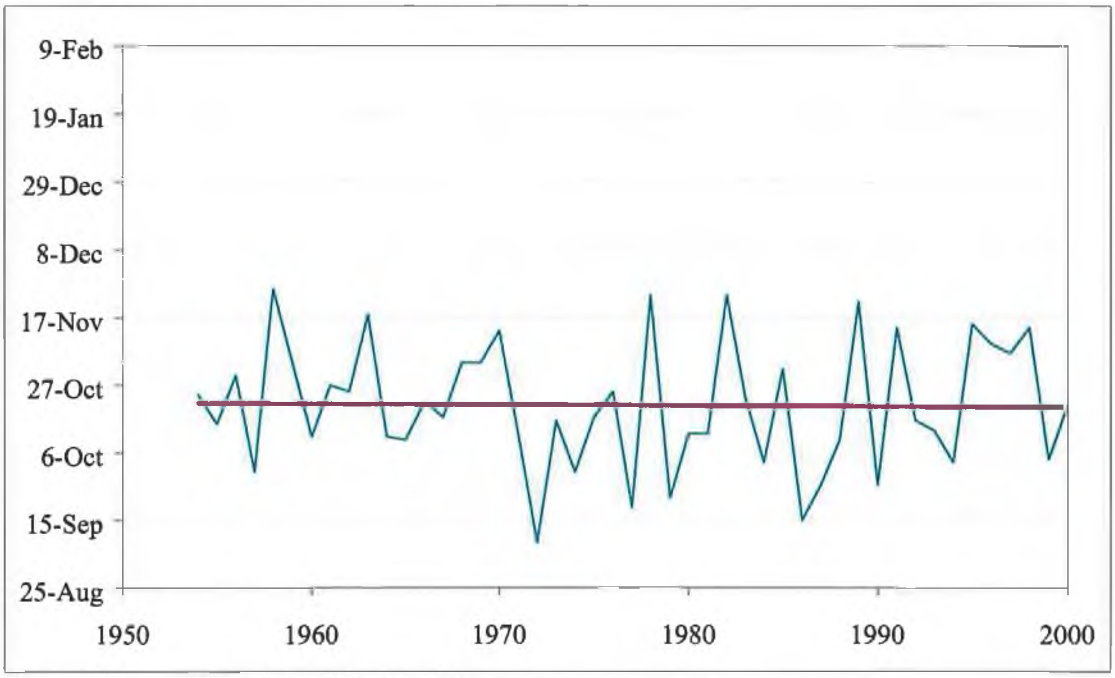


Figure 2.24a First date of frost at Birr

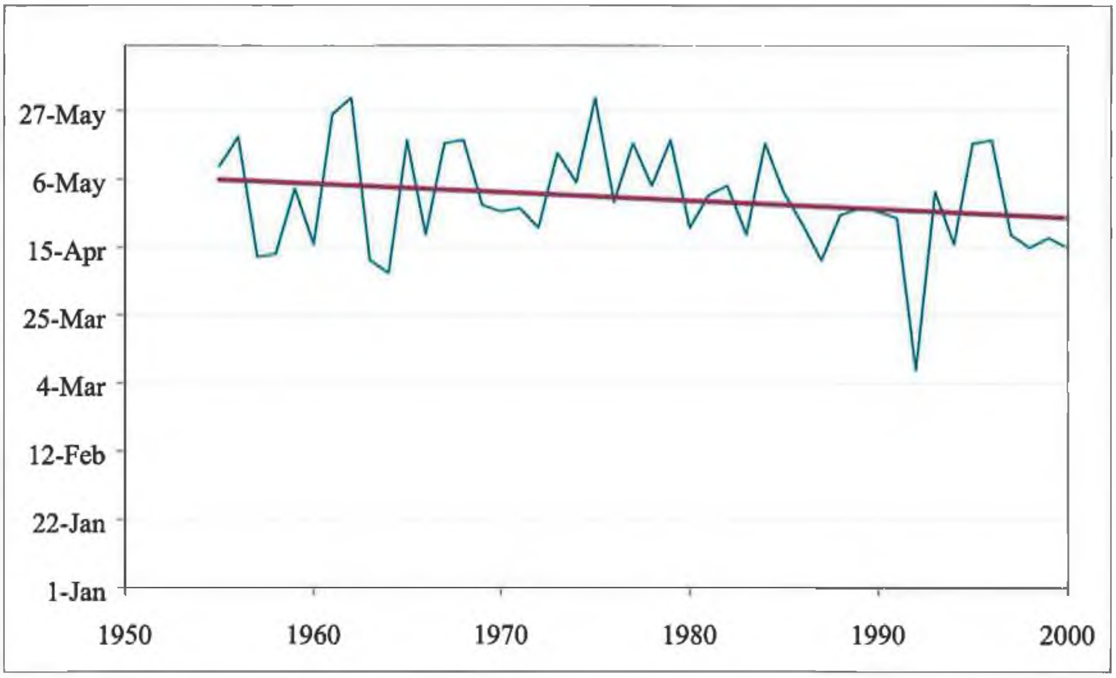


Figure 2.24b Last date of frost at Birr

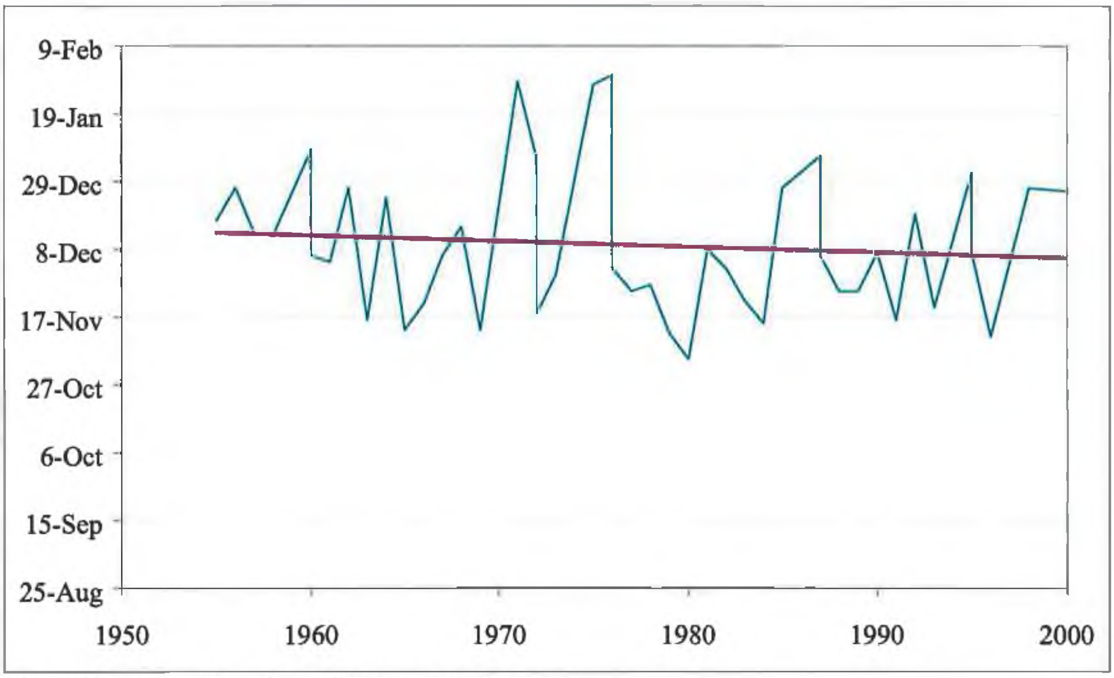


Figure 2.25a First date of frost at Malin Head

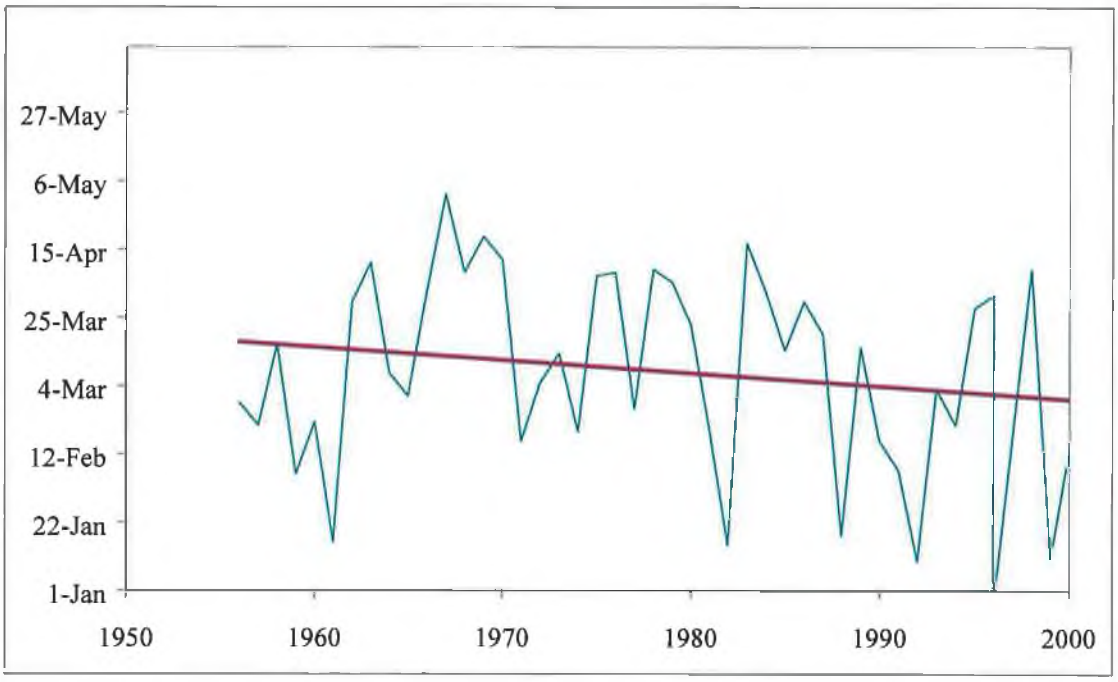


Figure 2.25b Last date of frost at Malin Head

2.5.3 Frequency of frost days

The frequency of frost days may be a more sensitive indicator of a changing climate. Studies in New Zealand and Australia (Plummer *et al*., 1999) relate the decreasing frequency of days below freezing with a warming in daily minimum temperatures, and subsequently a link to changes in atmospheric circulation in the region. Evidence of a decrease in the number of frost days in Europe since the 1930s also appears to be associated with increases in winter minimum temperatures (Heino *et al*., 1999).

The sea temperature surrounding Ireland has never been recorded below 0°C and air frost is infrequent at coastal locations (Rohan, 1986). Further inland, however, the number of days with frost increases rapidly and there can be up to 70 days with frost per year in the midlands. There are decreases in frequency of frost days at eight of nine stations, with little or no change in the frost occurrence at Dublin Airport. Significant decreases are revealed at Kilkenny, Shannon, Birr, Valentia, and Rosslare (all at the 99% level) and also at Belmullet (at the 95% level). As expected, the inland stations of Mullingar, Kilkenny and Birr record the highest frequency of

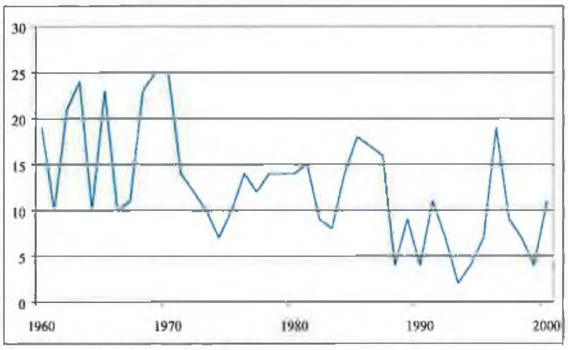


Figure 2.26 Valentia

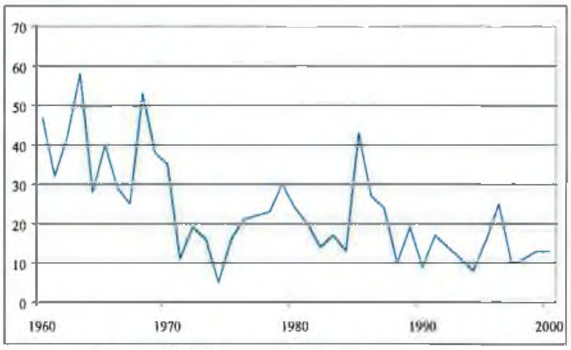


Figure 2.27 Shannon

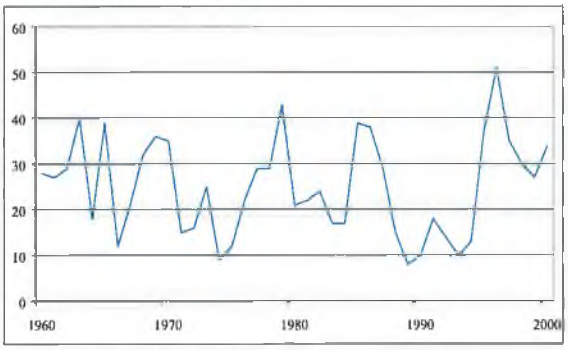


Figure 2.28 Dublin AP

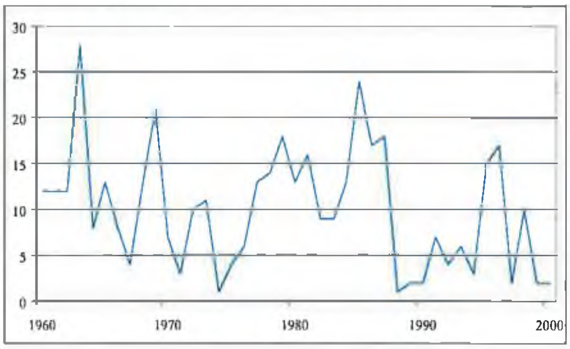


Figure 2.29 Malin Head

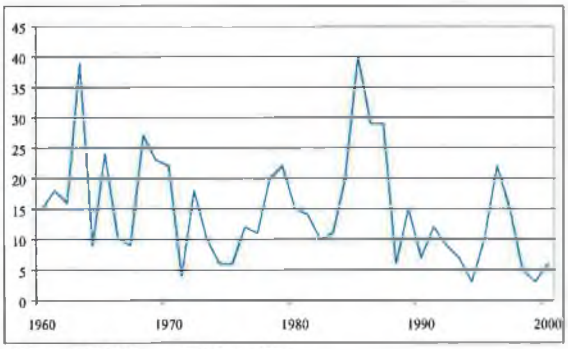


Figure 2.30 Belmullet

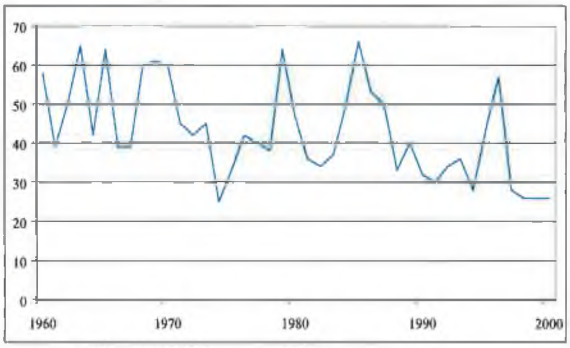


Figure 2.31 Birr

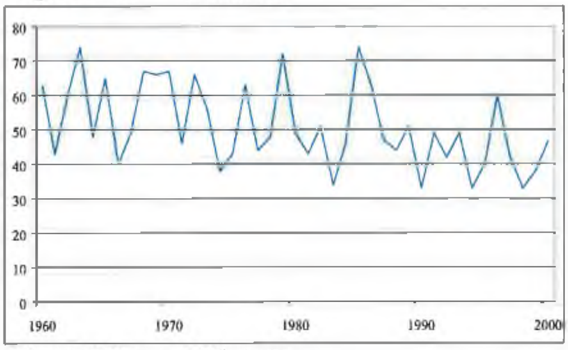


Figure 2.32 Kilkenny

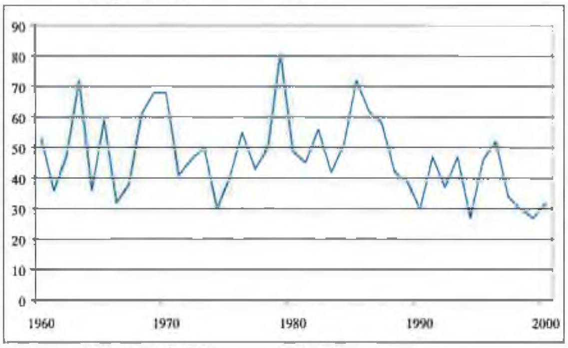


Figure 2.33 Mullingar

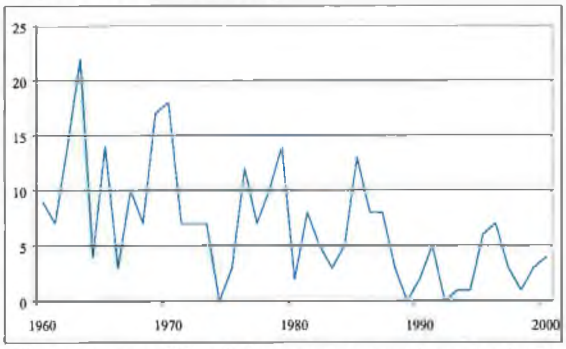


Figure 2.34 Rosslare

Frequency of frost days per year at each station.

days with Rosslare, Malin Head and Valentia the least number. The decline in actual number of frost days would appear to be related to the general increase in seasonal minimum temperatures. Figures 2.26 to 2.34 outline the observed decreases in frost days at each of the stations.

2.6 Annual and Seasonal Trends in Irish Precipitation

2.6.1 Global and Irish long-term precipitation trends

Precipitation has increased by 0.5-1% per decade during the 20th century over the mid-to high-latitudes. According to the IPCC (2001), it is also likely that there has been a 2-4% increase in the frequency of heavy precipitation events. It is the magnitude and frequency of precipitation events that will have the most severe consequences and, as such, it is necessary to understand the temporal and spatial distribution of these events. It is widely recognised that a warming of the lower atmosphere will inevitably cause changes in precipitation due to an altered hydrological cycle. It is also likely that these changes will have more important impacts on human and environmental systems than any change in mean temperature.

Trends in European annual precipitation reveal increases in rainfall in northern Europe of between 10 and 40% during the 20th century with little change or drying in southern Europe (Parry, 2000). Furthermore, climate modelling studies suggest more pronounced precipitation gradients from northwest to southeast in Britain and Ireland for the future (Hulme, 1999b). The general pattern for future precipitation changes is for wetter winters and wetter summers in northern Europe, and drier summers in southern Europe (Parry, 2000).

An examination of the precipitation records in Ireland shows that there are only 3 long-term stations for which monthly data were obtainable for this study - Malin Head, Birr and Roches Point. Roches Point became automated in 1990, and updated data for this station was not available. As a result this series has been supplemented by data from Rosslare. Total monthly rainfall amounts were in agreement, and generally follow the same trend. Total annual precipitation at the three stations was examined. There have been increases in rainfall in the north of the country. An increase of over 40% since 1890 has been recorded at Malin Head, which can be clearly seen in Figure 2.35. Four of the five wettest years have occurred in Malin Head in the 1990s: 1999, 1990, 1998 and 1992 respectively. The 1961-1990 mean rainfall total is 1060 mm - this value has been exceeded in most years since the mid-1970s.

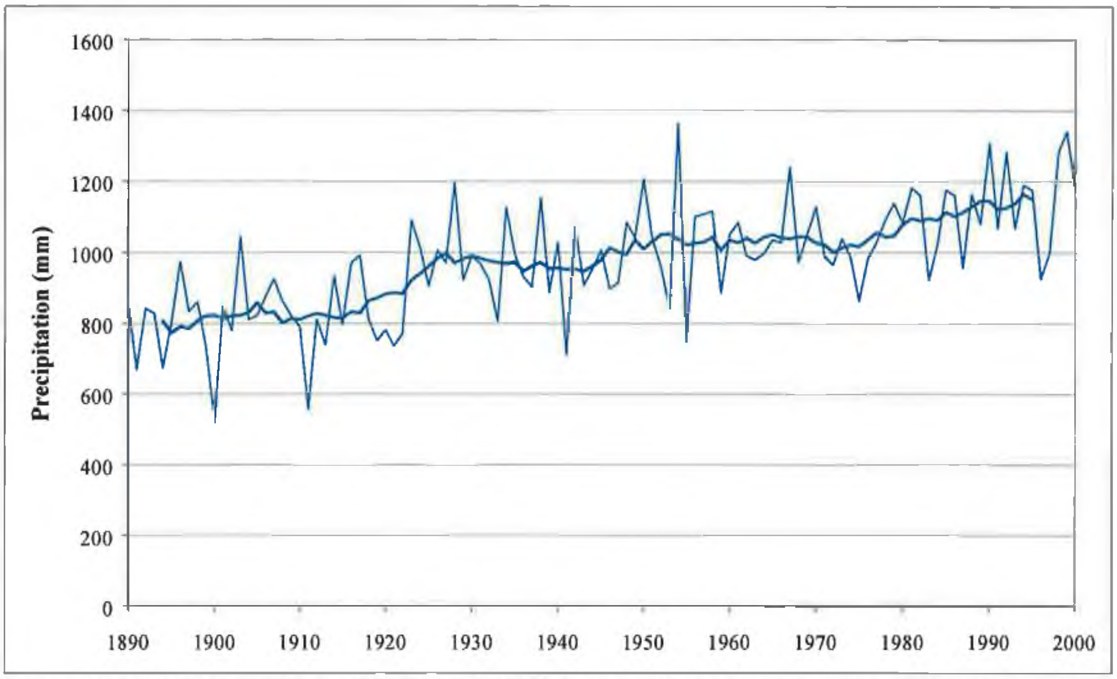


Figure 2.35 Total annual precipitation at Malin Head with 10-year moving average

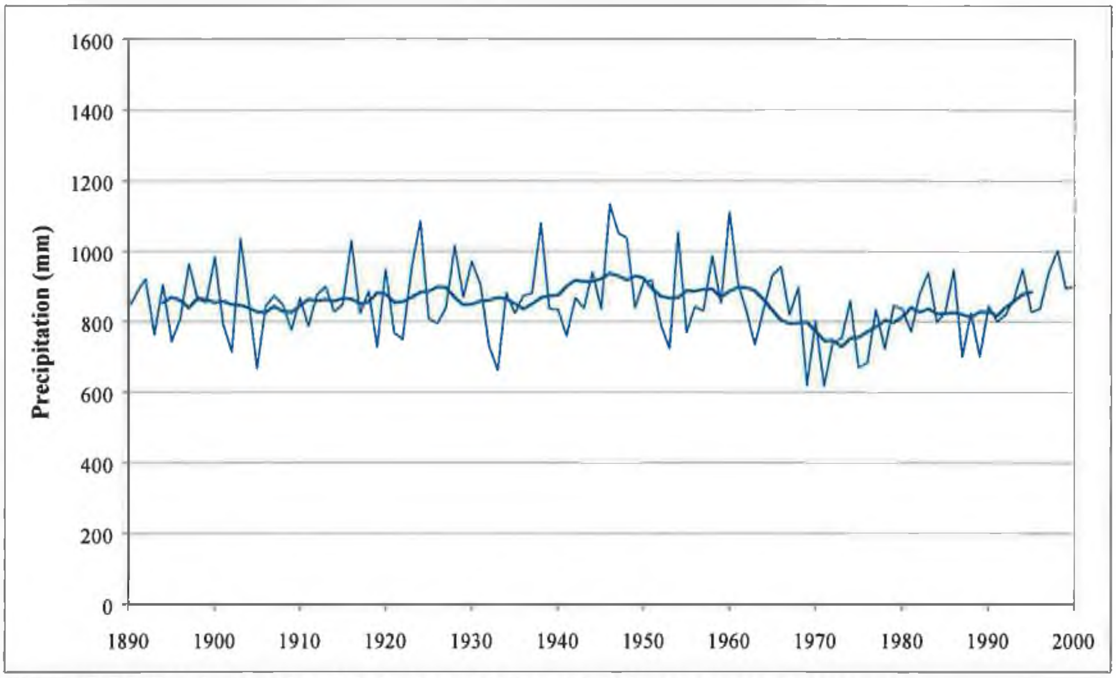


Figure 2.36 Total annual precipitation at Birr with 10-year moving average

No significant trends have been found in annual precipitation levels at either Birr or Roche's Point/Rosslare. A decrease of 150mm in the 1960s followed by a steady increase up to 2002 has been measured at Birr (Figure 2.36). The Roches Point/ Rosslare data (Figure 2.37) indicate a slight decrease in precipitation, from 1100mm to 1000mm, based on the ten-year moving average data. Hoppe and Kiely (1999) present corroborative results when they provide evidence of a highly significant increase in annual precipitation at Valentia, Malin Head and Belmullet since the 1970s. They also indicate that annual precipitation at Rosslare and Birr seems to decrease, but the change is not as clear (Hoppe and Kiely, 1999).

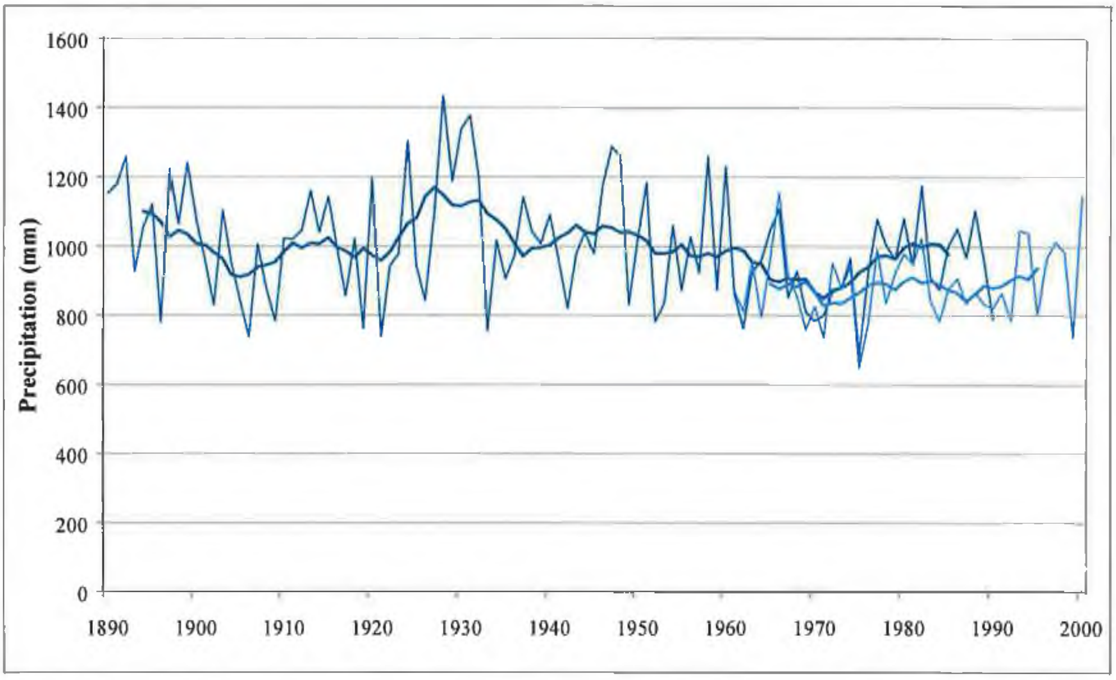


Figure 2.37 Total annual precipitation at Roche's Point/ Rosslare with 10-year moving average

2.6.2 *Seasonal changes in Irish precipitation*

Seasonal changes in precipitation may be concealed in annual data. A greater insight into the distribution of rainfall throughout the year may be provided by analysing seasonal data. A clear differentiation emerges between winter precipitation in the north of the country and summer precipitation in the south of the country in the long-term record, with the former increasing at a greater rate, and the latter decreasing at a greater rate. The increase in annual precipitation at Malin Head is accounted for primarily by an increased winter precipitation, while the decrease in precipitation at Roche's Point/ Rosslare is due to a larger decrease in summer precipitation. This is similar to results presented by Hulme (1999b), which demonstrated increased winter precipitation in Scotland and decreasing summer precipitation in southeast England.

However, an analysis of synoptic station data for the period 1961 to 2000 reveal conflicting results. Seasonal precipitation trends at nine synoptic stations reveal winter increases in all stations, with greater increases (of between 25 and 70%) on the west coast – at Valentia, Shannon, Belmullet and Malin Head. This can be seen clearly in Figure 2.41. Rosslare, Kilkenny and Birr in spring are the only stations and the only season to show signs of a decrease in rainfall, although only by 8%, 3% and 6% respectively. This is evident in Figure 2.38, which shows a decrease in rainfall receipt in the midlands and southeast of the country. In summer there are increases in rainfall receipt in all stations except Rosslare, where there appears to be no change. Figures 2.39 and 2.40 depict the seasonal change in rainfall receipt during summer and autumn. The reason for the inconsistency between the decreasing long-term summer rainfall trend, at Roche's Point/Rosslare, and the increasing 1961-2000 summer rainfall trend is that the decrease is generally between the period 1930 and 1960, rather than in recent years.

2.7 Secondary Precipitation Indices

2.7.1 Frequency of rain and wet days

Variation in precipitation totals can be caused by a change in the frequency of precipitation events, changes in the intensity of precipitation per event, or a combination of both. Globally, there is evidence of increases in the intensity of extreme rainfall events in some regions, but no clear large-scale pattern has emerged. In analysing the frequency of rainfall events in Ireland, thresholds were selected according to standard definitions used by the World Meteorological Organisation. A rain day is defined as a day having greater than or equal to 0.2mm of rainfall, while a wet day is a day with greater than or equal to 1.0mm. Daily precipitation data for the synoptic stations for the period 1961 to 2000 were used to examine whether changes in the frequency of rain and wet days were occurring.

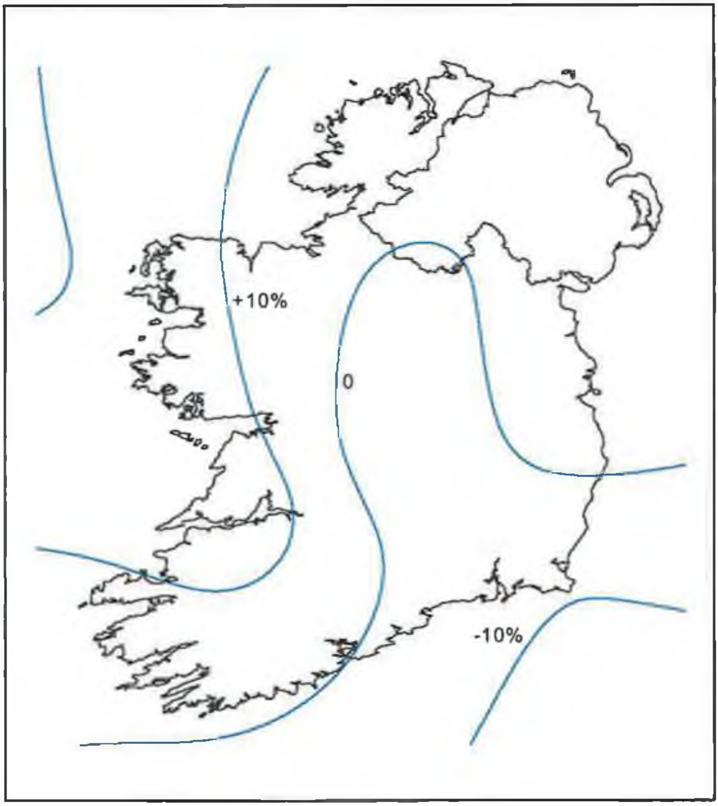


Figure 2.38 Percentage change in spring precipitation, 1961-2000

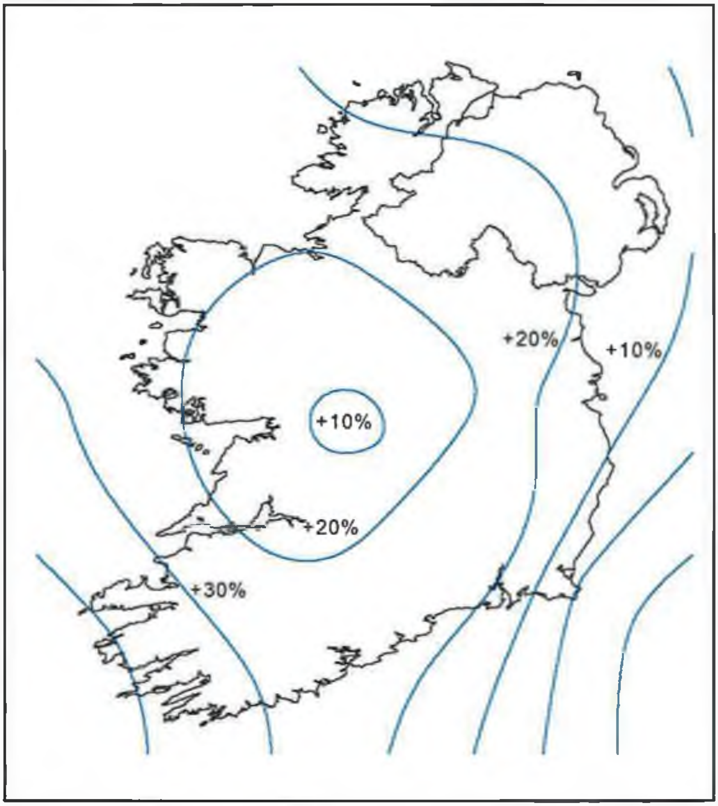


Figure 2.39 Percentage change in summer precipitation, 1961-2000

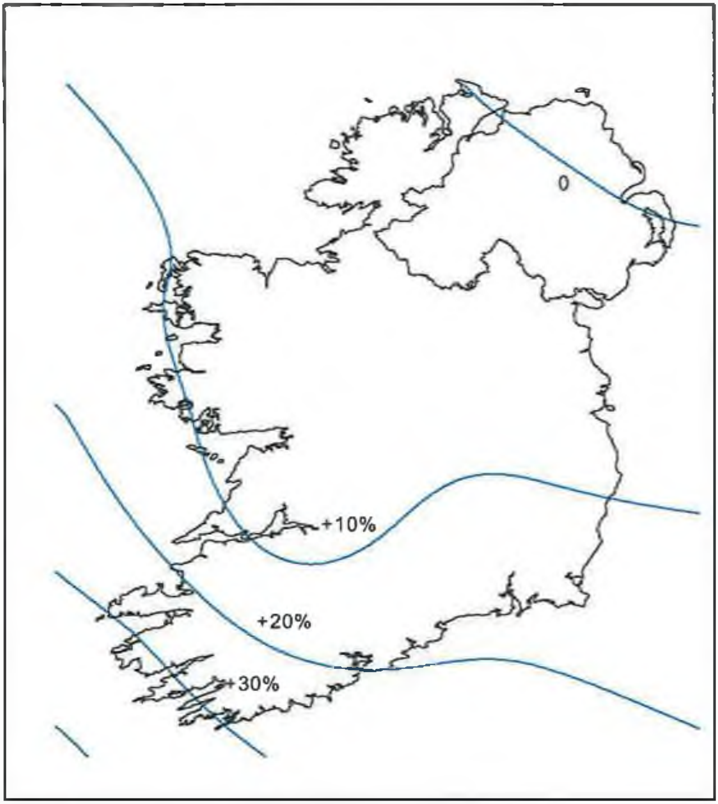


Figure 2.40 Percentage change in autumn precipitation, 1961-2000

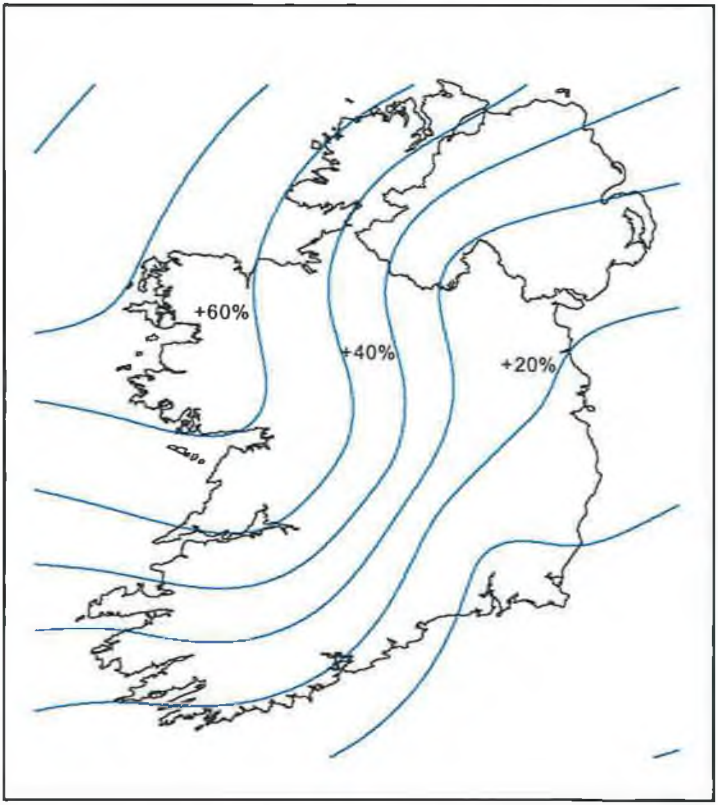


Figure 2.41 Percentage change in winter precipitation, 1961-2000

All stations reveal increases in the frequency of rain days in January, February, March, July and October. This is at the 95% significance level for Belmullet, Clones and Kilkenny in February and for Malin Head in March. All stations in May have a decreasing number of rain days, while in September, all stations but Rosslare and Kilkenny experience a decrease in rain days. With regard to wet days, in February, October and December there is an increase in frequency of wet days at all stations, and in May and September, a decrease in frequency. Only the changing wet day occurrence in Belmullet in February is significant however. These results are summarised in Table 2.3. Overall, there has been an increasing frequency of rain days and wet days at all stations in February and October, with a decreasing frequency of rain and wet days at all stations in May.

	Valentia		Shannon		Belmullet		Clones		Rosslare		Kilkenny		Casement		Birr		Malin	
	W	R	W	R	W	R	W	R	W	R	W	R	W	R	W	R	W	R
January	+	+	0	+	+	+	+	+	+	+	-	+	+	+	+	+	+	+
February	+	+	+	+	+**	+*	+	+*	+	+	+	+*	+	+	+	+	+	+
March	+	+	+	+	+	+	+	+	+	+	-	+	+	+	+	+	+	+*
April	+	-	-	-	+	+	+	+	+	-	-	-	-	-	-	-	+	+
May	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
June	-	+	-	-	0	+	-	+	+	-	+	-	0	+	-	-	-	-
July	+	+	+	+	+	+	+	+	-	+	-	+	-	+	+	+	+	+
August	-	-	-	0	-	+	+	-	0	+	+	+	-	-	-	-	+	0
September	0	-	-	-	-	-	-	-	0	+	-	+	-	-	-	-	-	-
October	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
November	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-
December	+	+	+	+	+	-	+	+	+	+	+	+	+	-	+	+	+	-

Table 2.3 Change in occurrence frequency of wet (W) and rain (R) days
+ indicates an increasing trend; - indicates a decreasing trend; 0 indicates no trend
** 99% significance level
* 95% significance level

2.7.2 *Frequency of extreme and heavy events*

Global studies on extreme and heavy rainfall intensities have observed that countries which experience a significant increase or decrease in monthly and seasonal rainfall have found this change to be directly related to a change of the same sign in heavy and extreme events (Easterling *et al.*, 2000). Groisman *et al.* (1999) demonstrate using daily precipitation data from North America, a large portion of Asia, areas of Europe and Australia that any change in the mean monthly total precipitation will influence the extremes more than any other precipitation rate. In a study on extreme precipitation events in the USA, Karl and Knight (1998) find a very significant increase during the 20th century. The increase has occurred due to both increases in the frequency of very heavy and extreme precipitation events as well as in their intensity. They found that the intensity of precipitation has increased for very heavy and extreme precipitation days only, but not for smaller rainfall events.

There has been very little work in Ireland on extreme precipitation events – either their occurrence or intensity. There are a number of standard indices which could be utilised, such as the number of days exceeding specific precipitation amounts. Commonly applied thresholds include, as previously analysed, wet and rain days, but also precipitation exceeding 10mm. While it is noted that this is not ideal on a global scale, it can be applied to Ireland. An analysis of heavy 1-day precipitation events is also a useful indicator of precipitation extremes. These events play a large role in flooding, especially in urban areas, and their monitoring is essential to detect long-term trends in their occurrence. Problems however, include large local differences and the splitting up of extreme 24-hour rainfall events by the regular observing hours at a particular station (Heino *et al.*, 1999). Accordingly, this is also not an ideal indicator.

For the mid- to high-latitudes, a number of climate modelling studies have pointed towards a decrease in the frequency of rainfall events, but with a greater proportion of rain falling in intense falls. This is possibly due to a poleward retreat of mid-latitude low pressure systems causing a decrease in precipitation events, with enhanced convection causing more intense events (Mayes, 2001). Such changes have occurred in northern Italy (Brunetti *et al.*, 2000) and in southwest Australia which has a Mediterranean-type climate (Yu and Neill, 1993; Mayes, 2001).

An analysis of rainfall days exceeding 10mm at synoptic stations in Ireland reveals that there are large local differences and conclusive results are difficult to determine. There are increases in the frequency of days with rainfall greater than or equal to 10mm for June and December at all stations, and also for January, February, March, July and October on the west coast at Valentia, Belmullet,

	Valentia		Shannon		Malin Head		Belmullet		Clones		Rosslare		Kilkenny		Birr	
	Freq./Magnitude		Freq./Magnitude		Freq./Magnitude		Freq./Magnitude		Freq./Magnitude		Freq./Magnitude		Freq./Magnitude		Freq./Magnitude	
January	+	-	+	+	+	+	+	+	+	+	-	-	-	+	+	-
February	+	-	+	-	+	-	+**	+	+	+	-	-	+	-	+	+
March	+	+	+	-	+	-	+	-	+	+	-	+	+	-	+	+
April	-	+	+	-	+	-	+	+	+	+	-	+	+	+	+	-
May	-	+	+	-	+	-	-	+	-	-	+	+	-	-	-	+
June	+	-	+	+	+	-	+	+	+	-	+	-	+	-	+	+
July	+	+	+	+	+	-	+	-	+	-	-	-	-	+	-	-
August	+	+	-	+	+	-	+	+	+	-	+	-	+	+	-	+
September	-	-	+	-	-	+	-	+	-	+	+	-	-	+	-	-
October	+	+*	+	-	+	+	+	+*	-	+	+	-	+	-	+	-
November	+	+	-	+	-	-*	+	0	-	0	+	+	+	+	+	-
December	+*	-	+	-	+	+	+**	+	+	-	+	+	+	-	+	-
Annual	+**	+	+**	-	+**	-	+**	+	+	+	0	0	+	0	+	-

Table 2.4 Change in occurrence frequency and magnitude of heavy rainfall events, greater than or equal to 10mm.

** 99% significant

* 95% significant

Shannon and Malin Head. Decreases in frequency of heavy rainfall events are found in September at all stations except Shannon and Rosslare, in May except Shannon, Malin Head and Rosslare and in January and July at the south east coast stations of Kilkenny and Rosslare. During the autumn months of September, October and November there are decreases at Clones. In terms of the change in average rainfall on these extreme days, there is an increase at Shannon, Belmullet and Birr in June, and at Malin Head, Belmullet and Rosslare in December. There is also decreased average rainfall for these extreme days at Shannon and Malin Head from February to May. Other results are summarised in Table 2.4. There have been increases in the frequency of days with precipitation greater than 10mm on an annual basis at all stations, significantly at Valentia, Shannon, Malin Head and Belmullet. The mean rainfall of these heavy events has increased at Valentia, Belmullet and Clones, with decreases at both Shannon and Birr and little change at Rosslare and Kilkenny. This appears to substantiate Kiely's study for the west coast sites of Ireland. The author found a greater number of extreme events since 1975, with 102 of the 160 highest events at Belmullet where the record extended at far back as 1956 (Kiely, 1999).

2.8 Conclusion

This chapter has outlined some of the changes which have occurred in the Irish meteorological record. Analysis of local and regional scale climate has been conducted in order to investigate whether the changes in global climate identified by the IPCC have or have not been matched by a comparable trend in Ireland. A temperature increase of 0.5°C has been observed over the course of the 20th century in the Irish long-term record, similar to the global increase of 0.6°C. Warming has also occurred in two distinct phases, most apparent in the 1990s. In recent decades, warming has been strongest in the winter season, with daytime temperatures increasing at a greater rate. Spring, summer and autumn minimum temperatures appear to be warming at a greater rate than maximum temperatures at most stations. There have also been considerable and significant decreases in the frequency of frost days at a number of stations and an associated increase in hot days. It would seem therefore, that Irish temperature records are analogous to global temperature trends.

Precipitation indicators for Ireland also appear to confirm global climate model predictions, with winter increases in the north and west of the country, and summer decreases in the south east in the long-term monthly record. Given the limited number of sites investigated, only preliminary conclusions can be drawn concerning spatial and temporal precipitation trends. Seasonal changes in precipitation in the period 1961 to 2000 reveal increases in all seasons in various parts of the country, with greatest increases in winter in the west and slight decreases in the southeast in spring. There have been increasing frequencies of rain and wet days in February and October while decreasing frequencies of rain and wet days have been detected in May.

Having outlined the changes occurring in Irish climate, both spatially and temporally, it is worthwhile to consider some of the physical mechanisms which may be responsible for the changes in local and regional climate. In the subsequent chapter, the necessity for, and methods of, determining the relationship between climate on a regional scale and atmospheric circulation on a large scale will be explored.

Chapter 3

Methodological Approaches: Atmospheric Circulation as a Driver of Change

3.1 Introduction

The climate conditions in any particular area are controlled by many different factors. These include the local orography, altitude and latitude, land-sea interactions, the atmospheric circulation as well as more localised small-scale features. However, many authors have found that it is atmospheric circulation which is the main forcing factor for the regional variability of temperature, precipitation and other climatic variables (Xoplaki *et al.*, 2000, Yin *et al.*, 2000; Quadrelli *et al.*, 2001). According to Pinto *et al.* (2001), pressure is a climatic element whose spatial-temporal behaviour may be of use in the detection of climate change. It may be possible to ascertain the physical mechanisms responsible for changes in local climate by determining the dominant modes of atmospheric variability and thus, the dependence of the surface climatic variables on the synoptic scale circulation. Atmospheric pressure is less strongly affected by local conditions and their modification, than other climatic variables, and this makes it ideal for studies on climatic change. Schönwiese and Rapp (1997) found considerable trends in seasonal temperature and precipitation in Europe over the past 100 years. To understand why these changes occurred, the authors realised that atmospheric conditions as well as local physical processes would need to be explored.

Atmospheric circulation exhibits variability not only on year-to-year scales but also on decadal scales (Xu, 1993). Beck *et al.* (2001) outlined the importance of focusing on the low-frequency variability of the relationships between the large-scale atmospheric circulation and climate on a regional scale. This is due to the reliance placed upon these relationships in attempting to locate recent, and possible future, climate and atmospheric circulation changes into the long-term context of the climate system. Most projections of future climate change are obtained by deriving changes in regional or local climate parameters from projected large-scale atmospheric circulation changes (by means of different downscaling methods). To downscale from the recent Global Climate Models (GCMs) an essential first step is to demonstrate that there are distinct and significant relationships between any circulation classification scheme and surface weather variables (Jones *et al.*, 2000).

There are a number of authors who have found links between circulation and weather variables. These links can be studied in different ways. They include the use of indices of atmospheric circulation, such as the North Atlantic Oscillation (e.g. Hurrell, 1995 and Hurrell and van Loon, 1997 for Europe; Chen and Hellström, 1999 for Sweden; Sweeney *et al.*, 2002 for Ireland), or classification of the circulation and pressure patterns which can then be related to temperature and precipitation (e.g. O'Hare and Sweeney, 1993 for Britain and Ireland; Romero *et al.*, 1999 for Spain; Busuioc *et al.*, 2001b for Sweden). This latter technique can be approached in two different ways. One method is to find statistical relationships between a subjectively defined circulation index or circulation type (e.g. Lamb Weather Type) and regional climatic variables, while the second method is to study the connection between objectively defined patterns of large-scale circulation and the regional climate. Both techniques will be reviewed in this chapter. An analysis of the capability of atmospheric classifications, based on mean sea level pressure (MSLP) and geopotential height fields, in characterising surface weather elements on both daily and monthly time-scales will be conducted.

Before any atmospheric circulation classification procedure can be applied there are a number of decisions which need to be made. These may include:

- the selection of data – whether surface or upper air; which variables; direct observations or Reanalyses;
- the choice of temporal and spatial scale – daily or monthly data; grid-cell spacing of Reanalysis and GCM data;
- the method of circulation classification – whether subjective or objective;
- within objective methods – either eigenvector based or correlation-based;.

The order in which each of these decisions is made depends on the overall research objectives and the availability of data. The following section will review each of these options.

3.2 Choice of Data

The first section of the analysis involves the decision as to what data are to be utilised: which surface climate variables to consider; what temporal scale; whether to use surface and/or upper air pressure data to define circulation patterns. The most important indicators of climate change are undoubtedly temperature and precipitation, but there is also justification in using wind speed and direction, cloud cover and sunshine hours. Generally, temperature responses to circulation exhibit clearer patterns of homogeneity when compared with precipitation. Precipitation responses are complex due to topographic features which cause orographic, rainshadow and channelling effects (Mock *et al.*, 1998).

Monthly data are more readily available and consistent, but daily data reveal more about the climate parameter, especially extreme conditions. Some authors, such as Hanssen-Bauer and Førland (2000) for Norway, have used regional series of temperature and precipitation rather than single series as this reduces the risk of including local phenomena like the urban heat island effect. In terms of downscaling, Kilsby *et al.* (1998) in predicting rainfall statistics for England and Wales, could not find a desired degree of explained variance at levels below monthly data, although they did acknowledge that daily data would be preferable in order to determine individual synoptic situations. However, monthly data, they inferred, have a number of advantages including the fact that time series can be treated as nearly stationary over one month and that autocorrelation for monthly precipitation data tends to be small and, as such, data may be treated as independent in time.

Another factor, which must be assessed, is whether to use a sample period of data or the full length of available data. By using only sample data, the outcome may not be compared with subsequent classifications as the results can vary significantly. Patterns over time may change which cannot be deduced from only a section of data. However, sample data might have to be used if there are computational and/or time restrictions.

3.2.1 Surface or upper-air data

In terms of classifying the circulation, a choice needs to be made between using mean sea level pressure (MSLP) or geopotential heights, or both. The flow at both the surface and upper levels influences daily weather patterns. While MSLP data are measured at all synoptic stations in Ireland, gaps in the surrounding ocean dataset make it necessary to use other sources such as Reanalysis data to augment it. Lund (1963) used mean sea level pressure in his correlation-based study while Kirchhofer used the 500-hPa geopotential height for his sums-of-squares approach (Kidson, 1997). Geopotential height data have the advantage of being barely affected by local factors. The most common geopotential height fields used in this type of study are the 500 and 700-hPa. The 500-hPa level is often used as it is representative of the mid-tropospheric circulation and storm tracks (Yarnal *et al.*, 2001). The upper tropospheric circulation provides steering of low-level systems and influences their development. Also, there is a smoother representation of flow at the upper levels which may be better suited to synoptic climatological classification (Kidson, 1997). Brinkmann (1999, 2000), chose the 700-hPa level as it had been used in many previous studies and been found useful in identifying relationships between circulation patterns and surface conditions (Leathers *et al.*, 1991; Brinkmann, 2000). According to Kidson (1997) the lower level charts are able to provide a good representation of synoptic-scale systems and are able to indicate the interaction of low-level flow with the topography. The ability to compare results when using the same height field is an obvious advantage. The authors of the Atmospheric Circulation Classification and Regional Downscaling report (ACCORD) concluded that the German scientists found the 500-hPa geopotential height to be a better classification variable than MSLP or 700-hPa, while Greek scientists found that 700-hPa was better (Jones *et al.*, 2000). The principal conclusion from Kidson (1997) is that map classifications based on multi-level data are desirable but difficult to apply in practice, and that the choice of level at which the map classification is applied has little influence on the skill of specification of climatic elements.

Zorita and von Storch (1999) used MSLP as the predictor for Iberian precipitation as they assumed that the MSLP data offered more advantages for this purpose than geopotential heights. Firstly, long standardised time series of the variable were available, which would allow for the setting up of a statistical model in some period and checking it on an independent dataset. Secondly, Zorita and von Storch (1999) pointed out that in climate change GCM experiments, geopotential heights tend to be much more affected by global warming, but these changes may be related to changes in the mean atmospheric density, and not necessarily related to changes in the atmospheric circulation. Therefore, using the geopotential heights for the large-scale field may have the effect of including a signal that is not physically related to the atmospheric circulation and therefore not to the local variable. The sea level pressure on the other hand is much less affected (Zorita and von Storch, 1999). Sea level pressure is also preferable where local climate is influenced by regional-scale processes, such as along seacoasts (Murphy, 1999).

3.2.1.1 Reanalysis data Reanalysis data are previously observed climate data which are analysed, quality controlled and interpolated by a state-of-the-art data/model assimilation system. Long, consistent time series simulated at 6-hourly intervals are provided. In this way, current climate anomalies can be compared to long-term reanalysis without changes in the data assimilation system (Kalnay *et al.*, 1996). The database is improved by the inclusion of observations which are not available in real time but which are provided by different countries and organisations (Kistler *et al.*, 2001). The use of reanalysis data however poses issues to consider. There are two main sources of data – National Centers for Environmental Prediction/National Centers for Atmospheric Research (NCEP/NCAR) and the European Centre for Medium-range Weather Forecasts (ECMWF). The ECMWF data have recently been updated to include 1960 to 2000 (ERA-40), but prior to the commencement of this thesis the data was only available post-1979. This was considered much too short for any study on climate detection where the length of data should be as long as possible. There are, however, issues with the NCEP/NCAR data which have been problematic for other studies, but only those at much higher latitudes. The ACCORD report (Jones *et al.*, 2000) found that the reanalysis data at higher latitudes, such as over

Greenland and the Barents Sea, was not particularly reliable when compared with observed values, and that differences of between 6-8 hPa were encountered. For the mid-latitudes these differences were only of the magnitude of 1-2 hPa which was not considered that substantial (2001). Although the MSLP Reanalysis data are known to have a positive bias prior to 1967, Reid *et al.* (2001) acknowledge that they can be reliably used within the window of interest for the ACCORD project (80°N-30°N, 60°W-70°E). This is also consistent with the domain of interest for this study. A major advantage of the Reanalysis data is the completeness of their spatial and temporal coverage. Due to ease of acquisition and their length of record, most studies have used NCEP/NCAR data.

3.3 Choice of Grid-points and Spacing

Consideration must also be given to the spatial outline of the data. How many grid points to use and how far apart they are spaced will have an impact on the pressure patterns observed. There is a choice of whether to use 5° latitude x 5° longitude, 2.5° latitude x 2.5° longitude or to follow the grid resolution of the Global Climate Model, such as 2.5° latitude x 3.75° longitude in the case of the HadCM3 model. Many authors classify circulation patterns for the whole of the Northern Hemisphere and relate the results to the climatic conditions at the surface in just one small region. Others use a smaller window as the classification system may be more strongly linked with the circulation features from regions outside the area of interest.

There is also the problem that data is given for four time slices each day, but this is just a 'snapshot' of the atmospheric movement at that time. In reality, more than one type may feature during the course of the day (Spellman, 1998).

In determining the size of grid and number of grid points to use, there are a number of issues which need addressing. With a larger grid size and a large number of grid points, there will be more map patterns classified. A smaller grid size will pick up the circulation features exclusively for the area under study but it may not resolve the large-scale synoptic circulation patterns affecting the region's climate. Yarnal (1982) illustrated this when he revealed that with bigger grid sizes and bigger spacing between grids, the smaller scale weather phenomena are filtered out. The number of grid points is also an important consideration. With an increased number of grid points, there is a corresponding decrease in the percentage of grids successfully classified and an increase in the number of patterns identified. This is due to the increased detail that can be categorised, with a greater number of high and low pressure patterns deciphered.

Overland and Hiester (1980) reveal that gridded data may be too coarse for a fine resolution investigation and, as such, they suggest a subjective, manual classification technique may be needed. Yarnal (1993) concluded that, for any study, it is necessary to know the scale of the atmospheric circulation feature you want to study before deciding on the number of grid points and their spacing.

In summary, all circulation classification methods suffer from 3 main problems. Firstly, there will be airflow differences on a smaller scale than the region to be classified. Secondly, days are classified on the basis of pressure patterns and not absolute values, which means that two charts may be classified equally but one may have significantly lower pressure or geopotential height values. Thirdly, each day is classified on the basis of a 'snapshot' of the atmospheric movement when in reality more than one type might feature during the course of the day (Spellman, 1998). It is difficult to overcome these problems completely, but with numerous choices and decisions to be made, they may be minimised.

3.4 Classification Approaches

The link between atmospheric circulation and regional climate can be studied in a variety of ways. The first method is the circulation-to-local climate approach which classifies or clusters atmospheric circulation and pressure maps before attempting to seek links with the local-scale climate. Conversely, the local climate-to-circulation approach structures the circulation data following the classification of the local climatic variables (Canon *et al.*, 2002). The first method is more commonly used, with classification-based climatologies produced either manually or automatically. The terms automated and manual are being used more frequently, as opposed to objective and subjective methods. This is because some objective methods may also involve subjective decisions. Examples of this will be outlined later.

3.4.1 Manual approach to atmospheric circulation classification

Manual procedures involve the subjective classification by the researcher of circulation patterns or weather types by visually analysing daily pressure maps. Recurring features of the maps, their differences and similarities, are recognised and classified accordingly. There are a number of well-known manual classifications including the Lamb catalogue (for Britain and Ireland) and the Grosswetterlagen (for Europe). Manual schemes are usually based on experience and distinctively defined patterns which make them straightforward and easy to interpret (Chen, 2000). The researcher is in control of the process and can tailor the classification to meet specific needs. This allows for a more informed analysis on the part of the researcher (Yarnal, 1993). Weaknesses however, include its high level of subjectivity, difficulties arising in duplicating the method by another researcher and labour intensiveness. The classifications are time consuming and usually region specific. There also exists the problem of the continuous nature of the information being classified. Atmospheric circulation is continuous so the boundary between classes may be difficult to define. As such, with a large number of classes it may be difficult to establish where one ends and the other begins. The result is either a large number of unclassified days or days which could be a member of two or more different classes (Barry and Perry, 2001).

3.4.2 Automated approach to atmospheric circulation classification

Automated classifications gained popularity because of their simple way of performing the same task as that done manually by the researcher (Yarnal *et al.*, 2001). Computer-based techniques are easily read and understood, and can also be calculated in much shorter time scales. They also have the advantage of being repeatable and effective. Automated techniques include procedures such as correlation-based map patterns (Lund, 1963; Kirchhofer, 1974) and eigenvector-based techniques (e.g. PCA and cluster techniques). Blasing (1975) considers neither correlation-based nor eigenvector-based techniques having superiority over the other

> 'Map pattern typing appears to have distinct advantages over principal components analysis at least when used for descriptive as opposed to predictive purposes. (However) ...lack of orthogonality between patterns can be a disadvantage if further statistical analyses are to be performed'

(in, Barry and Carleton, 2001: 551).

A number of researchers have used the inherent subjectivity in the automated approach as a criticism. A major drawback is the lack of comparability between locations. In eigenvector analysis, Galambosi *et al.* (1996) assert that the resulting clusters are theoretical and may not physically exist. The non-existing theoretical clusters are defined by means of some objective similarity measure such as Euclidean distance. Trigo and DaCamara (2000) acknowledged the potential and obvious mathematical advantages to objective, automated methods, but also asserted that it is not always possible to assign clear-cut physical meaning on a synoptic basis to the obtained circulation patterns. There is also the problem that if different periods are used the classification may vary. This can be problematic if the objective of the study is to identify long-term variations rather than simply reduce the dataset (Chen, 2000). The fundamental weakness of automated classifications is that some of the identified patterns may have little climatic significance. Others that occur infrequently may play an important role in controlling aspects of the surface environment but be missed entirely (Cannon *et al.*, 2002).

The choice of method, whether manual/subjective or automated/objective, will obviously depend on the data uses, the purpose of the study, and the resources available.

3.4.3 A manual and automated approach to atmospheric circulation classification

An attempt at incorporating the optimum elements of both approaches – manual and automated – has been proposed by Jenkinson and Collison (1977) with their automated version of the Lamb Weather Type classification. This type of classification is based on indices of airflow and vorticity. By defining objective rules for a subjective scheme, this method has a major advantage of being transferable to other regions. Originally the scheme was established using grid-point values of mean sea level pressure over the British Isles on a 5° latitude by 10° longitude grid spacing. The procedure has been applied to other regions in the mid-latitudes such as Sweden (Chen, 2000), Portugal (Trigo and DaCamara, 2000) and the Iberian Peninsula (Goodess, 2000a). Jones *et al.* (1993) correlated the objective Lamb types with the traditional Lamb classification and found that they were highly correlated, especially for the cyclonic and anticyclonic types. This method of automating the long established Lamb catalogue is also particularly useful for application to results from GCMs.

The remaining sections will outline the different methods of classifying atmospheric circulation patterns. These include manual schemes such as Lamb Weather Types (LWTs) and automated schemes, including those based on statistical methods such as Principal Component Analysis and Canonical Correlation Analysis. The basic principles of each, and the methodological concerns associated with them, are put forward with a view to developing an atmospheric circulation classification for use in an Irish context.

3.5 Manual Classification Schemes

3.5.1 Lamb Weather Types

The Lamb classification developed for the British Isles is the most widely used manual classification for describing the atmospheric circulation at the synoptic scale for Britain and Ireland. The original scheme involved eight directional types and three non-directional types – cyclonic, anticyclonic and unclassified. Lamb (1972) also established a set of hybrid types which arose when a directional type and an anticyclonic or cyclonic type existed together. In total there are 27 Lamb types identified. The airflow type is determined from both the mean sea level pressure and the 500-hPa pressure level (Mayes and Wheeler, 1997). The classification dates back to 1861 and as such, is one of the longest and most consistent manual classifications in existence. Others include the

Grosswetterlagen developed in Germany for Western Europe and the eastern North Atlantic. The Grosswetterlagen was initially developed by Baur from surface pressure patterns and modified by Hess and Brezowsky to include upper air data after 1949 (Yarnal, 1993).

A number of studies have utilised the Lamb classification, including for an examination of atmospheric circulation and its relationship with heavy rainfall events over Ireland (Houghton and Ó'Cinnéide, 1976), and in the development of a synoptic climatology for Northern Ireland (Betts, 1989). However, there are numerous limitations regarding its application. Firstly, there may be widespread regional variations in airflow over the British Isles due to the size of the area being classified and the size of the prevailing circulation features. Mayes (1991) recognised this and suggested that perhaps a more detailed regional approach would be more appropriate. Secondly, difficulties may arise in assigning the correct airflow type, as identified by O'Hare and Sweeney (1993). A day that is classified as cyclonic may have an easterly flow over Scotland yet have a northwesterly flow over Ireland. Thirdly, airflow types may change over the course of a 24-hour period and will influence the underlying climatic conditions. In some cases a single classification for each day would not be valid. And fourthly, as acknowledged by Houghton and Ó'Cinnéide (1976), the unclassified type is the fourth most frequent type in the Lamb classification and had a greater mean rainfall than northerly, southerly, easterly and northwesterly. It also had a similar mean rainfall to westerly circulation which obviously reduces the validity of the classification. As stated earlier, there is an intrinsic subjectivity within this method which increases the probability of inconsistencies in the categorisation and the problems with the transfer of the technique to other areas and studies (Frakes and Yarnal, 1997). Among the advantages of the classification however, is the relative ease with which individual days can be classified, which allows further updating to be carried out easily.

3.6 Automated Classification Schemes

3.6.1 Lund and Kirchhofer correlation-based approaches

The Lund and Kirchhofer classification schemes have been at the forefront of automated correlation based techniques. The correlation methods were first developed by Lund in 1963 while Kirchhofer proposed an alternative method in 1974. Lund used simple linear correlation techniques to group mean sea level pressure patterns at 22 stations in the northeastern United States into types. Using a threshold, for example, of r > 0.7, each of the day's pressure maps are correlated with every other map pattern and the day which has the largest number of maps correlated with it is designated type A. These days are taken out of the dataset and the next day with the greatest number of correlations is designated type B, and so on. The use of a higher or lower correlation value results in fewer or greater number of cases in each type, a greater or lesser similarity type and a greater or lesser number of cases not included in each type (El-Kadi and Smithson, 1992). Overland and Hiester (1980) compared this method, using two different threshold values (0.7 and 0.8), with a subjective weather type classification and found that the Lund technique performed slightly better than subjective methods. However, they did convey that it was necessary to understand the spatial scale at which circulation features occur, since coarser grids may not pick out important sub-synoptic features.

Kirchhofer developed a technique using sums-of-squares to compare normalised pressure grids and identify any recurring patterns (Yarnal, 1985). Each normalised grid was compared to all other grids and the pairs assigned a Kirchhofer S-score. This determined the similarity between the grid patterns of each day, but in contrast to Lunds' method, a grid row and grid column score were also calculated. Thus, there are three sums-of-squares calculations for each day for each grid, which are then reviewed. The day with the greatest number of scores associated with it was designated Keyday One and all associated days removed from the process. This is then repeated to determine Keyday Two, and so on, until all days have been classified or the minimum number of days to make a Keyday has not been reached.

There are a number of subjective decisions that have to be made using the Kirchhofer technique, such as the level of similarity between two pressure grids and the minimum number of days allowed per Keyday before it is labelled 'unclassified'. Decisions about the grid size, sample size and thresholds adopted can substantially influence any correlation-based classification. By using thresholds which have been used by other studies, an element of comparability is retained (Saunders and Byrne, 1999). Yarnal (1993) suggested that to provide a similar number of patterns and a high percentage of classified days, a lower threshold score must be used for upper air maps. With lower correlation thresholds there will be more internal variation but also less differentiation among the fewer map patterns. By setting high threshold values, there will be fewer grids with larger numbers of synoptic types (Frakes and Yarnal, 1997). The percentage of grids classified decreases so there is a greater number of unclassified or single patterns (Yarnal, 1993). The effectiveness of the categories in describing the synoptic climatology of the area is the critical factor in deciding on the optimum number of types. However, it is generally agreed that 20-30 types is an unmanageable number for interpretation and study.

The correlation-based classification is primarily a pattern recognition technique as it focuses on patterns of highs and lows across the grid, and not on the strength of the pressure features. A fundamental flaw is that it cannot differentiate between different seasonal patterns unless the gradients are drastically different (Yarnal, 1993). For surface pressure data therefore, it is necessary to standardise the grids to remove the seasonal changes in absolute pressure and pressure-pattern intensity.

While a number of authors have utilised the Lund and Kirchhofer correlation-based methods, Willmott (1987) found that both methods are virtually the same and perhaps the climatologist should look beyond correlation techniques as a way of classifying weather patterns. Blair (1998) also outlined a critical flaw in the Kirchhofer methodology. The sub grid scores, which is what makes the Kirchhofer technique more outstanding than other methods, have not been calculated with the appropriate normalised data. In calculating scores for the grid rows and grid columns, data normalised from the full grid have been used rather than data from the appropriate rows or columns. Grid averages and grid standard deviations have been used instead of row/column averages and row/column standard deviations. As a result the row and column averages do not necessarily detect dissimilar patterns (Blair, 1998). To overcome these difficulties he recommended other objective techniques, such as those based on eigenvectors.

3.6.2 Principal Component Analysis

There are a number of statistical techniques that can be used to investigate the relationships between large-scale circulation patterns and local weather. One of the most common techniques is Principal Component Analysis (PCA). This is an eigenvector analysis in which there are three factors: a climatic variable, time and space. There are six possible modes of decomposition: O, P, Q, R, S and T. These modes reflect the variation of two of either time, location or atmospheric variable, while holding the third fixed. However, only two of these are commonly used in climatic classifications. Synoptic typing uses the P-mode, which analyses a number of variables varying over time, while map-pattern classification and regionalisation use S-mode, which concerns one variable over space (Yarnal, 1993).

Principal Component Analysis is primarily used as a data reduction tool to characterise large datasets. These are generally time series of gridded mean sea level or upper air pressure data or observations of surface climatic variables. These values are reduced to 'scores' on a smaller number of principal components (PCs). The scores depend on the values of the original data and on how each PC contributes to the variance in these. Each PC defines a new variable that is a linear combination of the original variables (Cannon *et al*., 2002). The first PC accounts for the greatest proportion of variance in the original data, with the subsequent PCs accounting for most of the remainder. All the principal components will explain all the variance in the original data. However, to explain most of the variation only a few PCs are required. In choosing how many PCs to retain, there is no single deciding factor. There are a variety of methods including graphical representation such as the scree graph but also other methods such as the rule *N* and North's rule of thumb criterion (Xoplaki *et al*., 2003). The scores on the retained PCs are uncorrelated (independent). Therefore they can be used as linearly independent proxy variables for the original circulation or surface climate data. Linear independence and the ability to reduce data dimensionality make PCA well suited for use as a pre-processing step in synoptic classifications based on cluster analysis (Cannon *et al.*, 2002).

There are also a number of subjective decisions which must be made prior to any Principal Component Analysis. For example, whether to use a correlation or covariance matrix, whether to rotate the data or not and in the case of rotation, which rotation method to use. In most cases these decisions can be made once it is decided what is the object of the classification. Map pattern classification and regionalisation both require rotation because PCA identifies the spatial modes of variation over a mapped surface (Yarnal, 1993). If data reduction is the main aim of the PCA, rotation is not necessary, whereas it is if the object of the study is physical interpretation.

If the objective is regionalisation, then an S-mode analysis is needed which requires a covariance matrix, with oblique rotation. By using the covariance matrix, the spatial deviations are more accurately illustrated, with the pressure centres concentrated on areas of maximum variance (Yarnal, 1993). Oblique rotation allows shared variance among the PCs and relaxes the constraint of orthogonality, which ensures that the variables are more clearly defined. Each individual PC is rotated so distinct clusters are defined (Hawksworth, 1998). There is no need to cluster the component scores and the principal component loadings can be plotted to produce regions.

For a map-pattern classification, S-mode PCA is also necessary, but with a correlation matrix and orthogonal rotation. Map-pattern classification targets the main modes of spatial variation of just one variable (usually surface pressure or geopotential height) (Yarnal, 1993). The output of the rotated PC analysis consists of loading vectors (spatial maps) and the associated rotated principal components (time series) (Mitchell and Blier, 1997). After carrying out the PCA, the component loadings of each of the retained PCs are usually mapped to represent the spatial modes of variability of each PC. If each grid scores on just one PC it would be easier to assign the grid to a particular map pattern. However, each grid scores on all of the PCs and the information carried in every individual component score is critical (Yarnal, 1993). To identify the most common combination of PC scores, a clustering procedure can be applied to the scores matrix. There is no way to portray these clusters directly in map form however (Crane and Barry, 1988). An indirect way would be to average all the grids from each cluster to calculate average maps. The resulting maps are physically interpretable and are as useful as the output from any other automated synoptic climatology (Yarnal, 1993).

3.6.2.1 Application of PCA. A number of authors have applied PCA to geopotential heights and investigated their relationship with precipitation. Quadrelli *et al.* (2001), in their study on the links between observed Alpine precipitation in winter with large-scale circulation patterns, used a surface-to-circulation approach. They conducted a PCA on precipitation over the Alpine region and, by using covariance maps, investigated the relationship between the precipitation PCs and 500-hPa geopotential height anomalies and indices such as the North Atlantic Oscillation (NAO). The authors chose to study only the winter months (December-March) in the period 1971 to 1992 as winter precipitation variability shows a stronger link with large-scale atmospheric circulation anomalies. Galambosi *et al.* (1996) used PCA with k-means clustering analysis to obtain a set of circulation patterns based on the 500-hPa pressure field. This information was then used to model seasonal precipitation based on data from ten local sites. To apply PCA to sea level pressure, temperature and precipitation, Beck *et al.* (2001) analysed atmospheric circulation patterns by applying an orthogonally rotated T-mode PCA to January and July for the time period 1780 - 1995. The authors found that variations in temperature and precipitation were only partly attributed to changes in the frequency of North Atlantic/European circulation patterns. Large parts of the observed variability were due to within-type variability of the circulation patterns themselves (such as change in the variations of pressure gradients or changes in the position and extension of major pressure systems) (Beck *et al.*, 2001). T-mode PCA is less commonly used in climatological studies and concerns one variable varying over time (as compared to S-mode PCA which is one variable varying over space). Romero *et al.* (1999)

used a correlation matrix PCA, followed by CA, to determine eleven typical spatial patterns for significant rainfall days (1275 days) in Spain. They applied the same method to gridded ECMWF 925 and 500-hPa geopotential height data. A clear association emerged between each of the circulation types and a small number of the characteristic rainfall patterns. They also investigated torrential rain patterns and found which circulation patterns were important for these events. Salinger and Mullan (1999) set out to investigate the spatial distribution that occurs in surface climate variables. A rotated PCA was carried out on all data to identify characteristic patterns of interannual temperature and precipitation. To interpret the rotated PC patterns, each pattern was related to circulation variations by correlation analysis. Correlations were calculated between the rotated principal component scores and the various circulation indices. This procedure produced three temperature and eight rainfall regions with the anomalies showing the same results as the anomalies in the atmospheric circulation patterns.

3.6.3 Cluster Analysis

Cluster Analysis is a data reduction/classification method that uses measures of distance to relate (and group) observations within a dataset (Gong and Richman, 1995; Schoof and Pryor, 2001). There are a variety of clustering techniques, although they all share the same function: to maximise within-group similarity whilst minimising between group similarity (Balling, 1984). The differences and similarities between each of the observations help to derive clusters. There are a variety of clustering techniques which can each lead to a different set of clusters for the same dataset. As such, it is necessary to be aware of the different methodologies and the required outcome before deciding on a particular one.

Initially a measure of similarity is necessary. These can include the frequently used Euclidean distance or a method based on either a correlation coefficient or cosine angle between pairs of vectors. This similarity matrix is the basic input for the clustering technique.

There are a number of further alternative methods which need to be considered. Firstly, there are both hierarchical and non-hierarchical methods. Secondly, within hierarchical techniques, there are also agglomerative and divisive clusters. Hierarchical agglomerative techniques are the most commonly used in climatological literature. According to Kalkstein *et al.* (1987), this is because meteorological data are not strongly differentiated and often fail to exhibit distinct clusters. Hierarchical methods are also better suited to large datasets. Differences within hierarchical methods are defined by the method in which the distances between clusters are established. Agglomerative hierarchical methods begin with *n* clusters each containing one member and at each stage clusters are merged based on their distance or similarity with others (Hawksworth, 1998). Divisive hierarchical methods on the other hand start from one cluster containing all the data and lead to *n* clusters each containing one member. In both cases the results are analysed and the appropriate cluster grouping determined. Non-hierarchical methods choose the final number of clusters *a priori*. An initial 'seed' is established around which partitions can be made (Chessa *et al.*, 1999).

3.6.3.1 Application of CA. Schoof and Pryor (2001) use hierarchical methods of clustering, in which each observation is initially treated as a cluster and then adjacent clusters are merged based on intra- and inter-class similarity. They use Euclidean distance to determine the data similarity and five algorithms, which differ in the way the distances between the observations are measured, are applied. These are: Single Linkage (minimum distance between two clusters), Complete Linkage (maximum distance between observations in the two clusters), Average Linkage (either the average distance between observations in the two clusters, or the average distance between points in the newly formed cluster) and Ward's method (which minimises the within-cluster sum of squares). By experimenting with, and evaluating each of the different techniques, the authors were able to conclude that it was Average linkage (method type 1) which yielded the most realistic distribution of clusters and was thus chosen as the final clustering algorithm. A small number of studies previously have used non-hierarchical *k*-means clustering for atmospheric circulation patterns (Yarnal, 1984; Key and Crane, 1986; Galambosi *et al.*, 1996). As a non-hierarchical method, *k*-means clustering has a great advantage in that it requires much less computer resources and time.

3.6.4 Empirical orthogonal functions

There is another alternative method, namely Empirical Orthogonal Functions (EOF) which has been utilised instead of PCA. An Empirical Orthogonal Function is a unit length eigenvector. In contrast, a PC weights the eigenvectors by the square root of the corresponding eigenvalue so that these weights (loadings) represent the correlations (or covariances) between each variable and each principal component (Richman, 1986). Consequently Principal Components convey more information than EOFs. For classification, EOF analysis presents no advantage over PCA, but software for PCA is more readily available (Yarnal, 1993). Hence, it is PCA which is used more often. Nevertheless, a number of authors have used EOFs.

3.6.4.1 Application of EOFs. Busuioc *et al.* (2001b) identified the main characteristics of spatial and temporal variability of an observed data set by using rotated EOF analysis based on standardised monthly precipitation data. One of the disadvantages of using rotated EOFs is the loss of information about the dominant individual sources of variation in the data. The time coefficient series for the EOFs for each month were also analysed for trends and shift points, both for precipitation and MSLP. To determine the connection between the large-scale circulation patterns and monthly precipitation patterns Canonical Correlation Analysis (which will be discussed later) was used. The authors concluded that the changes in the observed characteristics in the Swedish precipitation variability were likely to be due to changes in the large-scale circulation. Tomozeiu *et al.* (2002) determined the connection between changes in seasonal mean maximum air temperature and their connection with large-scale circulation for Romania. To do this, an EOF analysis was performed on the sea level pressure with trend and shift point analysis carried out on the time series results of the first two PCs. These were then compared with the trend analysis and shift point detection that had been carried out on the temperature time series. The relationship between regional surface data and the geopotential height fields were also investigated by means of covariance maps using the PCs of the seasonal anomalies of the mean maximum temperature and 500-hPa heights. This was to try and identify the main patterns that could influence the variability of maximum winter temperature. It was concluded that the changes are controlled by real large-scale physical mechanisms (Tomozeiu *et al.*, 2002).

3.6.5 Canonical Correlation Analysis

Canonical Correlation Analysis (CCA) has the main advantage of selecting pairs of spatial patterns that are optimally correlated, making a physical interpretation of connection between large-scale atmospheric circulation and regional climate variables possible. Because of this, the method is also used as a GCM validation method (Busuioc *et al.*, 2001a). Barnett and Preisendorfer (1987) and Barnston and Ropelewski (1992) have recommended using PCA prefiltering and orthogonalisation of predictors, prior to performing CCA. In terms of regression modelling techniques, Canonical Correlation Analysis is considered one of the most superior, and all other linear modelling procedures can be shown to be special cases of canonical correlation (Knappenberger and Michaels, 1993). The first CCA pair gives the maximum correlation between the two time-dependent parameters followed by the second pair and so on. The skill of the downscaling model is dependent on the number of PCs retained for the CCA, and the number of CCA components used in the regression model. A number of alternatives can be tested before any final selection to determine the optimum number of PCs and CCA time components. The most common criterion is such that by increasing the number of PCs by one would only change the CCA by very little (Werner and von Storch, 1993).

3.6.5.1 Application of CCA. CCA is a method used by Werner and von Storch (1993) to investigate the relationship between the temperature field of eleven Central European stations to large-scale circulation. This is represented by the mean sea level pressure over the North Atlantic Ocean and Europe, and the relationship between them is calculated by means of a CCA. The authors refer to winter as the January-February period and they derived EOFs from the Jan-Feb mean temperature at the eleven stations. Werner and von Storch (1993) concluded that CCA fails to consistently link temperature to changes in North Atlantic/European MSLP. However, they do assert that changes in regional temperature may be controlled, not solely by circulation, but also by low-frequency variations of Atlantic sea-surface temperature. A number of authors found that using CCA to examine precipitation relationships is more complex than temperature. This is due to the fact that precipitation anomalies are more influenced by smaller time scale processes (Xoplaki *et al.*, 2000). Corte-Real *et al.* (1995) found that temperature patterns, for a CCA between geopotential height and sea level pressure with temperature and precipitation over the Mediterranean, explained more variance than precipitation. By using time lags of up to four months they were able to see the processes occurring and the development of the circulation-temperature relationships. Statistically significant coupled patterns were found, for both temperature and precipitation with surface and mid-tropospheric circulation variables, with CCA clarifying these relations. This acts as a basis for possible long-range forecasting methods. Busuioc *et al.* (2001b) use a subset of CCA pairs in a regression model to estimate the local spatial and temporal patterns of Swedish precipitation so as to determine the physical mechanisms responsible for these patterns. The CCA pairs can also be used to determine the changes in various characteristics of precipitation variability. The relationship between monthly MSLP anomalies and Swedish precipitation anomalies is strong in most months, but this was especially valid in the cold months. Three main structures were identified in the first three CCA pairs: an NAO pattern, a cyclonic/anticyclonic pattern and a dipole structure with a west/east gradient. Zorita *et al.* (1992) used CCA to show that 65% of the variability in the Iberian Peninsula winter-rainfall anomalies (29 stations) can be explained by the North Atlantic sea level pressure field anomalies, in the period 1950-1980. Other factors may influence the seasonal rainfall, but the authors concluded that it is likely that rainfall will be more sensitive to MSLP in any future changed climate. Continuing on from this analysis, von Storch *et al.* (1993) examined the rainfall anomalies for the period 1900-1986. Again they found that substantial changes which took place in Iberian rainfall since the beginning of the century could be described by similar changes in the Atlantic sea level pressure field. These results are then used in a model to reproduce rainfall from the observed MSLP based on GCM data.

One of the drawbacks with CCA however is the fact that it is generally only successful with monthly data. There have been a number of studies that have used daily precipitation data but have not relied on a linear regression model. This is due to the fact that the predictors, such as MSLP or geopotential height, are normally distributed whereas precipitation is highly skewed. To use linear regression CCA on normally distributed predictors and non-normally distributed predictands would generate a normally distributed output which is obviously not the case with daily precipitation. In addition, many more CCA patterns would be needed with daily data, whereas with monthly values, a few patterns describe most of the variance in the precipitation (von Storch, pers.comm.).

3.6.6 Automated Lamb Classification

An automated objective version of the Lamb Weather Types was proposed by Jenkinson and Collison (1977) as an alternative to the original manual scheme. This was initially developed for the British Isles in order to automatically reproduce the subjective LWT classification. Daily mean sea level pressure was used to classify atmospheric circulation data objectively, by surface flow direction and type. The scheme, or elements of it, have been applied to a variety of regions and climate-related studies including the British Isles (Wilby, 1997), the Iberian Peninsula (Goodess and Palutikof, 1998), Sweden (Chen, 2000) and Southern Scandinavia (Linderson, 2001). Automated, objective atmospheric circulation classifications have a number of advantages over more subjective methods. Firstly, they are easier to create and interpret. They are based on a single, widely available, free atmosphere variable – daily gridded mean sea level pressure (Goodess and Palutikof, 1998). They also have the advantage of being effective and repeatable (Chen, 2000). Downscaling using the objective classification method have been carried out for precipitation in the UK (Wilby *et al.*, 1995; Conway and Jones, 1998; Wilby, 1998a) and also in Spain (Goodess and Palutikof, 1998; Goodess, 2000a).

While automated methods are considered objective, it is inevitable that there are subjective decisions involved, and as such, no classification is ever truly objective.

3.7 Conclusion

There are a number of general conclusions which can be made from the above review.

- Most of the research cited thus far has been based on data on a monthly time-scale. This is because of a lack of reliable, homogenous and lengthy daily climatic datasets for many regions.
- There has been relatively little research on atmospheric circulation and climatic variability conducted for Ireland specifically, and only slightly more for the UK. It is evident though, that there have been many such studies carried out for other regions in Europe and elsewhere around the world and it is therefore a necessary and worthwhile activity to carry out research on this issue for Ireland.
- In general, studies of atmospheric circulation and climatic variability utilised MSLP and 500- and 700-hPa geopotential height data, with temperature and precipitation as the surface climatic variables. Studies on a seasonal basis, rather than annual, have been most common, a reflection of the fact that different synoptic scale circulation exists in different seasons.
- The terms subjective and objective to describe the two main methods of classifying atmospheric circulation have been replaced in terminology by manual and automated classification. This is because methods presented as objective, such as Lund, Kirchhofer, PCA and CCA have ample opportunities for subjective decisions.
- Manual schemes include the widely used Lamb Weather Type classification which is only applicable to the UK and the Grosswetterlag for Central Europe and the Northeast Atlantic. Difficulties in duplicating the classification for other regions and the high labour and time intensiveness of the methods are just some of the weaknesses which make manual schemes inapplicable.
- Automated schemes used for classifying circulation patterns either adopt a correlation-based approach or use eigenvector techniques. The most common technique applied when not using manual schemes is PCA and CA. Although these eigenvector techniques are considered to be mathematically more comprehensive, the results can sometimes be more difficult to interpret. In

some cases, clear physical meaning cannot be applied to the circulation patterns obtained. One of the major drawbacks of PCA is the lack of comparability between locations.

- Before conducting any study the investigator must be thoroughly familiar with the classification technique, the data and the climatology of the region so as to derive the best possible circulation classification.

This chapter has reviewed the main techniques for classifying atmospheric circulation patterns and the methods of quantifying links between large-scale circulation features and local climate variables. An outline of the many subjective decisions, which must be made prior to beginning a circulation classification scheme (e.g. choice of data, grid domain and classification approach), has been provided. In the following chapter, a method of classifying atmospheric circulation suitable for Ireland will be presented based on this framework.

Chapter 4

An automated atmospheric circulation classification for Ireland, 1961-1990

4.1 Introduction

Links between atmospheric circulation and surface weather have already been established for both large and small-scale regions. Examples include: an exploration of the relationship between climatic variability in the UK and the North Atlantic Oscillation index (Wilby *et al.*, 1997); the relationship between Australian temperatures and mean sea level pressure by way of PCA (Schubert and Henderson-Sellers, 1997); precipitation and atmospheric circulation patterns for Switzerland (Brandsma and Buishand, 1997); temperature variations on a seasonal and annual basis related to the NAO index for Sweden (Chen and Hellström, 1999) and the relationship between nine climatic variables in the Czech Republic and circulation types over Europe determined from 500-hPa heights by means of PCA (Huth, 2001). These studies highlight the importance of atmospheric circulation as a factor in shaping the climate and are essential for the understanding of the climatic variability of a region.

The identification of relationships between circulation and local climatic variables, such as temperature and precipitation, is also important for the development of statistical and empirical downscaling approaches. These relationships can then be applied to Global Climate Model (GCM) output to produce future climate scenarios at the local level. There are a variety of methods which can be used for downscaling from the large-scale circulation to the local climate, including multiple linear regression, neural networks (as a method of non-linear multiple regression) and stochastic weather generators. A more detailed discussion of downscaling will follow in Chapter 7.

However, the choice of appropriate atmospheric circulation classification scheme is a fundamental decision in any downscaling methodology, as it will have an influence upon the choice of transfer function used. As outlined in Chapter 3, there are a wide range of atmospheric circulation classification methodologies from which to chose. These range from manual schemes such as the Lamb Weather Type and Grosswetterlag classifications to automated correlation- and eigenvector-based techniques. There are advantages and disadvantages with each of the methods so it is essential that the approach selected will comply with one of the objectives of this thesis – to construct an automated daily atmospheric circulation classification for Ireland. This can then be used to detect if the changes already identified in Irish climate can be related to large-scale changes in atmospheric circulation patterns.

4.2 Choosing an automated daily atmospheric circulation classification for Ireland

Initially, each of the automated methodologies outlined in the previous chapter were examined to determine if they were suitable for classifying the atmospheric circulation of Ireland. In the first case, the correlation-based method, developed by Kirchhofer, was explored as it was rated favourably by a number of authors (Yarnal, 1984; El-Kadi and Smithson, 1992; Saunders and Byrne, 1996). Yarnal (1984) developed a set of program codes for the Kirchhofer algorithm, for use with a 30-point 5 by 6 matrix. There are 5 separate programs – NORMAL, SCORES, KEYDAY, SYNTYPE and SORT. However, to adapt these codes so as to be applicable to Irish data proved to be unfeasible. While it was possible to compile the NORMAL and SCORES programs, the program codes for KEYDAY uncovered statements and routines which were not possible to compile, either due to an old extension which works on one compiler and not on another, or program codes which are not standard. Furthermore, as outlined by Blair (1998), the Kirchhofer method gives inferior results as there is an error in the original code which makes the row and column scores ineffective. Even if they are resolved, the routine becomes insignificant as a large number of keydays are still selected – defeating the purpose of the classification in the first place.

The commonly used eigenvector-based techniques also have difficulties associated with them. Principal Components Analysis has a high level of inherent subjectivity, including the selection of mode of decomposition, matrix dispersion, whether to rotate or not and subsequently, which method of rotation. This wide range of decisions ensures that the method is never fully objective. Also, as each researcher has the ability to choose different options, comparability between PCA studies is relatively difficult. With regard to Canonical Correlation Analysis, the fact that most studies have utilised monthly data would seem to oppose the objective of a daily atmospheric circulation classification system. With monthly values, a few patterns can describe most of the variance in precipitation, whereas with daily data many more CCA patterns would be created.

Manual techniques are also not without their problems. The Lamb Weather Type (LWT) classification has been extensively used for the UK and Ireland (e.g. Sweeney, 1985; O'Hare and Sweeney, 1993; Jones *et al.*, 1993; Wilby, 1995; Wilby *et al.*, 1995). However, problems arise when a single circulation type is defined even though different synoptic situations may be taking place in different regions (Mayes, 1991). As outlined in Chapter 3, difficulties may arise when there are wide-ranging regional variations in airflow over the UK and Ireland due to the geographical size of the area being classified, and the size of the prevailing circulation feature. Furthermore, difficulties can emerge in assigning the correct airflow pattern, for example, when there may be depression to the east of England but northwesterly flow over Ireland. In this case, the day may be classified as cyclonic in the Lamb catalogue whereas NW may be more appropriate.

The subjectivity and inefficiency of subjective classification schemes can be overcome by defining objective rules for such schemes (Jenkinson and Collison, 1977; Chen, 2000). In this thesis, an automated version of the Lamb classification, as developed by Jenkinson and Collison (1977) is proposed for Ireland. The automated version of LWTs categorise surface flow by direction and synoptic type (Jenkinson and Collison, 1977; Jones *et al.*, 1993; Goodess and Palutikof, 1998). The scheme was originally based on data for the area: 45°N to 65°N, 20°W to 20°E, at intervals of 5° latitude by 10° longitude. Initially, the authors intended to derive an index of gale frequency for the British Isles, while also demonstrating how the scheme could successfully operate as an automated version of the LWTs.

Jones *et al.* (1993) compared the results from the objective scheme with the original manual version of LWTs over the 110-year period and found that they are both highly correlated. All directional types are well represented but it is cyclonic and anticyclonic types which show the best agreement. Any differences were attributed to the fact that Lamb was concerned with the steering of weather over the British Isles rather than surface winds, and also as a result of the automated version using only one ‘snapshot’ per day while Lamb utilised two to three charts (1993).

The development of automated, objective atmospheric circulation classification schemes has created an accessible alternative to eigenvector- and correlation-based techniques. Automated objective methods have a number of advantages over more subjective methods, including: they are easier to create and interpret; they are based on a single, widely available, free atmosphere variable - daily gridded mean sea level pressure (Goodess and Palutikof, 1998); and they have the advantage of being effective and repeatable (Chen, 2000). As with all automated methods which are considered objective, it is inevitable that there are subjective decisions involved, and as such, no classification is ever truly objective. However, it was felt that the subjectivity within the automated classification was less than that for other classifications. The ease with which the scheme can be applied to both the observed and modelled MSLP data was an obvious advantage.

4.3 Automated Classification Methodology

The automated version of Jenkinson and Collison (1977) is transferred to a new region, with a new domain size and grid cell spacing. Originally, the method was applied to a 16-point grid, centred on 55°N, with a resolution of 5° latitude by 10° longitude (Jenkinson and Collison, 1977). As long as the geostrophic flow units are modified to reflect the changed latitude and resolution of the gridded data, this method can be applied to any mid-latitude region (Goodess, 2000a). Mean daily sea level pressure for 1961-1990 from the National Centers for Environmental

Predication (NCEP) Reanalysis database has been used in this classification for Ireland. The NCEP Reanalyses are output from an assimilation/forecast model based on a synthesis of all available weather and satellite information, including land surface, marine, rawinsonde, pibal, aircraft and satellite data (Kalnay *et al.*, 1996). Data are available on a 2.5° x 2.5° grid. The Reanalyses are the result of a fixed analysis through time and provide a near consistent simulation of climatic conditions over the Reanalysis period (Reid *et al.*, 2001). One of the major benefits of the NCEP Reanalyses over observations is the completeness of their spatial and temporal coverage. However, there are data input errors prior to 1967 which may make the data less reliable. Reid *et al.* (2001) found that the annual time series of NCEP MSLP tends to be lower than the UK Meteorological Office (UKMO) observed data, especially south of 55°N for much of Europe. As a result, the majority of low-pressure centres before this period are model derived. The authors point out that this confirms earlier reports that NCEP Reanalyses are more reliable when looking at interannual variability and less reliable for interdecadal variability. Santer *et al.* (2000b) also apply this conclusion to European Centre for Medium-Range Weather Forecast (ECMWF) Reanalyses (Santer *et al.*, 2000b; Reid *et al.*, 2001). Nevertheless, Reid *et al.* (2001) do acknowledge that for the grid employed in the ACCORD project (80°N-30°N, 60°W-70°E) the data can be reliably used. The grid used in this work is also within this window.

The Reanalysis data were re-gridded onto a 32-point, 2.5° latitude by 3.75° longitude grid over the area 57.5°N-47.5°N and 22.5°W-3.75°E. This grid, centred on 52.5°N, can be seen in Figure 4.1. The 2.5° x 3.75° grid spacing allows for easier application of the scheme to both the Reanalysis data and GCM data. The higher resolution grid also ensures that small-scale features affecting Ireland can be detected.

Based on values of westerly (w), southerly (s) and resultant flow (F), as well as westerly shear flow (zw), southerly shear flow (zs) and total shear vorticity (Z), 27 circulation types were created. A positive value of w corresponds to air flowing from west to east, while a positive value of s corresponds to air flowing from south to north. The vorticity is a measure of atmospheric rotation, with positive values corresponding to low pressure (cyclonic weather) and negative values corresponding to high pressure (anti-cyclonic weather) (Kilsby *et al.*, 1998).

The classification is based on the following 6 indices to describe geostrophic wind and vorticity:

$$w = 0.25(23+24+25+26) - 0.25(7+8+9+10)$$

$$s = 1.64[0.125(10+2(18)+26+9+2(17)+25) \\ - 0.125(7+2(15)+23+8+2(16)+24)]$$

$$\mathrm{F} = (\mathrm{w}^2 + \mathrm{s}^2)^{½}$$

$$zw = 1.04[0.25(29+30+31+32) - 0.25(15+16+17+18)] \\ - 0.97[0.25(15+16+17+18) - 0.25(1+2+3+4)]$$

$$zs = 0.82\ [0.125(12+2(20)+28+11+2(19)+27) \\ -0.125(10+2(18)+26+9+2(17)+25) \\ -0.125(8+2(16)+24+7+2(15)+23) \\ +0.125(6+2(14)+22+5+2(13)+21)]$$

$$\mathrm{Z} = zs + zw$$

$$\text{Direction} = \tan^{-1} (w/s)$$

The numbers 1 to 32 refer to the grid points shown in Figure 4.1. The constants reflect the relative differences between the grid-point spacing, and the multipliers (0.25 and 0.125) reflect the number of grid points used here. The geostrophic flow and vorticity units are expressed as hPa per 10° latitude at the central latitude of 52.5°N.

- The westerly (zonal) flow is calculated from the pressure gradient between 50°N and 55°N.

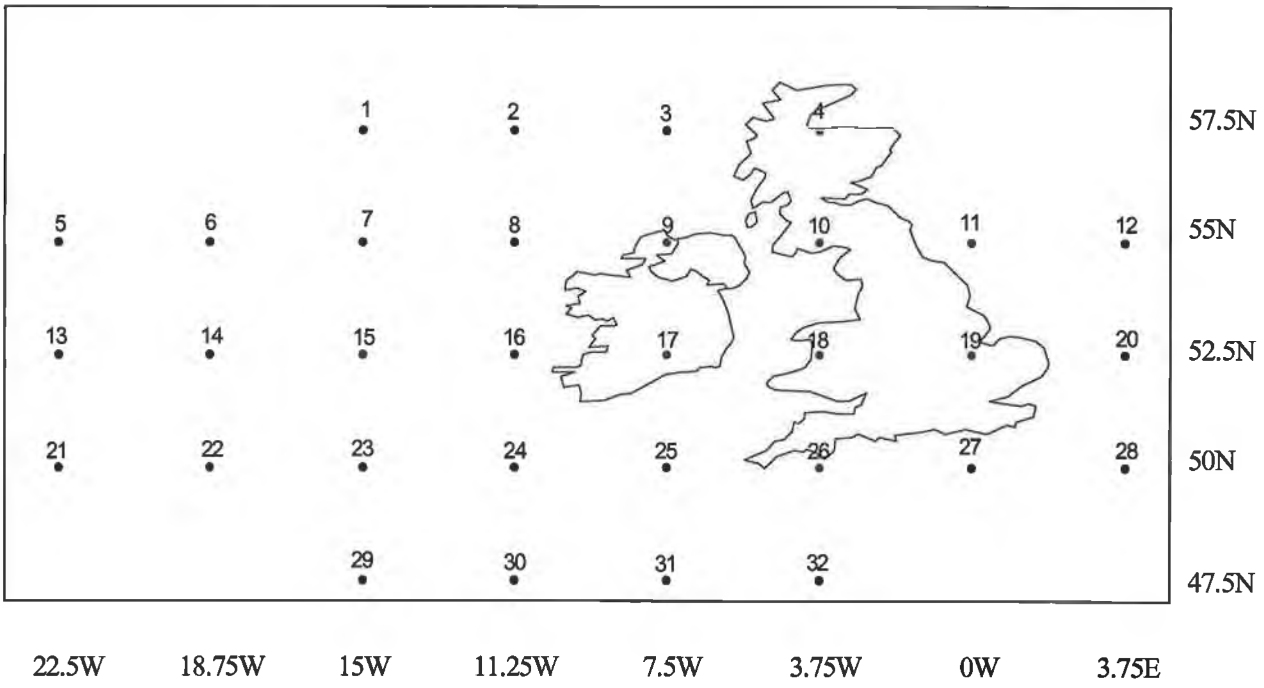


Figure 4.1 32-point grid used in atmospheric circulation typing scheme

- The southerly (meridional) flow is calculated from the pressure gradient between 15°W and 3.75°W.
- Resultant flow is the combined wind speed of westerly and southerly flow.
- Westerly shear vorticity is the difference of the westerly flow between 47.5°N and 52.5°N minus that between 52.5°N and 57.5°N.
- Southerly shear vorticity is the difference of the southerly flow between 52.5°N and 3.75°E minus that between 52.5°N and 22.5°W.
- Direction, in degrees from 0° to 360°, of the resultant surface flow, is calculated from w and s, with each directional category calculated on an 8-point compass with a resolution of 45°. If $s > 0$, add 180°, if $s<0$ and $w>0$, add 360°.

There are also a number of other important considerations when performing this classification:

If $\|Z\| < F$:	directional type	N, NE, E, SE, S, SW, W, NW
If $\|Z\| > 2F$:	emphasises rotation	$Z < 0$ = anticyclonic $Z > 0$ = cyclonic
If $\|Z\| <4$ and $F < 4$:	unclassified	U
If $F < \|Z\| < 2F$:	hybrid classification	$Z < 0$ = AN, ANE, AE, ASE, AS, ASW, AW, ANW $Z > 0$ = CN, CNE, CE, CSE, CS, CSW, CW, CNW

Lamb (1972) identified unclassifiable days as those in which patterns are (1) chaotic with weak flow, (2) change quickly during the day or (3) form 'incompatible' hybrids (Yarnal, 1993). Threshold values for the resultant flow (F) and total shear vorticity (Z) are chosen to define unclassified types. While initially attempting to imitate the LWTs for the British Isles, Jenkinson and Collison chose a cut-off value of six for both resultant flow and total shear vorticity. Maintaining this value for the classification of atmospheric circulation types for Ireland would mean that nearly 10% of days would be unclassified (1543 days). When considering the total number of days classified and the number of circulation types, this was considered to be too large. By lowering the limit for resultant flow and total shear vorticity, unclassified days are essentially those days when flow is indeterminate in direction and rotation, days when the circulation is weak and/or chaotic. For these reasons, the threshold value of four was chosen to define an unclassified circulation type. This amounts to 469 days over the 30-year period. Goodess and Jones (2002) recognise that the threshold values '...initially chosen to define LWTs in the British Isles...may not be the most appropriate for use in other regions'. The authors use the mean annual values of F ($F = 4.8$) and Z ($Z = 4.2$) as the thresholds for the unclassified CT, but in the case of this exercise this would have been unmanageable as $F = 10.27$ and $Z = -1.18$. Goodess (2000a), who uses a threshold level of four for HadCM2 data and a value of six for UKMO data, recognises that the choice of threshold value is arbitrary, and that there is '...no physical or other obvious justification for choosing this particular value over any other' (Goodess, 2000a: 117).

4.4 Changes in Circulation Types

4.4.1 Annual frequencies of CTs

Eight directional types, sixteen hybrid types and three non-directional circulation types (CTs) are generated. The most frequently observed circulation types are SW and W over the period 1961-1990, occurring 15% and 12% of the time, respectively. The least frequent types are CNE, CE and CN, only occurring on average between two and three days per year. The occurrence of the majority of types is less than 4%, while the dominant seven types – SW, W, A, S, NW, C, N - account for nearly two thirds of all classified days. There are a number of similarities and differences when comparing the frequencies of the automated CTs for Ireland, the Lamb Weather Types and the Jenkinson-Collison circulation types. There is a better agreement between the LWTs and the Jenkinson-Collison classification for both anticyclonic and cyclonic types, than either of the classification methods with the automated scheme for Ireland. The consistency between the hybrid types for Ireland and the Jenkinson-Collison scheme are in most cases greater than the Jenkinson-Collison scheme with the LWTs. This may be because the Lamb Weather Types are not looking at each day in isolation, but at the development of the weather circulation patterns over preceding and succeeding days (Jones *et al.*, 1993). The percentage frequency distribution of

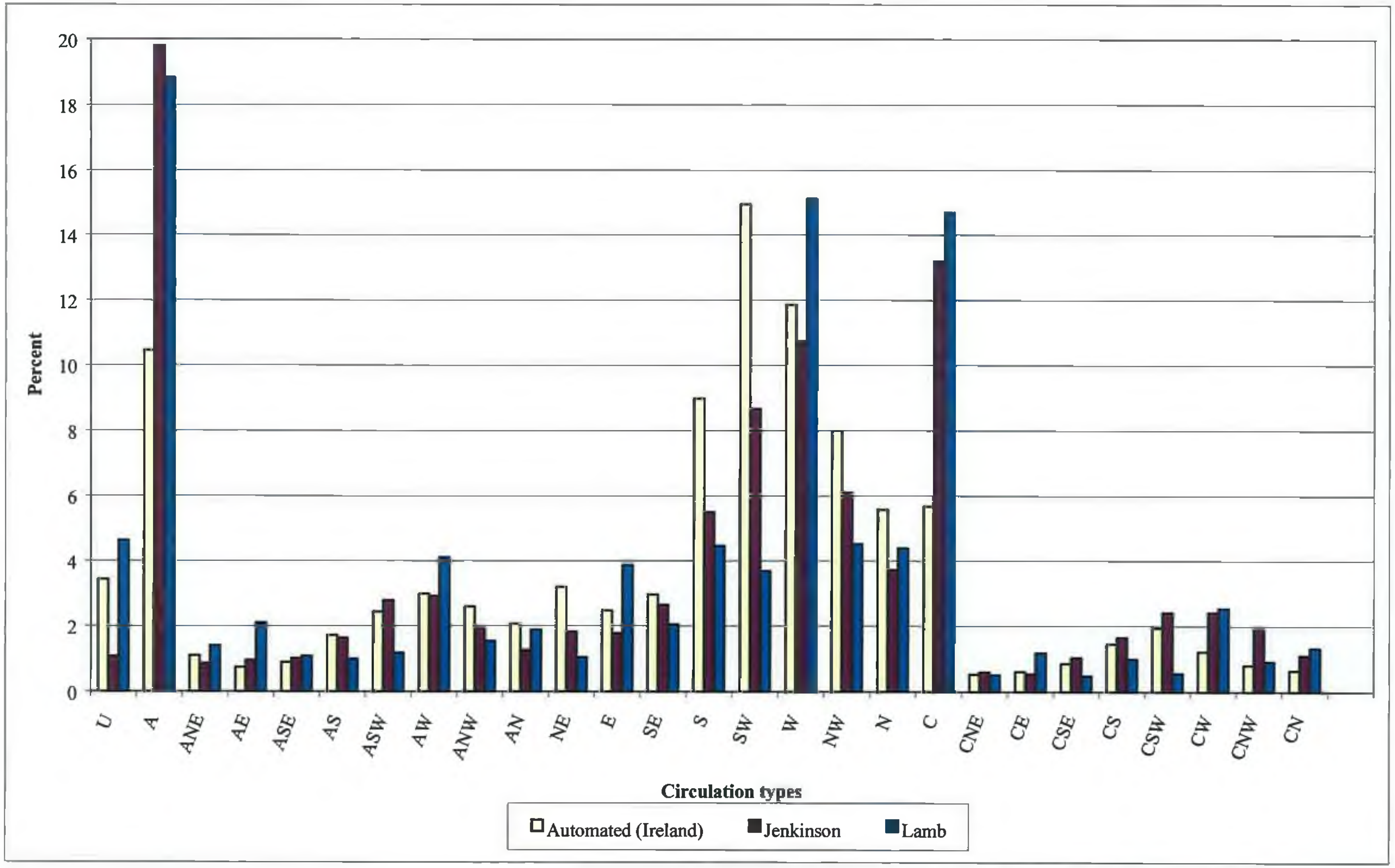


Figure 4.2 Frequency distribution of automated circulation types for Ireland, Jenkinson-Collison CTs for the British Isles and the original Lamb Weather Types for the British Isles, 1961-1990

each of the circulation types – the Lamb Weather Types, the Jenkinson-Collison scheme and the automated classification for Ireland are displayed in Figure 4.2.

4.4.2 Seasonal frequencies of CTs

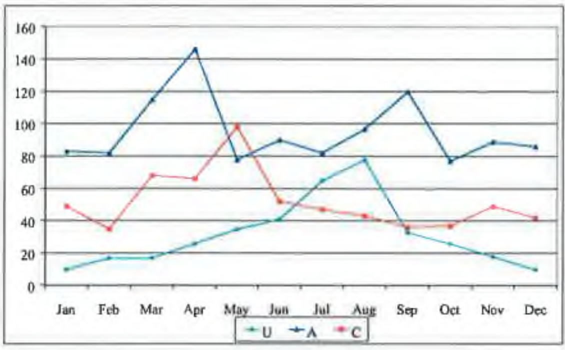
Many of the CTs are dominant in certain months and seasons, and it is interesting to note the differences in frequency of the circulation types. Table 4.1 gives the percentage monthly and seasonal frequencies, with frequencies over 10% highlighted in bold. The most common type in winter, summer and autumn is SW. This is followed by S in winter, NW in summer and W in autumn. In spring, the most persistent types are W, followed by SW and A. Cyclonic, anticyclonic and westerly circulation types have their maximum frequency in spring, occurring more often than they do in any of the other seasons. The least frequent types in autumn and winter are CNE, CE and CN. In spring, the least common circulation groups are ASE, AS and CNW, while in summer, the least common types are ASE, CE and CSE.

4.4.3 Monthly frequencies of CTs

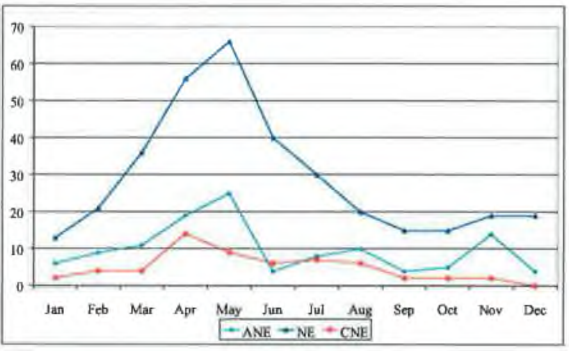
On a monthly basis, directional circulation types are common in all months, especially S, SW and W. Cyclonic types are frequent in May, while anticyclonic types are common in March and April, June, August and September. It is evident that the SW type dominates from August to January, having the highest percentage frequencies in these months, reaching a peak of 19.5% in December. The highest percentage of southerlies is in February, while the highest percentage of westerlies is in March. Anticyclonic circulation types are most common in April and cyclonic circulation types in May. ASE types have not occurred in May and CNE types have not occurred in December over the course of the 30-year period. Mean monthly frequencies of each circulation type are plotted in Figure 4.3. It is clear that certain types have a highly seasonal structure, occurring much more frequently at certain times of the year, while others, such as southwesterly and anticyclonic types occur throughout the year. Northeasterly and easterly types dominate in April and May. This may be related to the Scandinavian high and the resultant blocking that occurs.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Winter	Spring	Summer	Autumn
A	8.9	9.7	**12.4**	**16.2**	8.4	**10.0**	8.8	**10.4**	**13.3**	8.3	9.9	9.2	**10.5**	9.7	**12.3**	9.7	**10.5**
AE	0.4	0.7	0.6	1.1	0.6	0.6	0.5	0.4	0.9	0.6	1.2	1.0	0.7	0.7	0.8	0.5	0.9
AN	0.9	1.3	2.9	3.7	2.5	2.7	3.4	1.8	1.4	1.0	1.7	1.5	2.1	1.3	3.0	2.6	1.4
ANE	0.6	1.1	1.2	2.1	2.7	0.4	0.9	1.1	0.4	0.5	1.6	0.4	1.1	0.7	2.0	0.8	0.9
ANW	0.9	1.1	4.0	3.3	3.3	3.7	4.1	3.2	1.6	1.9	1.7	2.2	2.6	1.4	3.6	3.7	1.8
AS	2.8	2.4	0.4	0.1	0.1	2.3	1.3	1.8	2.6	3.3	1.9	1.5	1.7	2.2	0.2	1.8	2.6
ASE	1.9	1.4	0.1	0.6	0.0	0.3	0.1	0.9	0.9	1.3	1.2	1.9	0.9	1.8	0.2	0.4	1.1
ASW	3.4	1.7	1.0	1.1	1.1	2.0	3.0	2.8	4.7	3.7	2.7	2.0	2.4	2.4	1.1	2.6	3.7
AW	1.7	2.0	7.4	5.1	2.8	1.7	2.6	2.0	3.0	3.3	1.7	2.4	3.0	2.0	5.1	2.1	2.7
C	5.3	4.1	7.3	7.3	**10.5**	5.8	5.1	4.6	4.0	4.0	5.4	4.5	5.7	4.7	8.4	5.1	4.5
CE	0.2	0.5	0.6	1.2	1.9	0.7	0.2	0.1	0.1	0.6	0.7	0.3	0.6	0.3	1.3	0.3	0.5
CN	0.5	0.4	0.3	0.8	0.5	1.2	1.1	0.5	0.7	0.8	0.1	0.8	0.6	0.5	0.5	0.9	0.5
CNE	0.2	0.5	0.4	1.6	1.0	0.7	0.8	0.6	0.2	0.2	0.2	0.0	0.5	0.2	1.0	0.7	0.2
CNW	0.9	0.7	0.2	0.4	0.5	1.2	0.8	1.1	0.8	0.9	1.1	1.0	0.8	0.9	0.4	1.0	0.9
CS	1.3	1.7	2.2	2.0	3.2	1.3	1.1	0.9	1.1	0.9	0.7	1.1	1.4	1.2	2.4	1.1	0.9
CSE	0.8	0.6	1.3	2.2	1.6	0.3	0.1	0.3	0.6	0.4	0.7	1.4	0.9	1.0	1.7	0.3	0.5
CSW	1.5	1.2	2.8	2.3	4.6	1.2	1.0	1.5	1.9	1.5	1.7	1.9	1.9	1.5	3.3	1.2	1.7
CW	1.4	1.2	1.2	0.6	1.0	1.2	1.4	2.0	1.4	1.4	0.8	0.9	1.2	1.1	0.9	1.6	1.2
E	1.8	4.1	2.3	6.0	4.3	2.6	0.9	0.3	0.8	1.5	2.3	3.0	2.5	3.0	4.2	1.2	1.5
N	4.1	3.7	2.3	2.2	4.6	8.2	**10.1**	7.5	5.3	5.9	7.3	5.5	5.6	4.5	3.0	8.6	6.2
NE	1.4	2.5	3.9	6.2	7.1	4.4	3.2	2.2	1.7	1.6	2.1	2.0	3.2	2.0	5.7	3.3	1.8
NW	8.7	6.7	3.3	3.2	2.7	**10.4**	**12.5**	**10.3**	9.1	7.7	**11.3**	9.8	8.0	8.4	3.1	**11.1**	9.4
S	**13.5**	**17.5**	2.6	3.6	3.1	7.3	6.0	8.4	**10.6**	**15.4**	8.1	**12.2**	9.0	**14.3**	3.1	7.2	11.4
SE	4.6	8.0	2.4	2.7	2.5	2.3	1.2	1.9	1.8	2.4	4.0	2.2	3.0	4.9	2.5	1.8	2.7
SW	**18.1**	**14.4**	**16.6**	9.0	**13.2**	**13.9**	**11.7**	**13.0**	**16.2**	**17.8**	**15.8**	**19.5**	**15.0**	**17.4**	**13.0**	**12.9**	**16.6**
U	1.1	2.0	1.8	2.9	3.8	4.6	7.0	8.4	3.7	2.8	2.0	1.1	3.4	1.3	2.8	6.7	2.8
W	**13.0**	9.1	**18.6**	**12.4**	**12.3**	8.9	**11.3**	**11.7**	**11.3**	**10.2**	**12.2**	**10.9**	**11.9**	**10.9**	**14.5**	**10.7**	**11.2**

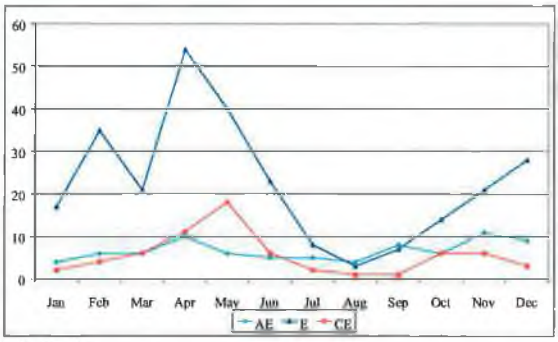
Table 4.1 Percentage frequency of each circulation type, annually, seasonally and monthly, 1961-1990
Frequencies over 10% are highlighted in bold.



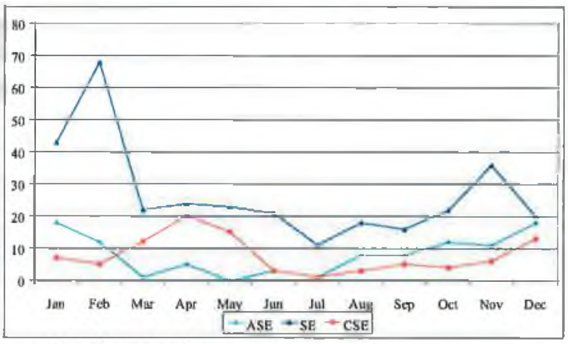
Anticyclonic/ Cyclonic/ Unclassified



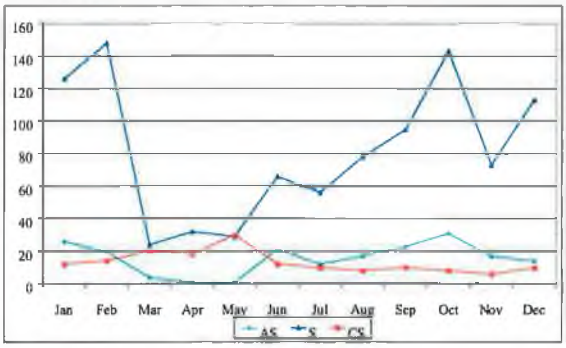
North-easterly



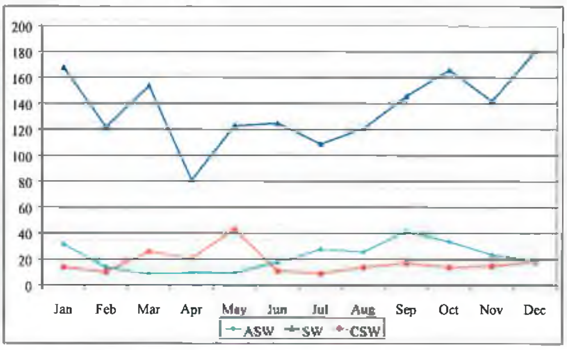
Easterly



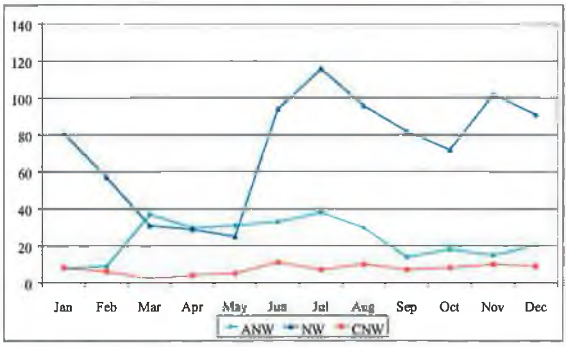
South-easterly



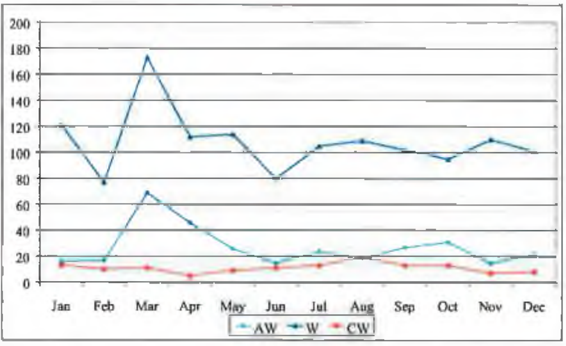
Southerly



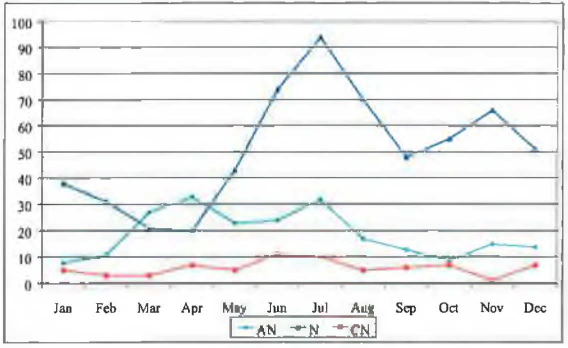
South-westerly



North-westerly



Westerly



Northerly

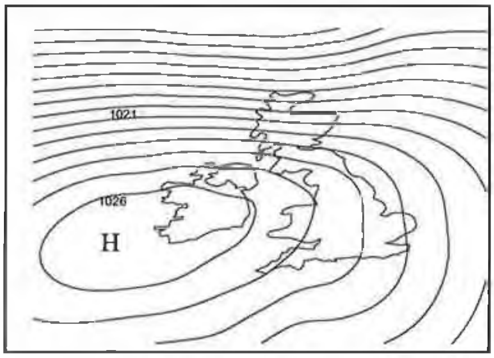
Figure 4.3 Mean monthly frequency of each circulation type.

According to Musk (1988), blocking is most frequent in the period January to April, with a minimum blocking in late summer in the Atlantic region. However, it can occur in any month of the year. Southeasterly types are recurrent in February and November while southerly circulation is more persistent in January, February and October. Westerly circulation is more pronounced in March although it does occur commonly throughout the rest of the year. The mid-latitude temperature gradient, which is at its maximum in winter due to polar cooling, causes an intensified westerly circulation pattern in winter. By late spring and early summer, the temperature contrast is at its annual minimum, which results in a higher frequency of blocking. As regards the Lamb classification, Mayes and Wheeler (1997) identify a higher frequency of W types in winter and a more extensive distribution in spring and summer (1997). This pattern is also clear in the frequency of automated westerly CTs. Maximum frequencies of northerly and northwesterly circulation types occur from July to December, although peaking in July.

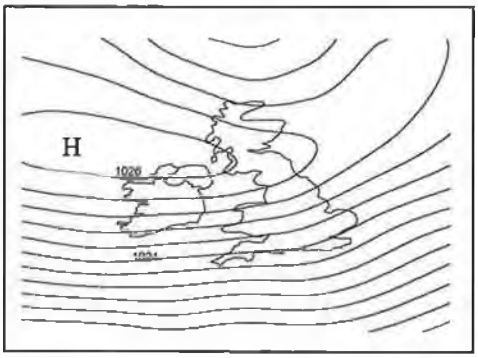
Though unclassified days account for 3.4 percent of the total annual number of types, it is noteworthy that they have a high percentage frequency in summer. As highlighted by Hulme *et al.* (1993), in their examination of the Jenkinson-Collison objective circulation types for the UK, this suggests that either a greater number of chaotic days are generated or very weak pressure fields exist during summer months (1993).

4.4.4 Composite maps of CTs

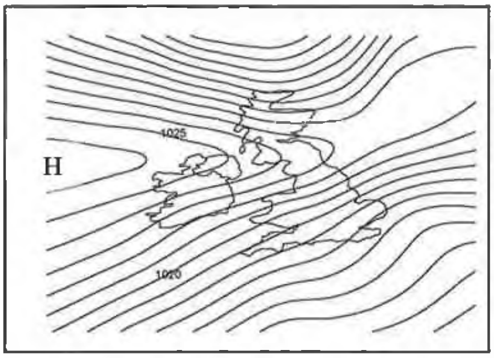
Composite maps of mean sea level pressure for each CT were calculated and show the location of the pressure centres as a result of the pressure differences. (Figure 4.4 (a) – (z)). Average values of mean sea level pressure (MSLP) for each grid point for each CT were calculated. Unfortunately, there are limitations in interpolating from these grid points, and the composite maps only give a coarse interpolation at the edges. This is especially evident in the cases of CNE, E and W. However, each of the 26 CTs produces the expected type and direction of surface flow over Ireland.



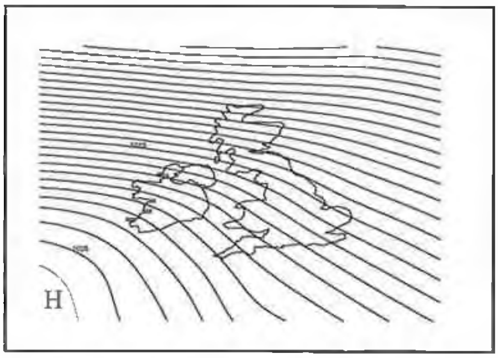
(a) Anticyclonic



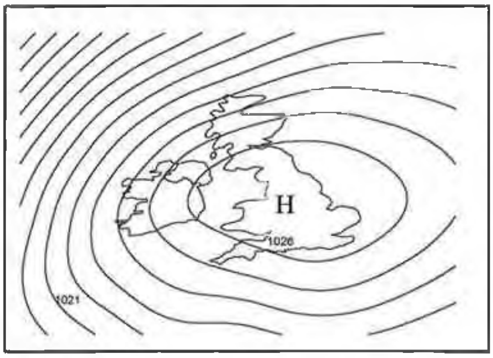
(b) Anticyclonic East



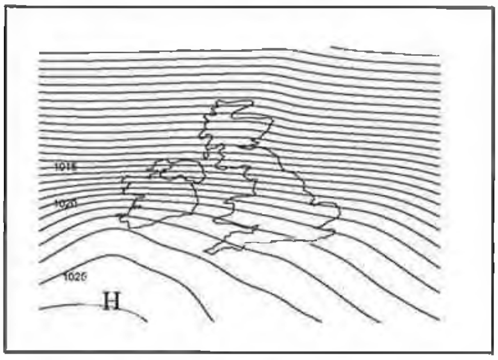
(c) Anticyclonic Northeast



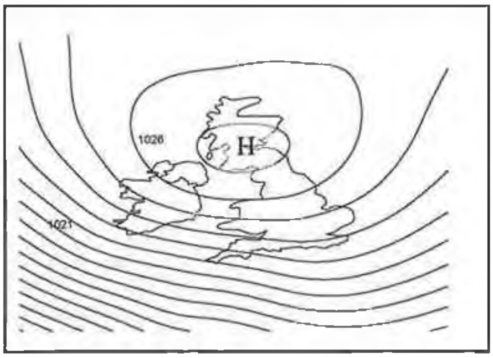
(d) Anticyclonic Northwest



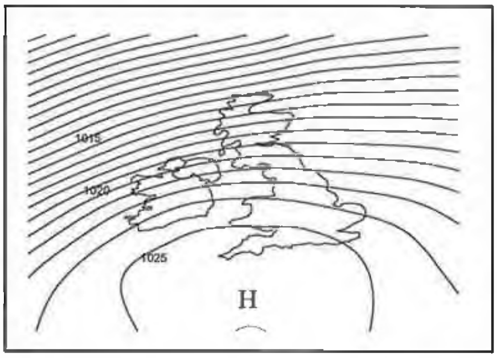
(e) Anticyclonic South



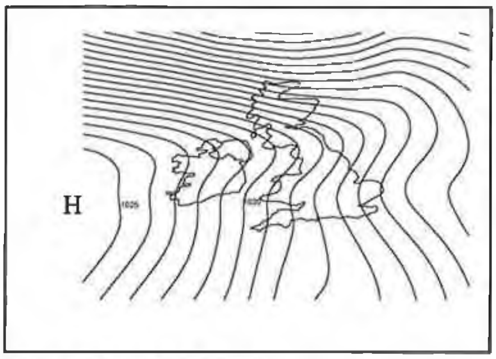
(f) Anticyclonic West



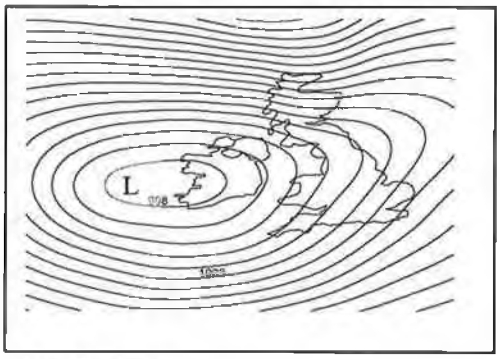
(g) Anticyclonic Southeast



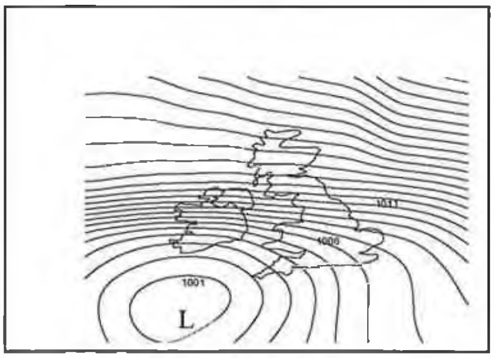
(h) Anticyclonic Southwest



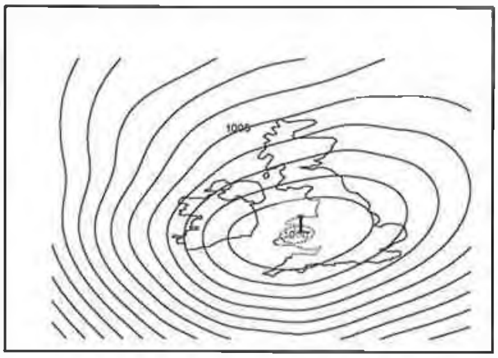
(i) Anticyclonic North



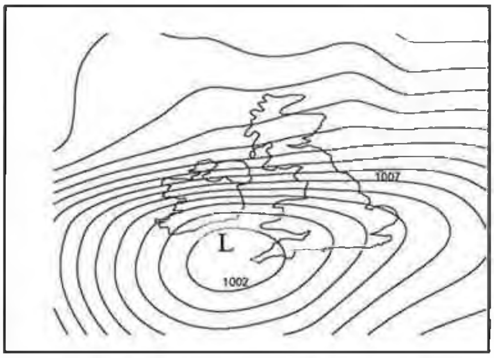
(j) Cyclonic



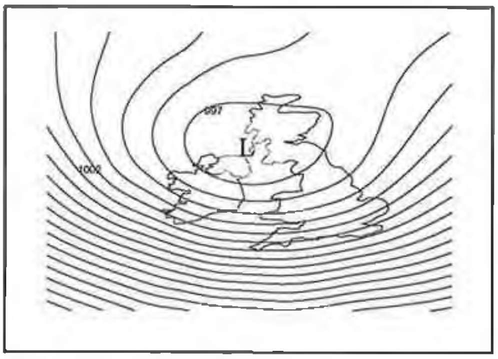
(k) Cyclonic East



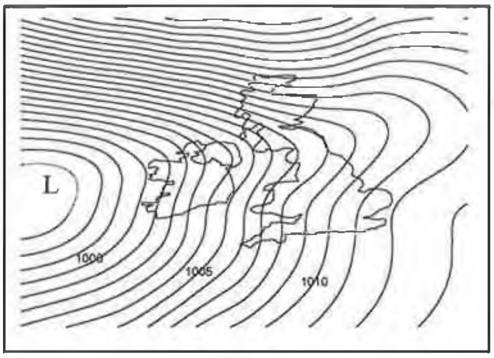
(l) Cyclonic North



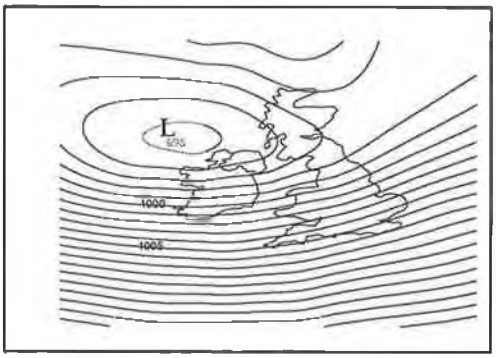
(m) Cyclonic Northeast



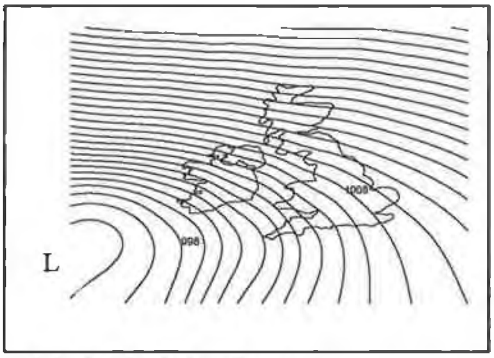
(n) Cyclonic Northwest



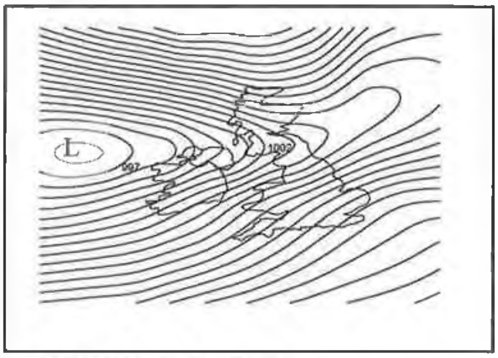
(o) Cyclonic South



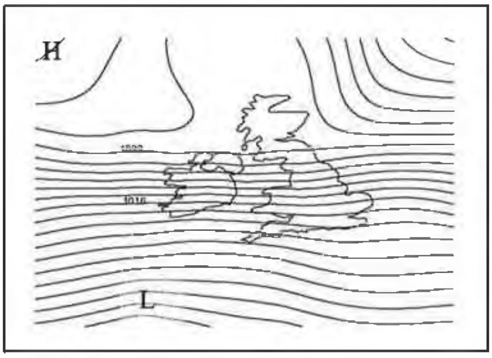
(p) Cyclonic West



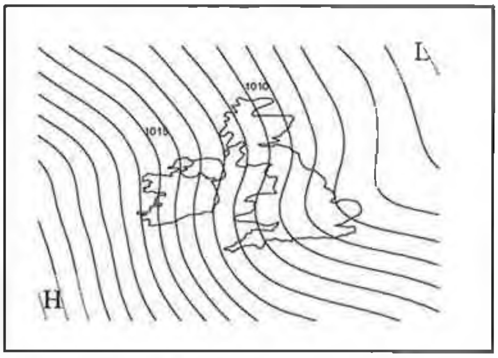
(q) Cyclonic Southeast



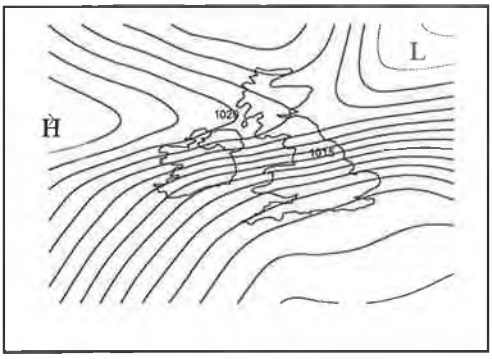
(r) Cyclonic Southwest



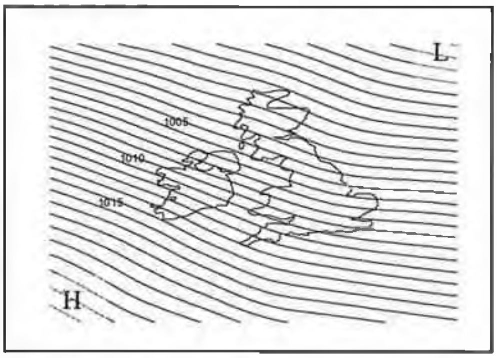
(s) Easterly



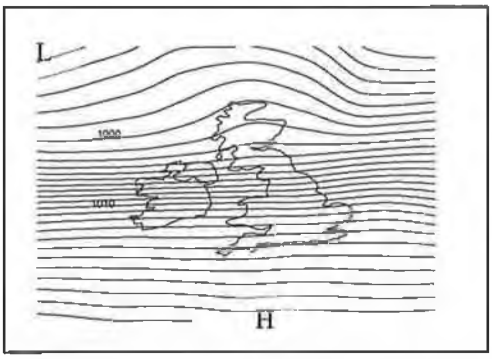
(t) Northerly



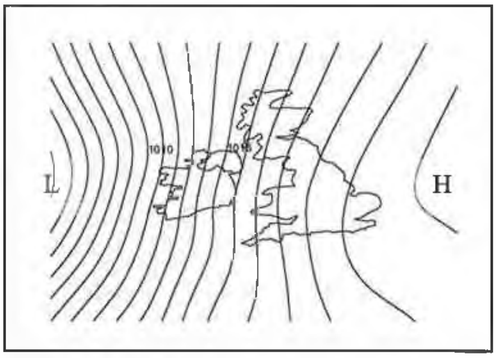
(u) Northeasterly



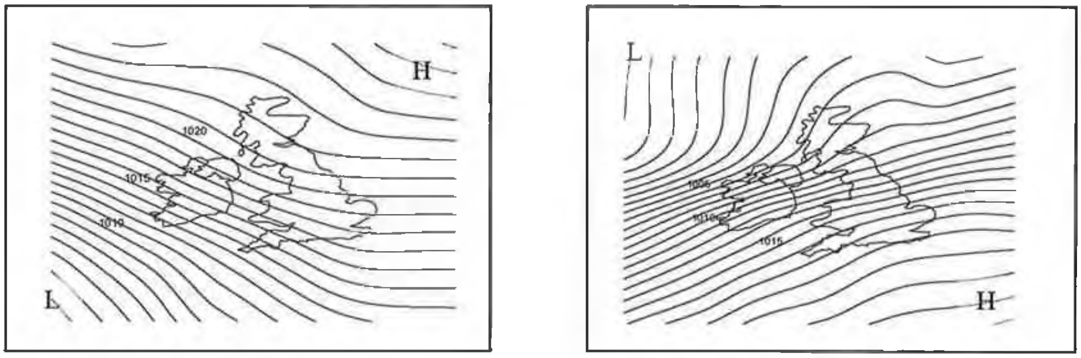
(v) Northwesterly



(w) Westerly



(x) Southerly



(y) Southeasterly

(z) Southwesterly

Figure 4.4 ((a)-(z)) Composite mean annual sea level pressure maps for each circulation type (except unclassified), 1961-1990.

	Spring	Summer	Autumn	Winter	Annual
A	+	0	+	-	+
AE	-	+	+	-	-
AN	+	0	+	+	+
ANE	-	+	-	-*	-
ANW	+	-	+	-	+
AS	+	-	-	0	-
ASE	+	-	(-)	-	(+)
ASW	+	+	+	(+)	+*
AW	-	+	(-)	-	-
C	-	(-)	-**	(-)	-
CE	+	-	-	-	-
CN	+	-	-*	+	0
CNE	-	+	-	-	-
CNW	+	+	-*	-	-
CS	-	+	+	-	-
CSE	-	+	-	0	-
CSW	-	+	+	(+)	-
CW	-	(+)	-	(-)	-
E	+	+	+	-*	-
N	+	+	-	-	0
NE	-	-	+	-	-
NW	+	-	+	-	-
S	-	+	(+)	-	+
SE	-	0	-	-	-
SW	0	0	+	+**	+*
U	+*	-	-	+	+
W	+	-	-	+	-

Table 4.2 Direction of trend of major circulation types. Negative and positive trends are indicated by minus and plus signs. Trends in parenthesis are less than 0.01.
** Trend significant at the 99% level
* Trend significant at the 95% level.

4.4.5 Temporal variations of the CTs

Temporal variations in the major circulation types were also analysed with significance levels determined by the Mann-Kendall test for trend. SW and ASW types are the only two that increase significantly (at the 95% level) on an annual basis over the 30-year period. U, A, AN, ANW, ASE and S types also increase, N and CN reveal no change, while all other types decrease. Seasonally, temporal variations of the major types are shown in Table 4.2. Some of the changes in the major CTs are highlighted below:

- Westerly circulation increases in winter and spring, while it decreases in summer and autumn. Increased westerly weather in winter is similar to the trends identified by Bardossy and Caspary (1990), who detected increased frequencies of zonal/west-east circulation in Europe between 1881 and 1989. The annual decrease in frequency of westerly circulation is caused mainly by the reduced number of W days in summer and autumn. This trend is also noted in the Lamb catalogue, with the frequency of westerly circulation declining, from a peak in the 1920s (Briffa *et al.*, 1990; O'Hare and Sweeney, 1993). An increase in westerly weather in winter would bring milder conditions, while the decline in summer days may mean fewer cold, cloudy days.
- An annual increase in southwesterly circulation is a result of increases primarily in winter (significant at the 99% level) and autumn, as there has been little or no trend detected in spring and summer. Anticyclonic-southwesterly circulation types increase significantly on an annual basis also, due to increases in all seasons. Increases in southwesterly circulation would result in wet and unsettled weather on the south, west and north coasts in all seasons, with mild weather in winter and cooler weather in summer (Lamb, 1964). This is clearly seen in Figures 2.38, 2.39, 2.40 and 2.41 (Chapter 2) with greater increases in precipitation on these coasts.
- Anticyclonic circulation decreases in winter, while there is no change in summer and increases in spring and autumn. This results in an overall annual increase in this CT. An analysis of the Lamb Weather Types for the period 1861-1991 also confirms this, with increases particularly evident in the 1980s (Briffa *et al.*, 1990; O'Hare and Sweeney, 1993). According to Briffa *et al.*

(1990) increasing frequencies of anticyclonic types would point towards a more varied climate. The weather on anticyclonic days is typically warm in summer and cold in winter. Thus, decreasing frequencies in winter may account for some of the decreasing frequencies of cold days and a tendency towards warmer temperatures in this season.

- Cyclonic circulation decreases in all seasons, significant at the 95% level during autumn. However, these results are in contrast to the increase in the LWT cyclonic circulation, outlined by O'Hare and Sweeney (1993), especially since the 1980s.
- There are also a number of CTs which decrease significantly, including easterly and anticyclonic-northeasterly circulation types in winter, with cyclonic-northwesterly and cyclonic-northerly types decreasing significantly in autumn (all at the 95% level).

4.5 Conclusion

This chapter outlined a methodology for automatically classifying atmospheric circulation patterns on a daily basis for Ireland. This follows the Jenkinson and Collison (1977) scheme for the UK. Mean sea level pressure data on a 2.5^{o} latitude by 2.5^{o} longitude grid obtained from NCEP Reanalysis database was regridded onto a 2.5^{o} by 3.75^{o} grid, similar to the grid spacing used in the HadCM3 global climate model. This allows for easier classification of both modelled and Reanalysis data. Indices to describe the geostrophic wind flow and vorticity were calculated. From this, annual, seasonal and monthly frequencies of the 27 circulation types were established for the baseline period of 1961-1990. The classification scheme provides a framework for the identification of relationships between daily circulation types and daily temperature and precipitation over the long-term. In the following chapter, this objective atmospheric circulation classification system will be applied to climatological variables to evaluate the capability of the method in determining the temperature and precipitation characteristics for Ireland.

Chapter 5

Identification of circulation weather types and rainfall/ temperature relationships, 1961 - 1990

5.1 Introduction

Before implementing a downscaling scheme to generate future rainfall and temperature scenarios it is first important to show that meaningful and distinct relationships exist in the observations at present - between the circulation types, rainfall and temperature (Goodess, 2000a). It is necessary to be able to explain the changes which have already occurred and have been detected in Irish climate in terms of changes in larger-scale atmospheric circulation patterns. By focusing on the mechanisms of atmospheric circulation patterns, it may be possible to determine what is forcing the change in surface climatic variables. This is in recognition of the fact that it has been established that there is a linkage between the large-scale circulation and regional climatic variables (Yarnal, 1993) and that local climatic variability can be connected to changes in atmospheric circulation (Lamb, 1977).

As observed in Chapter 4, the mean frequencies of each of the circulation types vary annually and seasonally, while some also occur more frequently than others. A number of approaches are utilised in establishing the relationship between local climate and circulation types. With regard to precipitation, it is important to know whether there are any particular circulation types which contribute more (or less) to precipitation than might be expected on the basis of their frequency of occurrence alone. This can be investigated by calculating the mean daily precipitation contribution to total seasonal precipitation for each circulation type (CT) at each station. Another method is to examine the relative wetness and proportion of wet days by CT for each season. Each of these techniques is carried out in the following sections. In terms of temperature, a link is established between maximum and minimum temperature at each station, in each season, for each CT. Finally, the relationship between the North Atlantic Oscillation and each of the CTs, and surface climate variables, is investigated.

5.2 Relationship between CTs and daily rainfall

Spatial and temporal variations in rainfall can be influenced to some extent by changes in atmospheric circulation. Strong local differences also play a part, due to the effects of hills and mountains, and also in response to prevailing winds and moisture content of the air (Lamb, 1972). One possible cause of a change in mean rainfall intensity would be a shift in the relative contribution of precipitation originating from frontal, orographic and convective mechanisms. A number of authors have found that with increased greenhouse gas contributions, some global climate models (GCMs) reveal greater precipitation intensity in the mid-latitudes, with shortened return periods of extreme events (Fowler and Hennessy, 1995; Hennessy *et al.*, 1997). These are driven in some cases by a shift from large-scale (frontal and orographic) to convective mechanisms of precipitation (Gregory and Mitchell, 1995). It has already been outlined that the possible physical linkages between the large-scale circulation and surface climatic variables need to be assessed before any downscaling can take place. In this section, the changes in circulation and their associated changes in daily precipitation are analysed.

5.2.1 Rainfall contributions

The mean daily precipitation for each of the circulation types in each of the seasons varies considerably. Specific circulation types may contribute more (or less) to mean seasonal rainfall than is expected based on their frequency of occurrence. This can be established by analysing the mean daily rainfall for each circulation type, and determining its contribution to total seasonal rainfall at each station. Large absolute differences in precipitation between stations can be removed by using rainfall percentages of the normal fall at each station. This has been conducted for nine synoptic stations in Ireland. Tables 5.1 (winter), 5.2 (spring), 5.3 (summer) and 5.4 (autumn) present the percentage frequency of days within each CT for each season, the mean daily precipitation (mm/day) and the relative contribution of those days to the total observed amount of rainfall within each CT at each station (% Tot.Prec).

In winter, (Table 5.1) the most frequent circulation type is southwesterly (SW), occurring 17% of the time. This is followed by southerly (S-14%), westerly (W-11%), anticyclonic (A-9%), northwesterly (NW-8%), cyclonic (C-5%) and southeasterly (SE-5%). Overall, these seven types account for nearly 70% of total days classified, and show that the pure directional CTs with the 2 rotational types (cyclonic and anticyclonic) are the most frequent in this season. In terms of the contribution each of the CTs has on total observed precipitation in winter, it is observed that the anticyclonic types contribute less than would be expected based on their frequency of occurrence. Anticyclonic days occur 9% of the time, yet at most stations they contribute less than 2% to the observed rainfall. This rises to just under 3% at Malin Head and Belmullet. Directional and cyclonic CTs on average contribute more to total rainfall, especially C, S, W and SW types. Rainfall as a result of cyclonic circulation is especially important at Casement Aerodrome, Rosslare and Kilkenny on the east coast. Conversely, W circulation contributes significantly to total rainfall at Shannon, Belmullet and Malin Head on the west coast. Southerlies also contribute more to rainfall at Rosslare, Valentia and Kilkenny than at any other station, while their influence on Malin Head precipitation is below average. It is worth noting that while S, SW and W types account for 42% of days classified, these CTs account for between 58% (Casement Aerodrome) and 69% (Valentia) of total observed precipitation in winter.

By assessing the mean daily precipitation associated with each CT at each of the stations, it can be seen from Table 5.1 that, for all stations, cyclonic-hybrid type rainfall is above average, while rainfall related to the directional types is below average. In the east of the country, at Casement Aerodrome and Rosslare, the cyclonic-easterly (CE) type accounts for mean precipitation above 4mm per day, while at all other stations it is less than 2mm. Cyclonic-southerly (CS) days represent approximately 1.3% of days in winter, although mean daily rainfall is greater than 8mm at Valentia and Rosslare and just under 5mm at Birr, Casement, Malin Head and Belmullet with this type.

In summer (Table 5.3), SW type is again the most frequent (at 13%), followed by W (11%) and NW (11%), A (10%), northerly (N-9%), S (7%), unclassified (U-7%) and C (5%). Together, these eight types account for nearly 75% of the total number of days classified. Mean daily precipitation for the cyclonic types is above average, while rainfall on anticyclonic days is generally quite small at all stations. It is primarily CS rainfall which is the heaviest, along with C for the midland stations of Birr, Kilkenny and Casement. CSW, S and SW also emerge as wet rainfall types. In relation to the relative contribution each of the CTs has on total observed precipitation at each of the stations, again it is SW circulation that accounts for the greatest proportion at all stations. This is followed by S at Valentia (17%) and Rosslare (15%); W at Shannon (15%), Malin Head (18%), Belmullet (15%) and Clones (15%); and C at Kilkenny (15%), Casement Aerodrome (14%) and Birr (14%).

Similar to summer and winter, the most frequent CT in autumn (Table 5.4) is SW (17% of days). This is followed by S (11%), W (11%), A (10%) and NW (9%). The above 5 types account for approximately 58% of all classified days in the 30-year period. Cyclonic circulation occurs least frequently in autumn, out of all seasons, at just 4% of days. As expected, hybrid cyclonic types account for the largest mean daily rainfall at the majority of stations, although W rainfall at Malin Head does account for the wettest type (6.5mm/day), followed by C and CW (6mm/day). CNE rainfall is wettest at Valentia and Rosslare, while CS is wettest at Birr, Kilkenny and Shannon. The wettest days at Clones and Casement Aerodrome occur on CSE days. In assessing the contribution each of the CTs has on total observed seasonal rainfall, the overall pattern is very similar to the percentage frequency of days, with SW rainfall accounting for the highest proportion of wet days at all stations. At Shannon, Malin Head, Clones, Casement and Birr this is followed by W type, while at Valentia, Belmullet, Rosslare and Kilkenny it is rainfall associated with southerlies which contributes second highest to total observed rainfall. Only at Casement and Rosslare does cyclonic rainfall account for a high proportion (13% and 11% respectively) of total autumn rainfall at any station.

Unlike the other seasons, it is westerly circulation which dominates in spring (Table 5.2), occurring on 14% of the days classified. SW and A follow with 13% and 12% respectively, while C occurs 8% of the time. These 4 major types account for nearly 50% of all days. Looking at mean daily rainfall for each CT, it is again clear that the cyclonic hybrid types are generally the wettest. Mean daily rainfall for CS is greatest at Valentia, Rosslare and Kilkenny, CSW is greatest at Shannon and Clones (along with C for Clones), while CN is the wettest type for Birr and CNE for Casement. At Malin Head and Belmullet, westerly circulation has the highest mean daily rainfall amounts, with a value of 4.2mm/day at both stations. Examining the contribution that each of the CTs have towards total observed rainfall, it is predominantly W rainfall which contributes the most to seasonal rainfall at each station, except at Rosslare and Valentia. SW contributes more - 19% for Rosslare and 25% for Valentia, at these stations. Cyclonic precipitation only plays a major role at Casement and Kilkenny, contributing over 17% to total spring precipitation.

Seasonal circulation-type frequencies and rainfall contributions have been analysed. Some relationships are clearly consistent from season to season. In general it appears that mean daily rainfall for the cyclonic circulation types (CS, CSW, CW, CNW) are high. Their contribution to total observed precipitation on a seasonal basis is low however, due to the fact that they do not occur frequently. Westerly circulation (SW, NW and W) types contribute more to total seasonal rainfall and are also the most frequent circulation types classified. This is to be expected given the warm and moist air passage over which these air masses travel. Orographic and frontal rainfall are important features on the west coast as the prevailing westerly and southwesterly winds are forced over mountainous regions. At the east coast inland stations of Casement Aerodrome, Kilkenny and Birr, cyclonic rainfall plays an important part in contributing to the overall observed rainfall in all seasons, especially in summer. This is largely convectional rainfall, with the warm, moist unstable air having passed over the Irish Sea.

		Valentia		Shannon		Malin Head		Belmullet		Clones		Rosslare		Kilkenny		Casement		Birr	
Winter	%days	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec
U	1.37	1.86	0.51	1.25	0.58	1.46	0.61	1.03	0.39	0.54	0.27	2.10	0.99	1.09	0.56	0.69	0.46	0.61	0.36
A	9.27	1.06	1.98	0.57	1.79	1.01	2.88	1.02	2.63	0.42	1.43	0.46	1.47	0.31	1.07	0.23	1.03	0.33	1.33
ANE	0.70	0.27	0.04	0.28	0.07	1.03	0.22	1.07	0.21	0.15	0.04	0.26	0.06	0.11	0.03	0.15	0.05	0.04	0.01
AE	0.70	0.00	0.00	0.00	0.00	0.82	0.18	0.43	0.08	0.17	0.04	0.32	0.08	0.04	0.01	0.82	0.28	0.02	0.01
ASE	1.77	0.63	0.22	0.16	0.10	0.29	0.16	0.09	0.04	0.03	0.02	0.23	0.14	0.11	0.07	0.06	0.05	0.03	0.02
AS	2.22	1.64	0.73	0.31	0.23	0.12	0.08	0.65	0.40	0.05	0.04	0.12	0.09	0.11	0.09	0.05	0.05	0.05	0.05
ASW	2.40	3.60	1.74	1.48	1.19	1.82	1.34	1.97	1.32	1.55	1.35	1.67	1.38	1.21	1.09	0.88	1.02	1.19	1.24
AW	2.03	1.87	0.77	1.48	1.01	3.67	2.29	2.63	1.49	1.87	1.38	0.91	0.63	1.08	0.82	1.08	1.06	1.22	1.07
ANW	1.37	2.49	0.69	2.40	1.10	2.54	1.06	1.79	0.68	1.23	0.61	1.02	0.48	1.07	0.55	0.69	0.46	1.28	0.76
AN	1.22	1.20	0.29	0.45	0.19	1.58	0.59	1.46	0.50	0.35	0.16	0.24	0.10	0.22	0.10	0.29	0.17	0.29	0.16
NE	1.96	0.33	0.13	0.20	0.13	0.86	0.52	1.41	0.77	0.15	0.11	1.21	0.81	0.57	0.42	1.92	1.82	0.29	0.24
E	2.96	0.51	0.30	0.45	0.45	0.63	0.57	0.31	0.26	0.42	0.45	1.55	1.58	0.58	0.64	1.74	2.50	0.48	0.62
SE	4.84	2.25	2.19	0.93	1.52	0.29	0.44	0.43	0.58	0.38	0.67	2.17	3.63	1.26	2.28	0.97	2.27	0.56	1.17
S	14.30	9.62	27.63	3.22	15.52	2.49	10.91	3.86	15.39	3.24	16.79	4.99	24.61	4.51	24.23	2.02	13.99	2.78	17.23
SW	17.40	8.34	29.18	5.01	29.39	5.06	27.02	6.62	32.12	4.67	29.45	4.79	28.71	4.33	28.30	3.48	29.38	4.33	32.60
W	11.05	5.34	11.85	5.83	21.70	6.35	21.53	5.30	16.30	4.54	18.17	2.72	10.37	3.31	13.75	2.70	14.45	3.89	18.61
NW	8.46	4.00	6.80	3.53	10.06	4.15	10.78	4.11	9.69	3.47	10.65	1.35	3.93	1.90	6.04	1.55	6.35	1.88	6.87
N	4.43	2.32	2.07	0.76	1.13	2.10	2.85	2.70	3.33	0.89	1.43	0.70	1.07	0.57	0.96	0.50	1.07	0.71	1.36
C	4.65	4.86	4.55	2.52	3.94	4.30	6.15	3.15	4.09	3.24	5.48	4.09	6.56	3.84	6.72	3.95	8.91	2.78	5.60
CNE	0.22	1.70	0.08	1.35	0.10	3.82	0.26	2.05	0.13	4.03	0.32	1.63	0.12	1.32	0.11	6.55	0.70	1.40	0.13
CE	0.33	1.20	0.08	1.68	0.19	1.07	0.11	0.70	0.06	1.38	0.17	4.46	0.51	1.28	0.16	4.30	0.69	0.77	0.11
CSE	0.92	5.44	1.01	2.16	0.67	4.80	1.36	4.58	1.18	4.79	1.60	7.26	2.31	5.06	1.76	4.47	2.00	3.19	1.27
CS	1.33	9.40	2.51	5.28	2.37	4.86	1.98	4.71	1.75	6.27	3.02	8.67	3.97	7.03	3.51	4.84	3.12	4.19	2.42
CSW	1.55	6.92	2.16	5.84	3.05	4.95	2.36	6.04	2.61	4.83	2.72	6.67	3.57	5.90	3.44	5.53	4.16	5.02	3.37
CW	1.15	4.79	1.10	6.05	2.33	5.58	1.96	6.28	2.00	4.97	2.06	4.44	1.75	4.69	2.02	2.58	1.44	3.96	1.97
CNW	0.85	6.20	1.06	3.29	0.94	5.40	1.41	5.57	1.32	4.35	1.34	1.91	0.56	2.45	0.78	4.27	1.76	2.68	0.99
CN	0.55	2.85	0.32	1.37	0.26	2.31	0.39	4.36	0.67	1.18	0.24	2.67	0.51	2.39	0.50	2.79	0.75	1.76	0.42

Table 5.1 Percentage frequency of days within each circulation type (% days), mean daily precipitation (mm/day) and relative contribution of those days to total observed precipitation within each CT for winter

		Valentia		Shannon		Malin Head		Belmullet		Clones		Rosslare		Kilkenny		Casement		Birr	
Spring	%days	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec
U	2.83	1.43	1.29	1.24	1.73	0.65	0.83	1.04	1.22	0.73	0.94	0.71	1.04	0.87	1.29	0.99	1.62	1.09	1.62
A	12.28	0.77	3.03	0.52	3.18	1.19	6.66	0.99	5.08	0.56	3.19	0.49	3.10	0.45	2.88	0.37	2.63	0.59	3.83
ANE	1.99	0.25	0.16	0.20	0.20	0.61	0.56	0.72	0.60	0.34	0.31	0.17	0.18	0.11	0.11	0.29	0.33	0.14	0.15
AE	0.80	0.60	0.15	0.52	0.20	0.14	0.05	0.24	0.08	0.31	0.11	1.63	0.67	0.63	0.26	0.63	0.29	0.35	0.15
ASE	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.05	0.00	0.00	0.13	0.02	0.10	0.01
AS	0.22	3.85	0.27	1.12	0.12	0.08	0.01	1.67	0.15	0.52	0.05	3.33	0.37	1.85	0.21	0.27	0.03	0.62	0.07
ASW	1.05	1.34	0.45	0.56	0.29	0.12	0.06	0.47	0.20	0.43	0.21	0.18	0.10	0.41	0.23	1.58	0.96	1.06	0.59
AW	5.11	1.71	2.80	1.55	3.90	2.86	6.64	2.43	5.19	1.89	4.44	0.86	2.27	0.89	2.38	0.95	2.81	1.12	3.02
ANW	3.55	1.53	1.74	1.02	1.78	2.70	4.36	2.33	3.45	1.92	3.15	0.64	1.17	0.89	1.64	1.08	2.21	1.10	2.06
AN	3.01	1.63	1.58	0.84	1.24	1.90	2.60	1.82	2.28	1.61	2.22	0.99	1.54	0.85	1.34	0.86	1.49	1.14	1.81
NE	5.72	0.67	1.23	0.69	1.96	0.79	2.06	0.97	2.32	0.79	2.09	1.02	3.01	0.97	2.91	2.01	6.65	1.15	3.47
E	4.17	0.88	1.18	0.52	1.07	0.17	0.33	0.26	0.45	0.33	0.64	0.86	1.85	0.61	1.33	0.69	1.66	0.62	1.36
SE	2.50	2.44	1.96	1.17	1.44	0.19	0.21	0.39	0.41	0.31	0.36	1.86	2.40	1.20	1.57	0.83	1.20	0.78	1.03
S	3.08	5.04	4.98	1.56	2.38	1.12	1.58	1.82	2.34	0.91	1.29	1.84	2.93	1.62	2.60	0.48	0.85	0.97	1.58
SW	12.97	6.01	25.02	2.81	17.99	2.51	14.78	3.83	20.74	2.96	17.69	2.82	18.84	2.53	17.14	1.53	11.45	2.37	16.23
W	14.46	4.32	20.02	3.59	25.65	4.15	27.27	4.17	25.15	3.66	24.33	2.14	15.93	2.39	18.06	2.45	20.46	3.07	23.42
NW	3.08	2.46	2.43	2.03	3.09	3.15	4.41	3.00	3.86	2.89	4.10	1.54	2.44	1.79	2.87	1.89	3.37	2.17	3.52
N	3.04	1.38	1.35	1.23	1.85	1.08	1.49	1.65	2.09	1.10	1.54	1.40	2.20	1.41	2.25	1.87	3.29	1.29	2.07
C	8.41	4.15	11.19	3.40	14.14	3.33	12.72	2.85	10.00	4.01	15.52	3.36	14.57	3.92	17.20	3.52	17.11	3.39	15.06
CNE	0.98	2.69	0.84	3.28	1.59	2.69	1.19	1.94	0.79	3.14	1.41	4.89	2.47	2.84	1.45	5.83	3.30	3.37	1.74
CE	1.27	1.91	0.78	1.82	1.14	1.63	0.94	2.94	1.56	2.09	1.22	3.39	2.22	2.50	1.66	4.40	3.23	2.45	1.64
CSE	1.70	3.93	2.15	2.95	2.48	1.40	1.08	2.19	1.56	2.91	2.28	4.73	4.15	4.07	3.62	2.89	2.85	2.94	2.64
CS	2.46	7.89	6.24	3.00	3.65	2.60	2.91	3.54	3.64	3.72	4.22	5.23	6.65	4.90	6.30	2.05	2.92	2.66	3.46
CSW	3.26	6.89	7.21	3.81	6.13	3.34	4.96	3.32	4.51	4.03	6.04	4.50	7.57	4.64	7.91	2.87	5.41	3.45	5.94
CW	0.91	3.91	1.14	3.43	1.53	3.82	1.58	3.56	1.34	3.66	1.52	2.61	1.22	3.02	1.43	3.79	1.98	3.05	1.46
CNW	0.40	3.05	0.39	2.15	0.42	1.55	0.28	2.07	0.34	3.06	0.56	2.96	0.61	2.71	0.56	3.78	0.87	2.98	0.63
CN	0.54	2.53	0.44	3.09	0.83	1.83	0.45	2.76	0.63	2.20	0.55	1.66	0.47	2.80	0.79	3.21	1.01	5.06	1.45

Table 5.2 Percentage frequency of days within each circulation type (% days), mean daily precipitation (mm/day) and relative contribution of those days to total observed precipitation within each CT for spring

		Valentia		Shannon		Malin	Head	Belmullet		Clones		Rosslare		Kilkenny		Casement		Birr	
Summer	%days	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec
U	6.7	1.95	4.51	1.70	5.15	1.07	2.86	1.30	3.48	1.53	4.40	1.14	4.05	1.57	5.56	1.40	5.12	1.58	5.05
A	9.7	0.58	1.98	0.29	1.26	0.71	2.79	0.83	3.26	0.37	1.54	0.14	0.71	0.19	0.99	0.18	0.94	0.23	1.07
ANE	0.8	0.00	0.00	0.00	0.00	0.04	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.01
AE	0.5	0.16	0.03	0.73	0.17	0.80	0.16	0.51	0.10	1.49	0.32	0.25	0.07	0.27	0.07	0.67	0.19	1.19	0.29
ASE	0.4	0.17	0.03	0.06	0.01	0.38	0.07	0.64	0.11	0.47	0.09	0.16	0.04	0.10	0.02	0.13	0.03	0.03	0.01
AS	1.8	1.60	1.01	0.68	0.56	0.32	0.23	0.76	0.56	0.13	0.10	0.21	0.21	0.21	0.20	0.06	0.06	0.38	0.33
ASW	2.6	3.44	3.12	1.65	1.96	2.50	2.62	3.32	3.49	2.29	2.57	1.08	1.51	1.17	1.62	0.94	1.34	1.30	1.62
AW	2.1	1.35	0.99	0.97	0.93	2.80	2.37	2.74	2.32	1.52	1.38	0.40	0.45	0.64	0.71	0.77	0.89	1.05	1.06
ANW	3.7	1.43	1.82	0.89	1.48	1.76	2.60	1.59	2.34	1.20	1.89	0.50	0.98	0.69	1.33	0.83	1.66	0.95	1.67
AN	2.6	0.12	0.11	0.28	0.34	0.67	0.71	0.78	0.83	0.28	0.31	0.16	0.23	0.57	0.80	0.25	0.37	0.35	0.45
NE	3.3	0.45	0.51	0.29	0.43	0.24	0.32	0.13	0.16	0.21	0.30	1.17	2.04	0.46	0.80	0.30	0.53	0.17	0.26
E	1.2	2.48	1.06	1.94	1.09	0.16	0.08	0.29	0.14	0.29	0.15	2.01	1.32	0.89	0.58	0.17	0.12	0.38	0.22
SE	1.8	2.96	1.86	2.02	1.66	1.51	1.10	1.70	1.24	1.60	1.25	2.65	2.57	2.47	2.37	1.67	1.66	2.39	2.07
S	7.2	6.78	17.10	3.81	12.57	2.85	8.31	4.44	12.94	3.41	10.62	3.90	15.12	3.42	13.14	1.85	7.36	2.89	10.01
SW	12.9	5.89	26.35	3.79	22.16	4.92	25.44	4.49	23.22	4.13	22.82	3.38	23.23	3.05	20.77	2.76	19.43	3.51	21.58
W	10.7	3.79	14.03	3.17	15.38	4.09	17.55	3.57	15.30	3.22	14.74	2.06	11.74	1.89	10.68	2.21	12.88	2.62	13.36
NW	11.1	1.68	6.48	1.42	7.19	2.74	12.24	2.08	9.26	2.06	9.80	1.10	6.55	0.99	5.81	1.58	9.61	1.54	8.15
N	8.6	0.62	1.85	0.53	2.07	0.84	2.91	0.80	2.78	0.93	3.45	0.98	4.54	1.01	4.63	1.57	7.41	1.01	4.15
C	5.1	4.14	7.41	5.03	11.77	3.26	6.76	4.11	8.51	5.01	11.08	4.17	11.46	5.68	15.48	4.93	13.90	5.86	14.42
CNE	0.7	2.28	0.55	2.34	0.73	1.31	0.36	1.08	0.30	0.97	0.29	6.63	2.44	3.01	1.10	5.52	2.08	3.42	1.13
CE	0.3	2.23	0.25	5.61	0.83	0.36	0.05	3.52	0.46	2.86	0.40	2.20	0.38	2.11	0.36	0.81	0.14	5.44	0.85
CSE	0.3	4.63	0.41	6.19	0.71	2.46	0.25	4.39	0.45	0.59	0.06	1.31	0.18	2.91	0.39	0.93	0.13	1.14	0.14
CS	1.1	9.08	3.43	7.05	3.49	7.14	3.12	8.02	3.51	7.20	3.36	5.77	3.35	6.25	3.60	5.60	3.33	5.31	2.76
CSW	1.2	4.35	1.87	5.16	2.89	5.70	2.82	4.48	2.22	6.39	3.38	4.01	2.64	4.70	3.07	4.06	2.74	5.14	3.03
CW	1.6	2.61	1.42	4.06	2.88	4.23	2.65	2.11	1.32	5.16	3.46	2.74	2.28	3.70	3.05	4.80	4.10	4.65	3.47
CNW	1.0	3.79	1.34	3.22	1.49	2.65	1.08	3.05	1.24	3.68	1.60	2.20	1.20	3.15	1.69	3.80	2.11	2.93	1.42
CN	0.9	1.55	0.51	1.84	0.79	1.42	0.54	1.24	0.47	1.53	0.62	1.37	0.69	2.36	1.18	3.62	1.87	3.13	1.41

Table 5.3 Percentage frequency of days within each circulation type (% days), mean daily precipitation (mm/day) and relative contribution of those days to total observed precipitation within each CT for summer

		Valentia		Shannon		Malin Head		Belmullet		Clones		Rosslare		Kilkenny		Casement		Birr	
Autumn	%days	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec	mm/day	%Tot.Prec
U	2.82	2.32	1.39	1.79	1.69	1.98	1.51	2.14	1.48	1.59	1.54	2.95	2.85	2.34	2.58	1.65	2.14	1.76	1.97
A	10.48	0.93	2.07	0.55	1.94	1.32	3.74	1.33	3.42	0.54	1.93	0.48	1.71	0.48	1.96	0.33	1.60	0.47	1.94
ANE	0.84	0.27	0.05	0.12	0.03	0.60	0.14	0.67	0.14	0.12	0.04	0.66	0.19	0.11	0.04	0.26	0.10	0.20	0.07
AE	0.92	0.27	0.05	0.10	0.03	0.32	0.08	0.12	0.03	0.02	0.01	0.39	0.12	0.05	0.02	0.34	0.14	0.04	0.02
ASE	1.14	0.00	0.00	0.00	0.00	0.31	0.10	0.05	0.01	0.05	0.02	0.06	0.02	0.01	0.00	0.04	0.02	0.01	0.00
AS	2.60	2.14	1.18	0.42	0.37	0.64	0.45	1.55	0.99	0.50	0.45	0.96	0.86	0.64	0.65	0.15	0.18	0.37	0.39
ASW	3.66	2.67	2.07	1.41	1.73	2.39	2.38	3.17	2.86	1.33	1.66	1.36	1.71	1.25	1.79	0.65	1.09	1.16	1.68
AW	2.67	3.43	1.94	2.64	2.38	4.65	3.37	5.10	3.36	3.30	3.02	1.89	1.74	1.90	1.98	1.54	1.89	2.53	2.69
ANW	1.72	1.76	0.64	1.56	0.90	2.57	1.20	2.79	1.18	1.73	1.02	0.69	0.41	0.49	0.33	0.75	0.59	0.73	0.50
AN	1.36	1.48	0.42	0.88	0.40	1.27	0.47	1.80	0.60	0.62	0.29	0.19	0.09	0.33	0.17	0.16	0.10	0.47	0.25
NE	1.79	0.32	0.12	0.12	0.07	0.84	0.41	0.98	0.43	0.36	0.22	1.37	0.84	0.28	0.19	1.21	0.99	0.41	0.29
E	1.54	0.28	0.09	0.56	0.29	0.72	0.30	0.21	0.08	0.19	0.10	2.80	1.48	0.95	0.57	1.44	1.02	0.65	0.40
SE	2.71	3.06	1.75	1.70	1.55	0.44	0.32	1.13	0.75	1.05	0.97	2.84	2.64	2.49	2.63	2.43	3.02	1.72	1.85
S	11.39	10.14	24.44	3.70	14.17	2.84	8.76	5.62	15.74	3.48	13.56	4.51	17.63	4.43	19.71	1.96	10.23	3.01	13.61
SW	16.63	7.57	26.66	4.77	26.67	5.58	25.15	6.82	27.90	4.91	27.95	4.89	27.92	4.13	26.83	3.58	27.29	4.32	28.51
W	11.25	4.61	10.98	4.95	18.74	6.49	19.78	5.55	15.35	4.07	15.69	2.42	9.36	2.57	11.31	2.60	13.43	3.70	16.51
NW	9.38	3.94	7.81	3.13	9.87	4.82	12.26	3.21	7.40	3.10	9.96	1.33	4.30	1.52	5.58	1.28	5.50	1.86	6.91
N	6.19	2.24	2.94	0.65	1.36	2.08	3.48	2.07	3.16	0.95	2.00	0.86	1.83	0.55	1.33	0.74	2.10	0.83	2.04
C	4.47	6.58	6.22	4.99	7.51	5.97	7.24	5.16	5.67	6.35	9.72	7.34	11.26	5.39	9.41	6.27	12.85	5.30	9.39
CNE	0.22	12.50	0.58	3.60	0.27	4.78	0.28	6.98	0.38	1.50	0.11	14.95	1.13	6.97	0.60	4.50	0.45	4.35	0.38
CE	0.48	6.91	0.70	4.46	0.71	5.22	0.67	9.76	1.14	3.89	0.63	5.18	0.85	4.94	0.92	4.84	1.06	4.55	0.86
CSE	0.55	10.27	1.19	4.56	0.84	4.85	0.72	3.29	0.44	6.98	1.31	9.51	1.80	7.54	1.62	10.44	2.63	5.23	1.14
CS	0.88	7.66	1.42	7.20	2.13	5.02	1.20	5.93	1.28	5.88	1.77	6.94	2.10	8.05	2.77	5.40	2.18	6.52	2.27
CSW	1.68	6.93	2.47	5.27	2.98	4.66	2.13	7.02	2.91	4.95	2.86	6.41	3.71	5.87	3.87	5.39	4.17	4.54	3.03
CW	1.21	6.48	1.66	5.37	2.18	5.96	1.95	5.92	1.76	3.97	1.64	5.73	2.38	4.03	1.90	4.77	2.64	5.07	2.43
CNW	0.92	4.34	0.84	3.19	0.98	5.08	1.26	5.17	1.16	3.50	1.10	1.99	0.63	2.29	0.82	3.70	1.55	1.80	0.65
CN	0.51	2.89	0.31	1.13	0.19	4.77	0.66	2.91	0.37	2.36	0.41	2.59	0.46	1.94	0.39	4.37	1.03	1.04	0.21

Table 5.4 Percentage frequency of days within each circulation type (% days), mean daily precipitation (mm/day) and relative contribution of those days to total observed precipitation within each CT for autumn

5.2.2 Rainfall probabilities and intensities

According to Goodess and Palutikof (1998), a high rainfall contribution from a particular type may be because a high proportion of days of a particular type are wet and/or a large amount of rainfall occurs on each wet day. To examine this hypothesis, a similar analysis to the one in the previous section was carried out for daily precipitation on a seasonal basis, but only including 'wet' days (greater than or equal to 1mm). The first option - that a high proportion of days of a particular type are wet - is calculated from the ratio $PROP_{ct}/PROP_{tot}$, where $PROP_{ct}$ is the proportion of circulation type days that are wet and $PROP_{tot}$ is the proportion of all days that are wet. The second option - that a large amount of rainfall occurs on each circulation type day - is calculated from the ratio $PREC_{ct}/PREC_{tot}$, where $PREC_{ct}$ is the mean amount of rainfall on a wet type day and $PREC_{tot}$ is the mean amount of rainfall on all wet days. Figures 5.1, 5.2, 5.3 and 5.4 display the first probability, that a high proportion of days of a particular CT are wet, for each of the seasons (spring, summer, autumn and winter), while Figures 5.5, 5.6, 5.7 and 5.8, present the ratios for the possibility that a large amount of rainfall occurs on each wet day. When the ratio is greater (or less) than 1.0, the probability of rain or the intensity of rain per wet day is greater (or less) than the seasonal station mean.

The probability of wet days at most stations is above average for SW, W, C, CS, CSW and CW for all stations and all seasons, along with CNW for all stations in summer and winter. For S, the probability of a high proportion of days being wet is above average for nearly all stations in winter, summer and autumn, yet below average for all stations except Malin Head in spring. Circulation types associated with below average probability of wet days for all stations include A, ANE, AE, ASE, U and E in all seasons. Similarly, there is below average probability of a wet day for NE, AN and AS at all stations, in all seasons, with the exception of spring. SE types also have a below average probability of rainfall at all stations in all seasons, except for Rosslare and Kilkenny in the summer months.

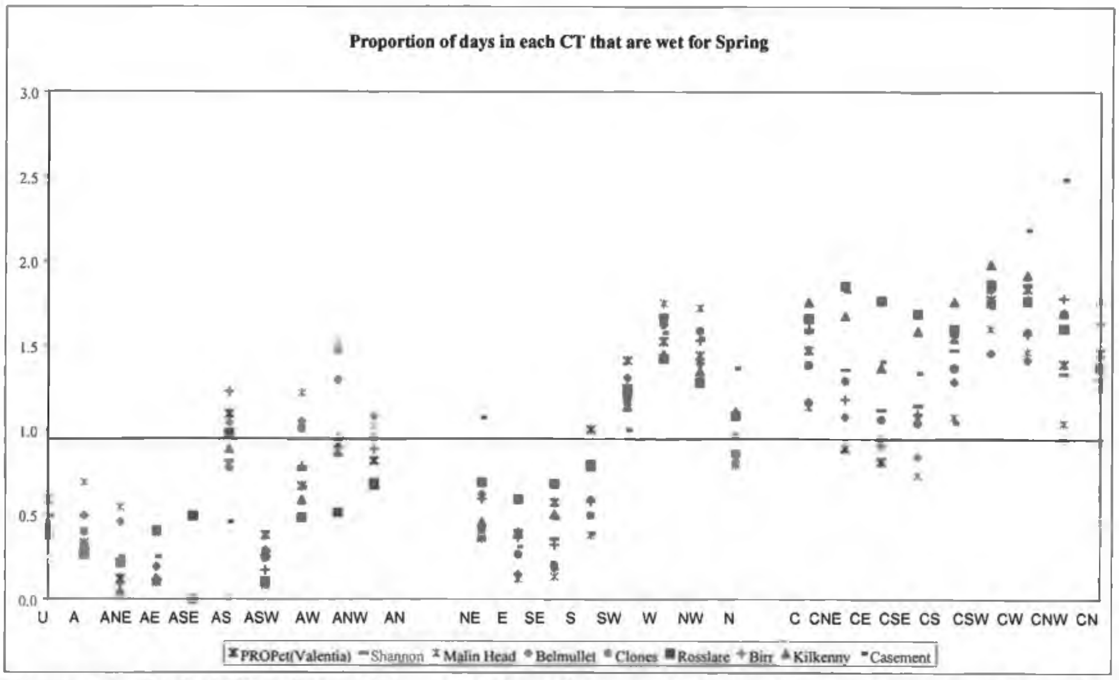


Figure 5.1 Probability that a high proportion of days of a particular circulation type in spring are wet

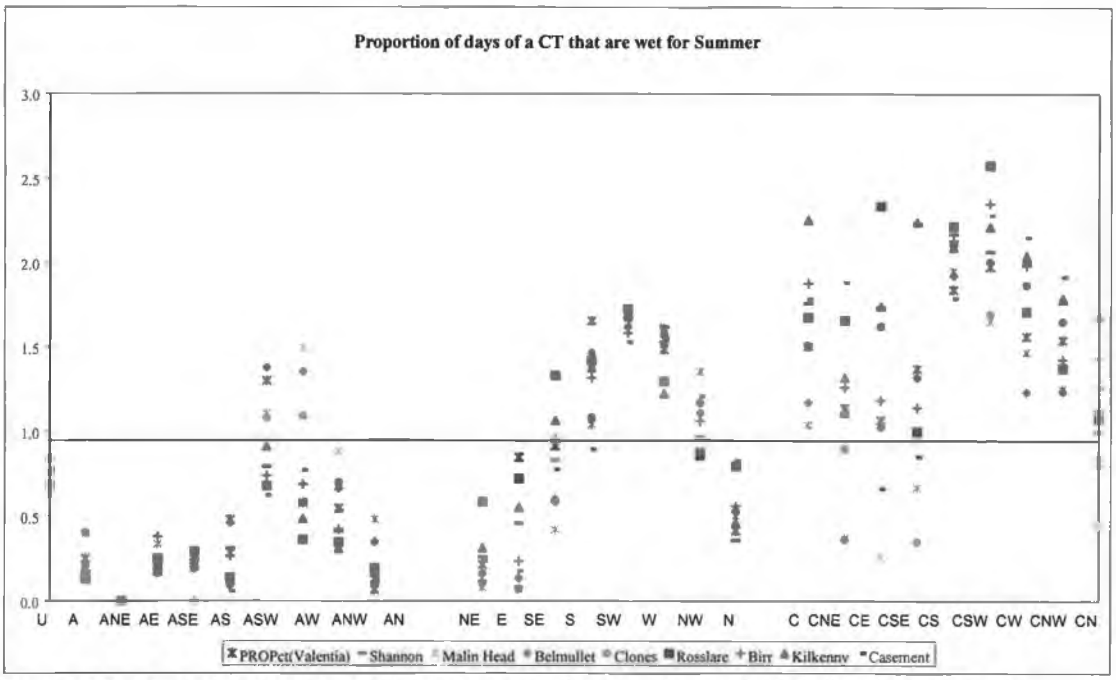


Figure 5.2 Probability that a high proportion of days of a particular circulation type in summer are wet

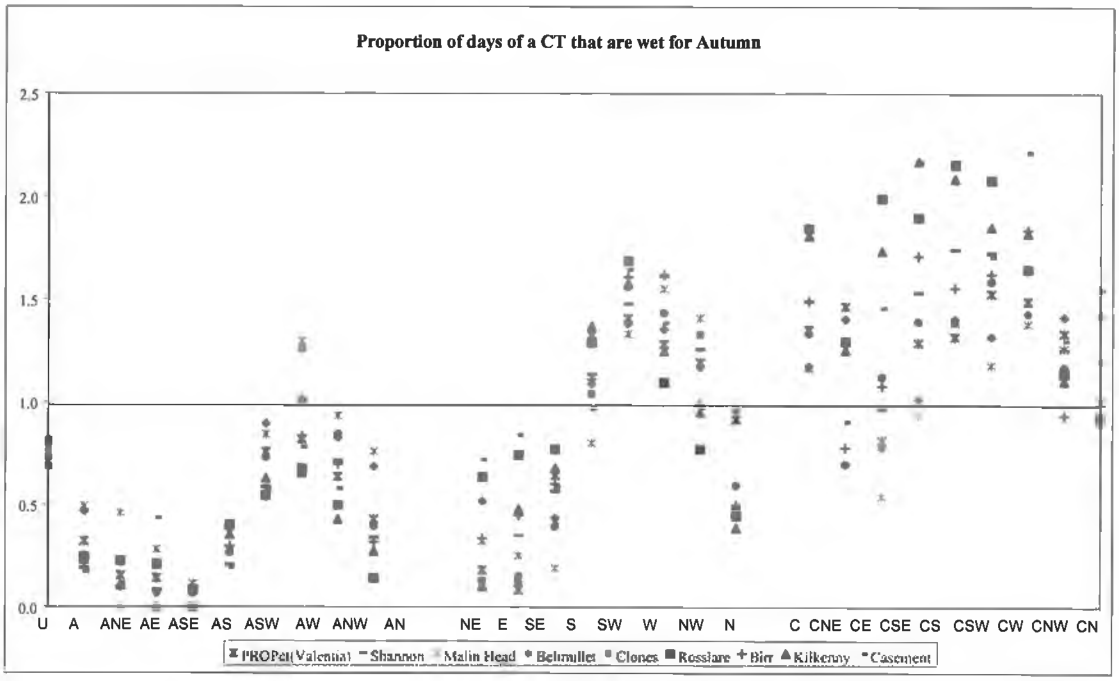


Figure 5.3 Probability that a high proportion of days of a particular circulation type in autumn are wet

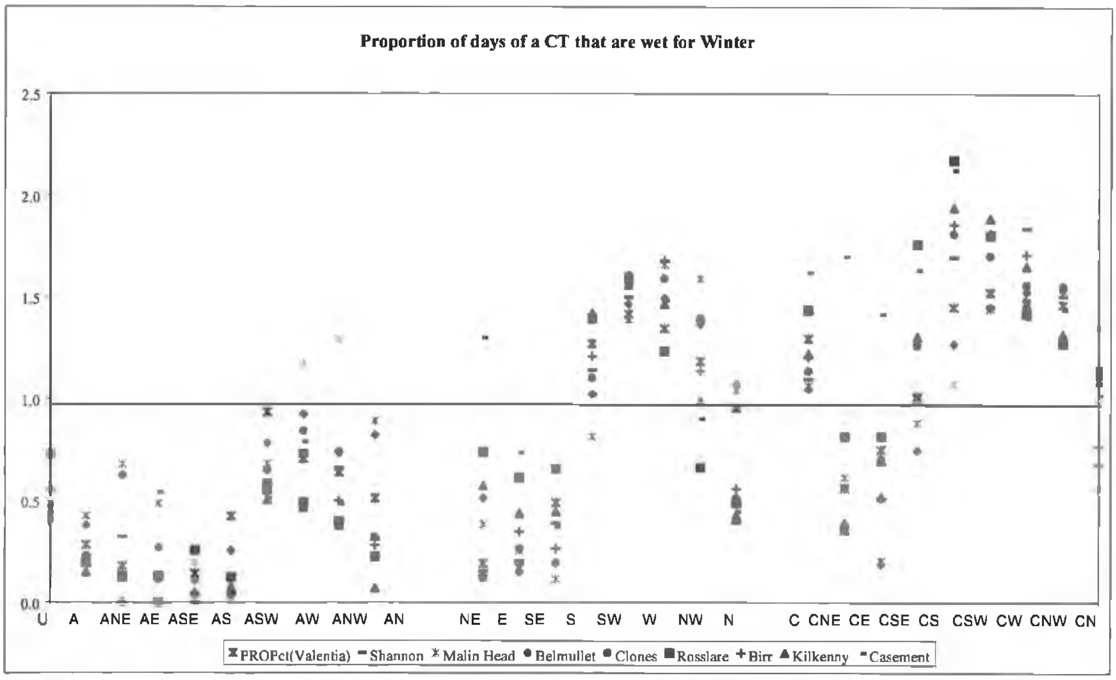


Figure 5.4 Probability that a high proportion of days of a particular circulation type in winter are wet

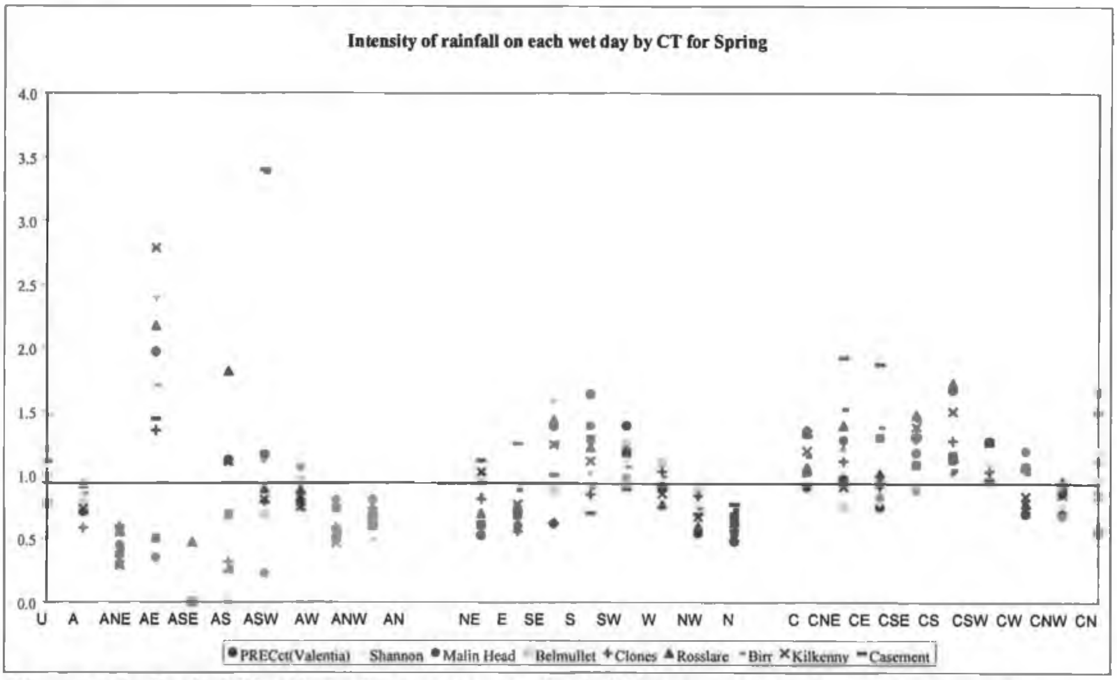


Figure 5.5 Probability that a large amount of rainfall occurs on each wet day in spring

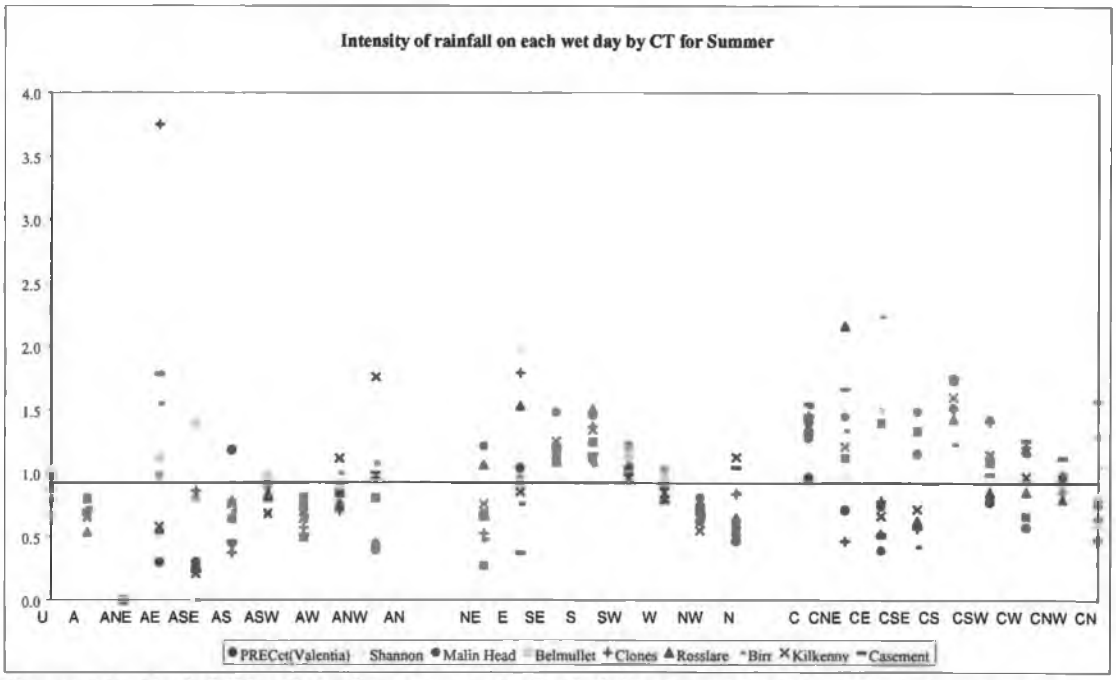


Figure 5.6 Probability that a large amount of rainfall occurs on each wet day in summer

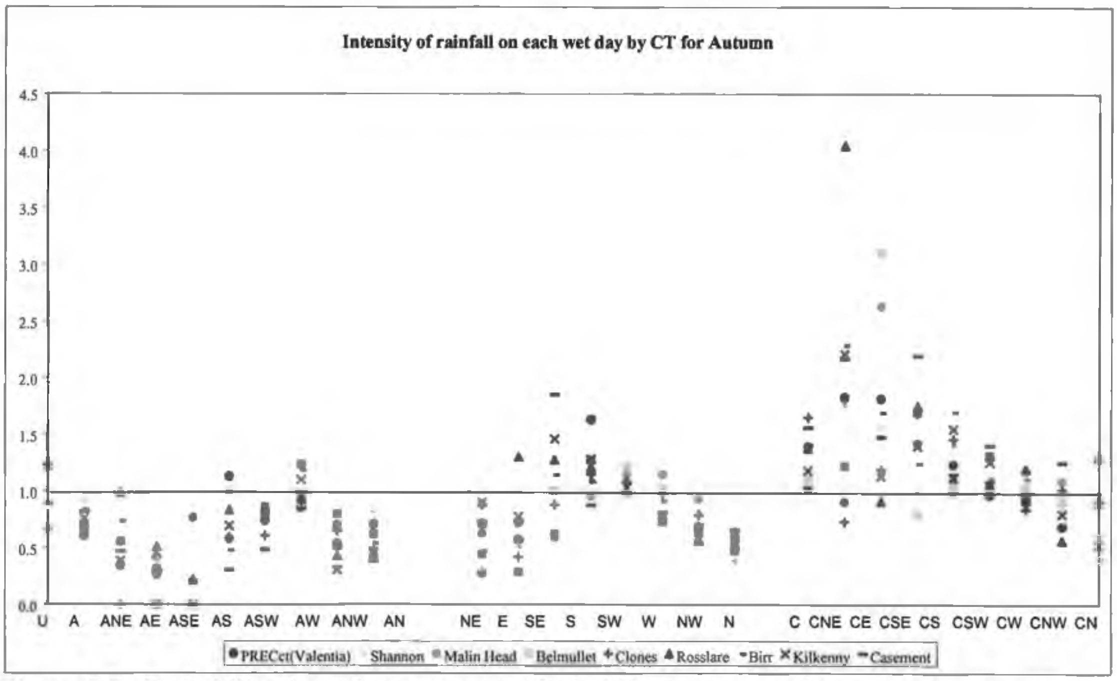


Figure 5.7 Probability that a large amount of rainfall occurs on each wet day in autumn

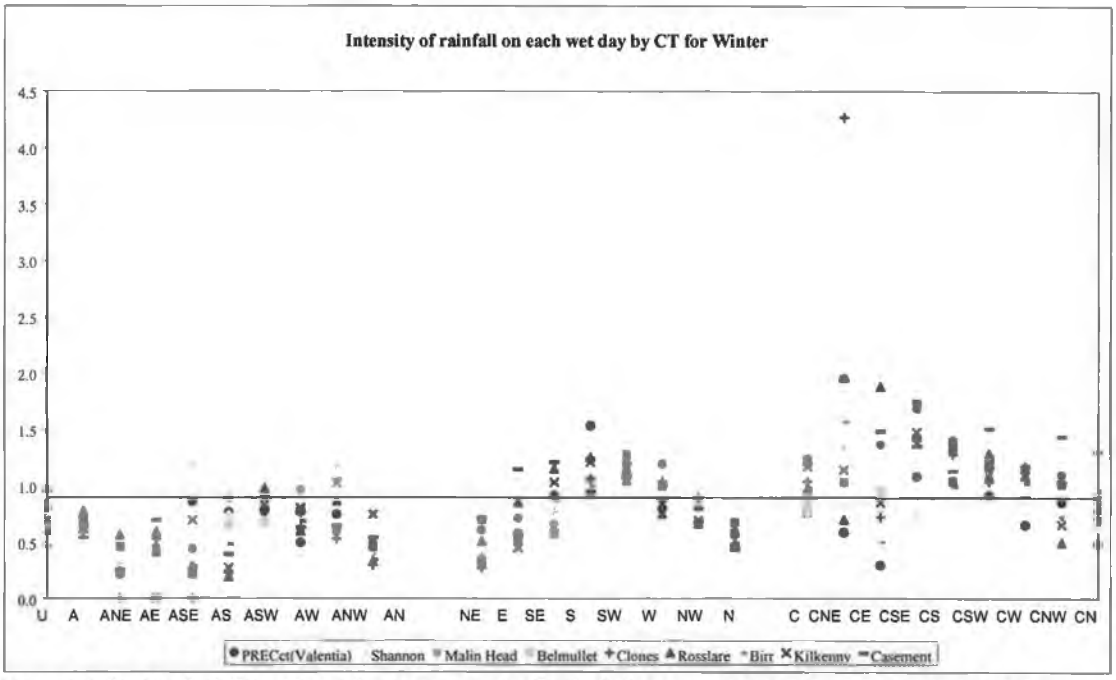


Figure 5.8 Probability that a large amount of rainfall occurs on each wet day in winter

CS circulation is the only type to have above average intensity of rainfall for all stations in all seasons, along with SW in autumn and winter, C in autumn and S and SE in summer. Below average rainfall intensity is measured for NW, ANE and A-type days at all stations in all seasons. A number of other groups are common in a few seasons but not all. For example, AN and N type days have below average intensity of rainfall in spring, autumn and winter; AW types are below average in summer, autumn and winter; ANW and ASE in spring and autumn; AE and NE in autumn and winter.

On an annual basis, above average intensity of rainfall is quite uniform over the country for particular circulation types. Precipitation intensity at all stations is above average for S, SW, C, CNE, CSE, CS, CSW and CW. In contrast, A, ANE, ANW, AN, NE and N circulation types are low intensity rainfall types at all stations.

In summary, it can be concluded that SW, C and most hybrid cyclonic types have both a high proportion of wet days on average, and these wet days are wetter than the mean. A, ANE, AN, NE and N types have below average frequency of wet days, and rainfall on these wet days is also below average at all stations.

5.3 Relationship with daily maximum, minimum and mean temperature

Air masses from different sources prevail over Ireland, depending on the large-scale circulation pattern. Different air masses exhibit different meteorological characteristics. For example, air coming from northern polar regions in winter would be much colder and drier than the warmer, wetter air coming from the North Atlantic Ocean. These air masses therefore, are responsible for differences in local temperature variability. The interaction of several components on day-to-day variability of temperature ensures that surface temperature is not only associated with the direction of airflow but also with the intensity and direction of rotation (Schubert and Henderson-Sellers, 1997).

	valentia max	valentia min	shannon max	shannon min	dublin max	dublin min	malin head max	malin head min	belmullet max	belmullet min	birr max	birr min	kilkenny max	kilkenny min	mullingar max	mullingar min	rosslare max	rosslare min
U	15.6	8.1	16.3	8.6	15.3	8.5	13.6	8.3	14.8	7.5	16.1	7.2	16.6	7.1	15.8	7.0	14.7	9.8
A	13.5	5.3	13.6	5.3	12.6	5.3	11.7	6.6	12.7	5.9	13.2	3.7	13.5	3.4	12.9	3.9	12.2	6.9
ANE	12.6	4.5	12.5	3.2	10.9	4.0	10.0	5.8	11.3	4.4	11.7	1.9	12.1	2.8	11.2	2.9	10.5	6.4
AE	12.8	4.5	12.7	3.5	11.0	4.9	10.4	5.3	12.0	3.7	11.8	2.3	12.1	3.0	11.4	3.2	10.6	7.5
ASE	11.9	4.3	10.3	2.5	9.7	4.1	9.5	3.5	10.6	2.5	9.7	0.8	9.9	0.6	9.3	1.6	9.8	6.8
AS	14.8	7.4	14.3	6.5	13.0	6.3	12.7	6.7	13.4	6.8	13.8	4.9	13.7	3.7	13.4	4.4	12.7	8.0
ASW	14.8	8.4	15.5	7.9	14.9	7.6	13.6	8.4	13.7	9.1	15.0	6.5	15.4	4.9	14.5	5.9	14.0	8.3
AW	13.2	7.6	13.5	7.2	13.3	6.4	11.9	7.3	12.4	7.7	13.1	5.9	13.9	5.1	13.1	5.3	13.4	6.9
ANW	13.3	8.0	13.9	7.4	13.7	6.3	11.9	7.5	12.7	7.5	13.6	5.9	14.2	5.6	13.4	5.4	14.1	7.2
AN	12.8	5.9	13.1	4.9	12.0	4.2	10.6	6.3	11.9	5.8	12.3	3.4	12.7	3.6	12.0	3.5	11.7	6.1
NE	12.9	5.9	13.2	4.8	11.2	5.4	10.3	6.5	11.7	5.4	12.2	3.7	12.3	4.6	11.8	4.3	10.7	7.1
E	11.9	4.8	11.6	4.1	9.6	4.9	9.2	5.1	11.0	3.7	10.5	2.8	10.8	3.5	9.8	3.3	9.4	6.6
SE	12.8	6.6	11.6	4.9	10.0	5.2	9.6	5.0	11.3	4.4	11.0	3.6	10.9	3.7	10.1	3.6	9.9	6.8
S	14.5	8.9	14.2	8.0	13.1	7.3	12.9	7.3	13.2	7.6	13.8	6.9	13.5	6.2	13.2	5.8	12.8	8.7
SW	13.9	8.8	14.5	8.2	14.4	7.8	13.1	7.5	13.0	8.1	14.2	7.1	14.4	6.3	13.7	6.3	13.3	8.6
W	12.9	8.0	13.1	7.3	13.1	6.3	11.6	6.6	12.1	7.0	12.7	6.0	13.5	5.4	12.5	5.2	13.1	7.2
NW	12.7	7.9	12.9	7.0	12.3	5.7	11.3	6.9	12.0	6.9	12.3	5.5	12.9	5.4	12.0	4.9	13.2	6.7
N	12.8	7.2	13.1	6.1	12.1	5.4	11.1	7.1	12.0	6.6	12.3	4.7	12.7	5.0	11.9	4.6	12.2	6.9
C	12.8	7.1	12.8	6.7	11.8	6.6	10.9	6.6	12.0	6.2	12.3	5.8	12.6	5.7	11.7	5.4	12.3	7.6
CNE	12.7	7.0	13.0	6.6	11.4	6.7	10.5	7.0	11.9	6.4	12.3	5.8	12.6	6.3	12.0	5.7	11.5	7.8
CE	12.5	6.5	12.4	6.4	11.0	6.7	10.2	6.8	11.8	5.9	11.6	5.4	12.0	5.8	11.0	5.7	11.2	7.9
CSE	13.3	7.2	12.4	6.5	10.7	6.1	10.1	6.0	11.8	5.7	11.9	5.3	11.8	5.5	11.0	4.8	11.0	7.4
CS	13.8	8.0	13.9	7.5	12.5	7.0	12.3	6.8	12.9	6.9	13.4	6.6	13.1	6.1	12.8	5.7	12.3	8.0
CSW	13.2	7.7	13.5	7.4	13.4	7.1	12.3	6.7	12.3	6.9	13.2	6.4	13.5	5.8	12.9	5.6	12.8	8.0
CW	13.1	7.9	13.3	7.3	13.1	6.6	11.9	6.7	12.6	6.9	12.9	5.9	13.5	5.5	12.6	5.4	13.5	7.6
CNW	12.2	7.3	12.6	6.8	12.1	6.0	11.1	6.7	11.9	6.4	12.0	5.5	12.6	5.4	11.8	5.0	12.9	6.9
CN	12.7	6.9	13.2	6.0	12.2	6.0	11.1	6.6	12.2	6.0	12.3	5.1	12.5	5.1	11.8	5.0	12.3	7.2

Table 5.5 Annual maximum and minimum temperatures by circulation type, 1961-1990

Daily maximum, minimum and mean temperatures for the synoptic stations are examined to demonstrate the link between circulation patterns and temperature. The mean maximum and minimum temperature on an annual basis for each CT was calculated. It is evident from Table 5.5 that warmer temperatures are associated with airflow from the south and west - ASW, AW, SW and S circulation types, while cooler temperatures are associated with southeast and northeast circulation types - ASE, E, SE and ANE.

Figures 5.9, 5.10, 5.11 and 5.12 illustrate mean seasonal 1961-1990 temperatures by circulation type. Warmest temperatures in spring (Figure 5.9) are associated with southerly and southwesterly circulation - S, CS, SW, CSW and ASW types, while cooler temperatures are associated with northerly and easterly types - AN, CN, CNE, AE and ASE circulation. In summer (Figure 5.10), it is southerly and easterly CTs which are warmest - AE, SE, CSE, ASE and S, whilst northerly and northwesterly circulation types are coolest (ANW, CNW, NW, AN, CN, N). Northeasterly days are the coolest in both autumn (Figure 5.11) and winter (Figure 5.12), along with northerly days in autumn and easterly days in winter. Southeasterly to westerly days (SE, S, SW, W) are warmer in autumn, and southerly to northwesterly days (S, SW, W, NW) are warmest in winter.

On a monthly basis, it appears that mean temperatures for all circulation types show a seasonal cycle, with the highest temperatures in June and July and lowest temperatures in December, January and February. There are only small temperature variations for W and SW CTs, due to the moderating influence of the North Atlantic Ocean, whereas a larger temperature range exists for E and SE types.

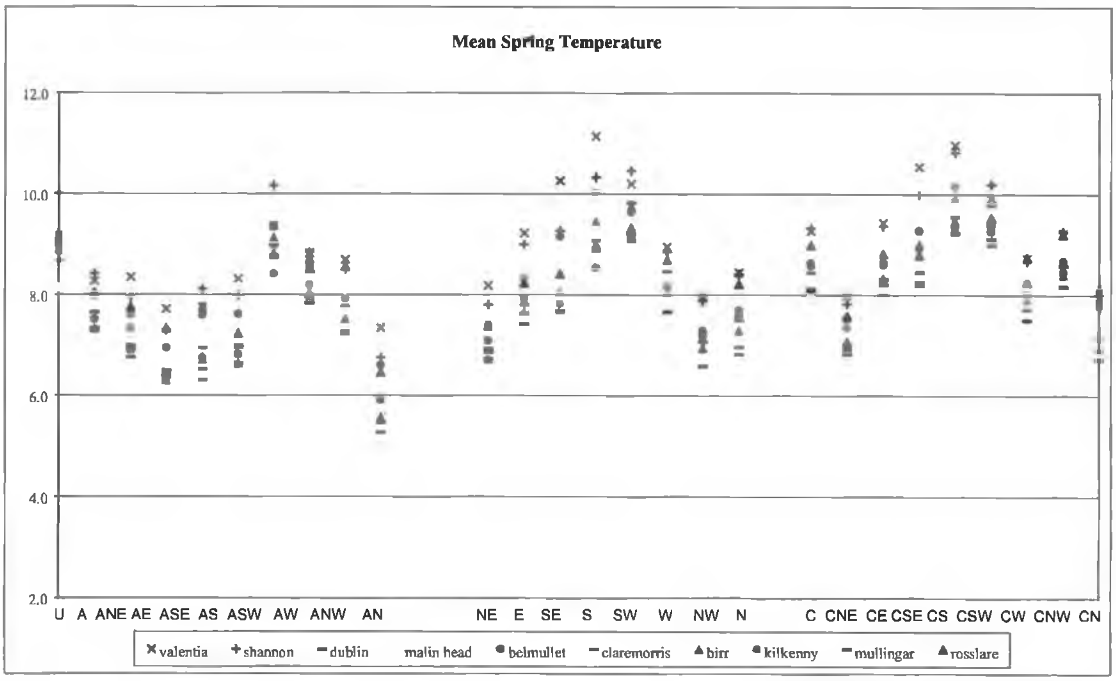


Figure 5.9 1961-1990 mean spring temperature by circulation type

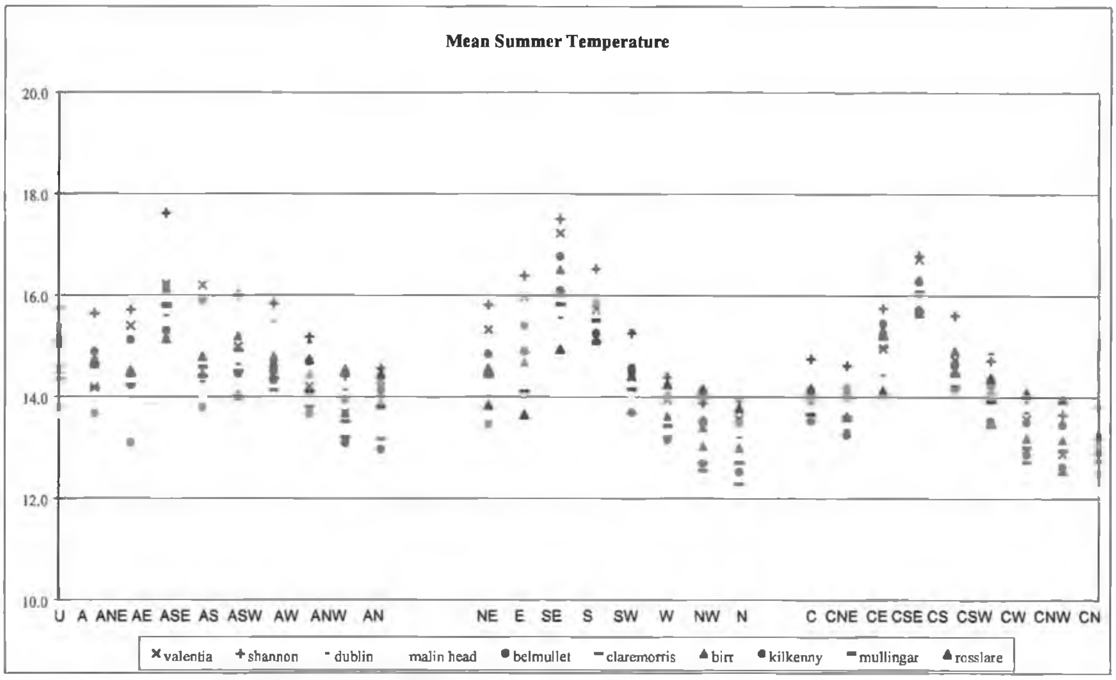


Figure 5.10 1961-1990 mean summer temperature by circulation type

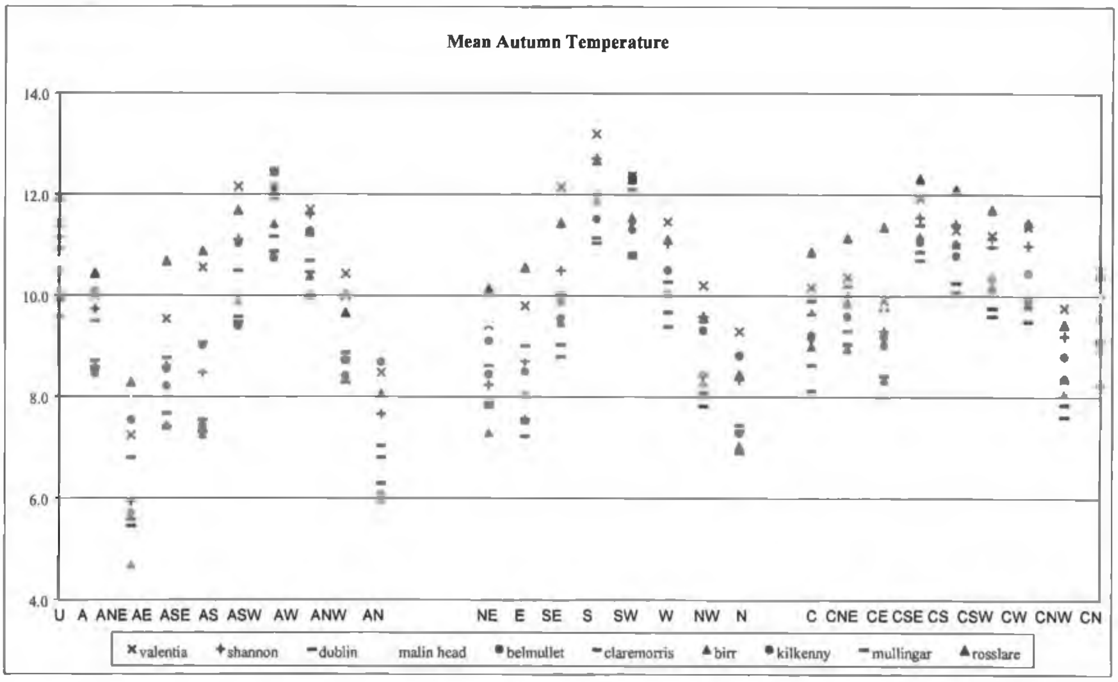


Figure 5.11 1961-1990 mean autumn temperature by circulation type

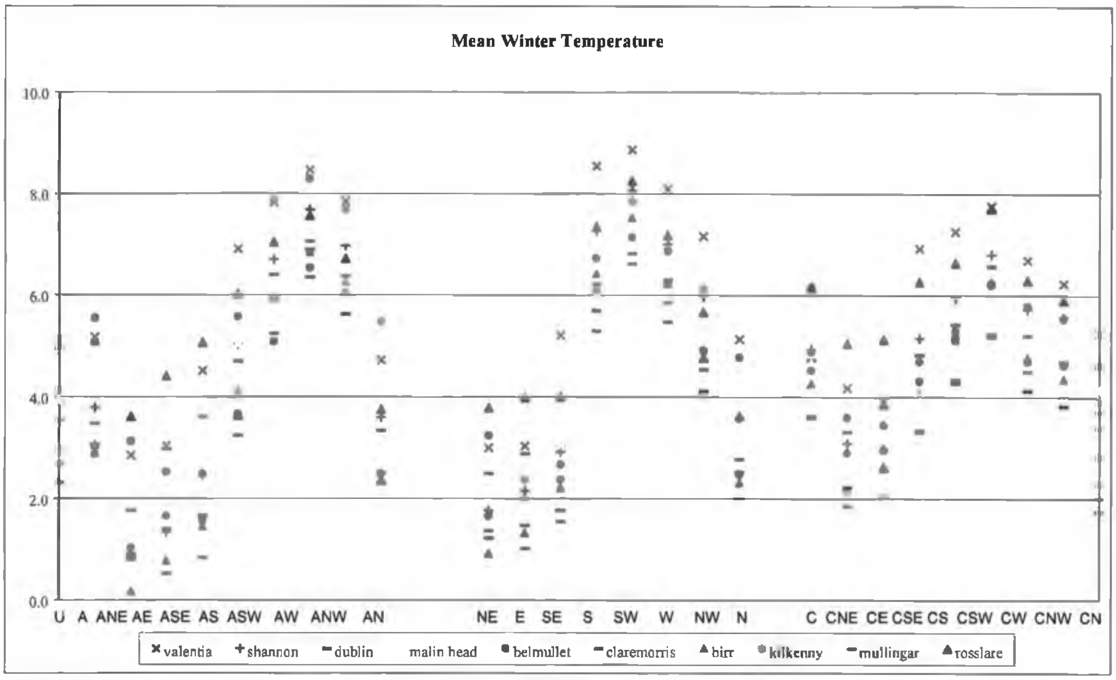


Figure 5.12 1961-1990 mean winter temperature by circulation type

5.4 Seasonal change in CT frequency and related temperature and precipitation trends

In relation to seasonal changes in circulation types, and the related trends in temperature and precipitation, the following section will outline the change in CT frequency (direction of trend) over the 30-year period. An analysis of the direction of trends in maximum, minimum and mean temperature as well as precipitation, for the synoptic stations, for each type is also conducted. In general, two complementary statistical techniques are commonly used: linear and non-parametric methods. The linear method, such as least squares linear regression can be used to determine the magnitude of the trend, while the non-parametric method, such as Spearman or Mann-Kendall's rank correlation test, can be used to detect statistical significance (De Luis *et al.*, 2000). With the least squares method, the sum-of-squares of the differences between the actual and predicted values are minimised. The form of the equation fitted is

$$Y = a + bX,$$

Where Y = dependent variable, a = the intercept of the equation, b = the slope of the equation and X = the independent variable.

Non-parametric tests make no assumptions about the distribution, for example, whether it is normal or not; sample sizes of the data are more flexible and data are usually in ranks or frequencies. Both Spearman's and Mann-Kendall's rank order correlation tests describe the degree of association between two sets of ranked data. However, the second test is used more often in climate analyses as it is possible to determine the period from when the trend is demonstrated (Sneyers, 1990). In the following sections, least squares linear regression is utilised to establish the slope of the trend, while Kendall's rank correlation coefficient establishes statistical significance of the trend.

5.4.1 Spring

In spring, there has been a significant trend in the frequency of the unclassified circulation type, which has increased at the 95% significance level (see Table 4.2, Chapter 4). There has also been an observed increase in maximum, minimum and mean temperatures for U type days significant at the 95% level or greater for all stations as outlined in Table 5.6. Therefore, as the number of unclassified types is increasing, the temperatures on these days are also increasing. Other CTs which indicate significant temperature increases include A, ASE, SE, CSE, AS, S, CS, ASW and CNE types. The temporal trend for these CTs include increasing frequency of A, ASE, AS and ASW, while the number of SE, S, CNE, CSE and CS days has decreased over the 1961 - 1990 period. Northwesterly, westerly and northerly days have, in general, shown decreasing temperature trends, while the trend in frequency of these type days is increasing for ANW, N, W, NW, N, CNW and CN types, while decreasing for AW and CW types. It appears that temperatures associated with northeasterly, southeasterly and southerly days are increasing, even though their frequency of occurrence is generally decreasing. In contrast, westerly, northwesterly and northerly temperatures are decreasing, while their occurrence on the whole is increasing.

In relation to precipitation (Table 5.8) the mean seasonal rainfall amount on CS and AW days are decreasing for all stations, while they are increasing for ANW, NW and CNE days.

5.4.2 Summer

Temporal variations in the frequency of summer time circulation types reveal no significant changes. Nonetheless, there have been significant trends observed for maximum, minimum and mean temperatures associated with specific circulation types (see Table 5.7). Anticyclonic circulation type days, while revealing no change in frequency of occurrence have been getting warmer, with significant increases observed at all stations except Mullingar. AE, ASE, ASW, AW, ANW, AN, NE, E, SE S, SW, W, N and CNW types have increasing temperature trends at most stations. On the contrary, CNE, CSE, CS, CSW and CN have decreasing temperature trends.

Increases in precipitation in summertime are revealed for southwesterly and cyclonic days, with significant increases for a number of southwesterly days (see Table 5.9).

Spring	U	A	ANE	AE	ASE	AS	ASW	AW	ANW	AN	NE	E	SE	S	SW	W	NW	N	C	CNE	CE	CSE	CS	CSW	CW	CNW	CN
valentia max	+*	+*	+	+	+	+	+	-	-	-	-	+	+	+**	-*	-**	-	+	-	+	-	+	+	-	+	-	-
valentia min	+*	+	+	+	+	+	+	-	-	(-)	-	-	+	+**	-	-**	-	(-)	-	+	-	+*	+*	-	-	-	-
valentia mean	+*	+	+	+	+	+	+	-	-	-	-	(-)	+	+**	-	-**	-*	0	-	+	-	+*	+*	-	0	-	-
shannon max	+**	+	+	+	+	+	+*	-	-	-	-	(+)	+	+**	-*	-**	-	-	-	+	(-)	+	+*	-	+	-	-
shannon min	+**	+**	+	+	+	+	+*	(+)	-	+	+	+	+	+**	(+)	-*	-	+	+	+	-	+	+**	-	+	-	+
shannon mean	+**	+**	+	+	+	+	+*	0	-	(+)	(+)	+	+	+**	-	-**	-	0	(+)	+	-	+	+**	-	+	-	-
dublin max	+**	+*	+	+	+**	+	+	(-)	-	-	+	+	+*	+**	-	-**	-	+	+	+	(-)	+**	+**	-	-	-	-
dublin min	+	+	+	+	+	+	+*	-	-	0	-	-	+*	+**	+	-**	-*	0	0	+	-	+	+**	-	-	-	-
dublin mean	+**	+*	+	+	+	+	+*	(-)	-	-	(+)	+	+*	+**	(-)	-**	-	+	+	+	-	+*	+**	-	-	-	-
malin_max	+**	+	(+)	+	+	+	(-)	-	-	-	-	+	+	+**	-*	-**	-	+	+	+	(-)	+**	+**	-	0	-	-
malin_min	+*	+	0	-	+	+	+	-	-	(+)	-	0	+	+**	0	-**	-	+	+	+	+	+*	+**	-	-	-	+
malin_mean	+**	+	(-)	0	+	+	+	-	-	-	-	+	+	+**	-	-**	-	+	+	+	+	+**	+**	-	-	-	+
belmullet max	+*	+	(+)	+	+	+	+	-	-	-	-	+	+	+**	-	-**	-	-	+	+	0	+**	+**	-	+	-	-
belmullet min	+*	+	+	(-)	-	+	+	-	-*	-	-	(-)	+	+**	-*	-**	-	0	-	+	-	+	+**	-	-	-	-
belmullet mean	+**	+	0	+	+	+	+	-	-*	-	-	+	+	+**	-*	-**	-	(-)	(-)	+	-	+*	+**	-	+	-	-
birr max	+**	+*	+	+	+	+	+	-	-	-	(+)	+	+	+**	-*	-**	-	+	0	+	0	+**	+**	-	+	-	-
birr min	+	+	+	+	+	+	+	-	-	+	-	0	+	+**	0	-**	-*	(-)	(-)	+	-	+	+*	-	-	-	+
birr mean	+**	+*	+	+	+	+	+	-	-	(-)	-	+	+	+**	-	-**	-	0	0	+	-	+*	+**	-	-	-	-
kilkenny max	+**	+*	+	+	+	+	+	-	-	-	(+)	(-)	+	+**	-	-**	-	+	-	+	-	+**	+**	(-)	+	-	-
kilkenny min	+	+	+	+	+	+	+	-	-	0	0	0	+	+**	(-)	-**	-*	+	(-)	+	-	+	+**	-	-	-	+
kilkenny mean	+**	+*	+	+	+	+	+	-	-	-	0	0	+	+**	-	-**	-*	+	-	+	-	+*	+**	-	-	-	-
mullingar max	+**	+	+	+	+	+	+	-*	-*	-	0	+	+	+**	-**	-**	-*	0	(-)	+	(-)	+**	+*	-	-	-	-
mullingar min	+	+	+	+	+	+	+	-	-	+	-	-	+	+**	-	-**	-*	+	-	+	-	+	+**	-	-	+	(+)
mullingar mean	+*	+	+	+	+	+	+	-	-	-	-	(+)	+	+**	-**	-**	-*	+	(-)	+	-	+*	+**	-	-	-	-
rosslare max	+**	+	+	-	+**	+	+	-	-	-	+	+	+	+**	-	-**	-	+	+	+*	-	+*	+**	-	+	-	-
rosslare min	+**	+**	+	-	+	+	+	+	-	+	-	-	+	+**	+	-**	-	+	+	+	-	+*	+**	-	-	-	-
rosslare mean	+**	+	+	-	+	+	+	-	-	-	-	+	+	+**	+	-**	-	+	+	+*	-	+*	+**	-	-	-	-

Table 5.6 Direction of trend in maximum, minimum and mean temperature for each circulation type in spring, 1961-1990.
+ indicates increasing trend; - indicates decreasing trend; 0 indicates no trend; (brackets) indicate very slight increasing/decreasing trend.
** represents trends significant at the 99% level;
* represents trends significant at the 95% level.

Summer	U	A	ANE	AE	ASE	AS	ASW	AW	ANW	AN	NE	E	SE	S	SW	W	NW	N	C	CNE	CE	CSE	CS	CSW	CW	CNW	CN
valentia max	+	+*	-	+	+*	-	+	+**	+	+	+	+	+	+	+	(+)	-	+	-	-	-	-	-	-	-	+	-
valentia min	+*	+**	-	(+)	+	-	+	+*	+	+	+	+	+	+	+*	+	-	+	-	(-)	+	-	-	-	+	+	-
valentia mean	+*	+**	-	+	+*	-	+	+**	+	+	+	-	+	+	+*	+	-	+	-	-	+	-	-	-	0	+	-
shannon max	+	+**	(+)	+	+	(-)	+	+	+	+	+	+	+**	+	+**	+	-	+	-	-	-	-	-	-	-	+	-
shannon min	+**	+**	+	+*	+	+	+	+**	+**	+**	+	+	+**	+	+**	+**	+	+*	+	-	+	-	-	0	+	+	-
shannon mean	+**	+**	+	+*	+	+	+	+**	+**	+*	+	+	+**	+	+**	+**	+	+**	(-)	-	+	-	-	-	(+)	+	-
dublin max	+**	+**	-	+*	+	+	+	+	+**	+	+	+	+**	+**	+	+*	-	+	0	-	+	-	-	-	+	+	+
dublin min	+*	+**	+	+	+	+	+	+	+	+	+	+	+**	+	+	+	-	+	-	-	+	-	-	-	+	+	-
dublin mean	+**	+**	+	+	+	+*	+	+	+*	+	+	+	+**	+**	+	+	-	+	0	-	+	-	-	-	+	+	(+)
malin_max	+	+	-	+	+	-*	+	+	+	-	-	(+)	+*	+	+	(-)	-**	-	(-)	-	-	-	-	-	(+)	+	(-)
malin_min	+	+**	(-)	+*	+	+	+	+*	+	+	(+)	+	+*	+	+	+**	(-)	+	0	-	+	-	+	-	+	+	(+)
malin_mean	+	+**	-	+*	+	-	+	+*	+	+	-	+	+**	+	+	+	-	(+)	(-)	-	+	-	-	-	0	+	(-)
belmullet max	+	+	-	+	+*	0	+	+	+	+	(+)	-	+*	+*	+	(+)	-*	+	-	-	-	-	-	-	(-)	-	-*
belmullet min	+	+**	+	+	+	+	+	+*	+	+	+	+	+*	(+)	+	+	-*	+*	0	-	+	-	-	(-)	+	+	-
belmullet mean	+	+**	(-)	+	+	(+)	+	+*	+	+	+	-	+**	+	+	+	-**	+**	-	-	+	-	-	+	+	+	-
birr max	+	+**	-	+*	+	+	+	+	+	+	+	+	+**	+*	+*	+	-	+	-	-	-	-	-	-	-	+	0
birr min	+**	+**	+	+	+	+	+	+	+	+	-	+	+**	+	+*	+*	-	+	0	-	+	-	-	-	-	+	-
birr mean	+**	+**	-	+*	+	+	+	+	+	+	+	+	+**	+*	+**	+	-	+	-	-	-	-	-	-	-	+	-
kilkenny max	+	+**	-	+*	+	+	+	+	+	+	+	+	+**	+**	+**	+	-	+	-	-	-	-	(-)	-	+	+	-
kilkenny min	+**	+**	-	+*	0	+	+	+	+**	+**	+	+	+**	+	+	+**	+	+	(+)	-	+	-	-	-	(+)	+	-
kilkenny mean	+**	+**	-	+	+	+	+	+	+**	+**	+	+	+**	+*	+**	+*	0	+	-	-	+	-	-	-	+	+	-
mullingar max	(-)	+	-	+	+	0	+	-	-	+	+	+	+*	+	-	-*	-**	-	-	-	-	-	-	-	-	-	-
mullingar min	+	+	+	+	+	+	+	+	+	+	-	(+)	+**	+	+	+	0	+	-	-	+	-	-	-	0	+	-
mullingar mean	+	+	-	+	+	0	+	(-)	+	+	0	+	+**	+	0	(+)	-**	+	-	-	+	-	-	-	-	+	-
rosslare max	+	+**	-	+	+	+	+	+	+	+	+	+	+*	+	+	+	+	+	-	-	+	-	-	-	-	-	-
rosslare min	+**	+**	-	+	+	+	+	+	+*	+*	+	+	+	+	+	+	+	+	-	+	+	-	-	-	+	+	-
rosslare mean	+	+**	-	+	+	+	+	+	+*	+	+	+	+	+	+	+	+	+	-	-	+	-	-	-	+	+	-

Table 5.7 Direction of trend in maximum, minimum and mean temperature for each circulation type in summer, 1961-1990.
+ indicates increasing trend; - indicates decreasing trend; 0 indicates no trend; (brackets) indicate very slight increasing/decreasing trend.
** represents trends significant at the 99% level;
* represents trends significant at the 95% level.

Spring	U	A	ANE	AE	ASE	AS	ASW	AW	ANW	AN	NE	E	SE	S	SW	W	NW	N	C	CNE	CE	CSE	CS	CSW	CW	CNW	CN
Valentia	-	-	-	(+)	0	+	-	-	+	0	+	-	+	-	+	+	+*	-	+	+	+	-	-	-	+	-	+*
Shannon	-	-	-	(+)	0	+	-	-	+	-	+	-	+	-	+	+	+	+	(+)	+	0	-	-	0	+	+	+
Malin Hd	-	(-)	+	-	0	-	+	-*	+	-	+	(-)	-	0	+	+	+*	0	(+)	+	-	+	(-)	0	-*	-	+
Belmullet	+	(-)	0	(+)	0	+	-	-**	+	(+)	+	-	+	0	+	+	+	(+)	+	+	-	-	-	(+)	-	+	-
Clones	+	(-)	-	-	0	+	-	-**	+*	+	-	-	(+)	+	+	(+)	+	+	0	+**	+	-	-	-	-	-	+
Rosslare	-	(+)	-	+	+	+	-	-	+	-	-	+	-	(+)	-	+	+	-	(+)	+	+	-	-	-	0	-	+
Birr	+	-	-	(+)	+	+	-	-*	+	+	+	+	0	-	0	0	+	-	+	+**	+	-	-	-	(+)	-	+
Kilkenny	+	-	-	-	0	+	+	-	+	+	0	-	-	-	0	(-)	+	-	(-)	+	+	-	-	(-)	(+)	+	+
Casement	-	-	-	(+)	+	0	-	-	+	+	(-)	+	-	-	-	-	(+)	+	(-)	+	+	-	-	0	-	+	+

Table 5.8 Direction of trend of precipitation for each circulation type in spring, 1961-1990.
+ indicates increasing trend; - indicates decreasing trend; 0 indicates no trend; (brackets) indicates very slight increasing/ decreasing trend.
** represents trends significant at the 99% level
* represents trends significant at the 95% level.

Summer	U	A	ANE	AE	ASE	AS	ASW	AW	ANW	AN	NE	E	SE	S	SW	W	NW	N	C	CNE	CE	CSE	CS	CSW	CW	CNW	CN
Valentia	(-)	-**	0	-	-	+	-	-	-	-	-	-	0	(-)	+	+	(+)	(-)	+	+	+	-	-	+	-	-	-
Shannon	+	-	0	+	-	0	-	-	(-)	-	-	+	+	+	+	+	0	-	(-)	+	-	+	-	+	-	-	+
Malin Hd	+	+	-	+	-	+	-	+	+	-	+	-	0	+	+**	+	0	-	+	+	+	-	-	-*	+	+	+
Belmullet	+	+	+	+	-	+	+	-	-	(+)	-	-	+	+	+*	(-)	0	+	+	-	-	+	-	-	0	-	+
Clones	+	(-)	-	-	-	+	-	+	+	+	-	-	(+)	+	+**	+	(-)	-	+	+	+	-	-	(-)	+	+	+
Rosslare	+	-	0	+	-	+	-*	-	(+)	+	(-)	+	+	(-)	+	-	-*	-	+	+	+	-	-	+	+	+	-
Birr	+	(-)	+	+	-	0	-	-	0	+	-	+	+	+	+*	(-)	-*	-	+	+	-	+	-	-	-	-	0
Kilkenny	+	+	0	-	-	+	-	-	+	+	-	(-)	+	+	+*	(+)	-	-	+	(+)	-	+	-	+	-	+	(-)
Casement	+	-	-	+	-	+	-	+	-	(-)	-	-	-	+	+	(+)	-	-	+	(-)	-	-	-	+*	+	+	-

Table 5.9 Direction of trend of precipitation for each circulation type in summer, 1961-1990.
+ indicates increasing trend; - indicates decreasing trend; 0 indicates no trend; (brackets) indicates very slight increasing/ decreasing trend.
** represents trends significant at the 99% level
* represents trends significant at the 95% level.

5.4.3 Autumn

Cyclonic, cyclonic northwesterly and cyclonic northerly types decrease in frequency in autumn (Chapter 4, Table 4.2), at significance levels above 95%. As illustrated in Table 5.10, temperatures on cyclonic days increase at all stations, with Shannon minimum and mean temperatures being significant. While CNW types decrease in frequency, temperatures increase at Dublin, Birr, Kilkenny and Mullingar. Minimum temperatures at these stations and also at Rosslare increase on CN days, while all other temperatures (maximum, minimum and mean) at all stations decrease. Rainfall on CNW days increase at stations on the north and west coasts, significantly for Shannon, Malin Head and Belmullet. In terms of other non-significant circulation type frequencies, temperatures associated with A, AE, ASE, S, SW, CE, CS, CW and CSW are on the whole decreasing, while significant temperature increases have been observed for NW circulation (at all stations), ANW, AN, W, N, CNE and CSE circulation types. Mean rainfall increases have been observed for nearly all stations for AS, NE, C, CNE, CE, CW and CN days.

There are mean seasonal rainfall decreases on northerly and westerly days at most stations, significant at the 99% level for Malin Head on northerly days (see Table 5.12).

5.4.4 Winter

There are significant decreases in ANE and E circulation types (at the 95% level) in winter, again highlighted in Table 4.2. However, from Table 5.11, it becomes clear that there are differing trends in temperature for ANE types. There are decreasing temperatures at Valentia, Malin Head and Belmullet, while temperatures are increasing at Kilkenny (max, min and mean), Dublin (min, mean), Shannon (min, mean) and Rosslare (min, mean).

Temperatures associated with E circulation types are increasing for all stations, with significant maximum temperature increases at Valentia, Shannon and Birr. It would appear that while the frequency of E types is decreasing, temperatures associated with easterly circulation coming off the European continent are warming. An examination of the surface air temperature composite decadal anomalies from the NCEP Reanalysis database, shows that continental temperatures in the 1970s and 1980s were positive compared to the 1961-1990 mean. This may provide one explanation for the increasing temperature on easterly days, with a warming occurring in the source region of this circulation type. Figures 5.13 and 5.14 illustrate the 1971-1980 and 1981-1990 winter anomaly maps. However, mean seasonal rainfall on easterly type days (AE, E and CE) appears to be decreasing at nearly all stations (Table 5.13).

There has been a significant increase in the frequency of the SW circulation type (at the 95% level), and also a general increase in temperatures associated with this type. Some stations have very weak trends though, such as minimum temperatures at Birr, Mullingar, Belmullet and Valentia. It is interesting to note that only the frequency of U, W, SW, AN and CN types increase in winter, while all other CTs decrease or have weak trends. Temperatures associated with these increasing circulation types are diverse: at nearly all stations temperatures on unclassified days are decreasing; on W days temperature trends are generally weak but are both increasing and decreasing; on CN days they are mostly increasing with the exception of Belmullet; on SW days temperatures at all stations are increasing, significantly for maximum temperatures at Dublin, Belmullet and Rosslare; and on AN days, minimum and mean temperatures at Valentia, Rosslare and Shannon are increasing significantly. For the CTs which are decreasing in frequency, the most significant temperature changes are related to A, AE, ASE, SE and CNE circulation types, where temperatures are increasing at nearly all stations. Again, this seems to highlight the decreasing frequency of easterly and easterly-hybrid CTs but also an increase in temperatures associated with them. NW and CNW circulation types are decreasing in frequency and temperatures associated with these types are also decreasing, significantly for maximum temperatures for most stations for the NW type. The most significant mean precipitation increases in any season occur on CS days in winter, with increases significant at the 99% level observed for all stations, except Rosslare and Casement. Rainfall means also increase on ASW, S and CN days at all stations.

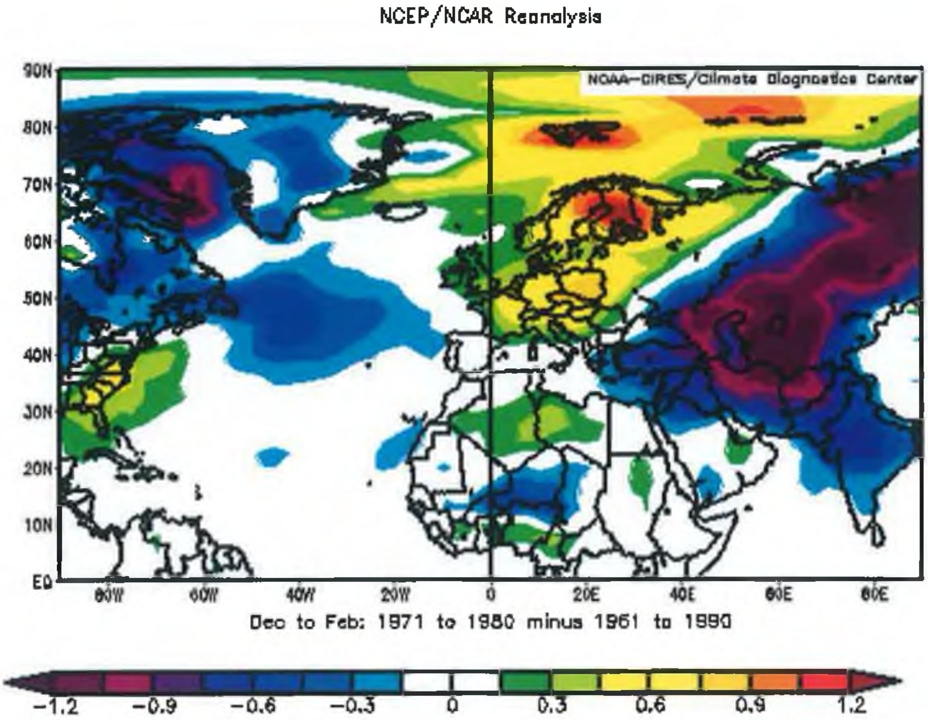


Figure 5.13 Surface air temperature anomaly for winter 1971-1980 from the 1961-1990 anomaly period.

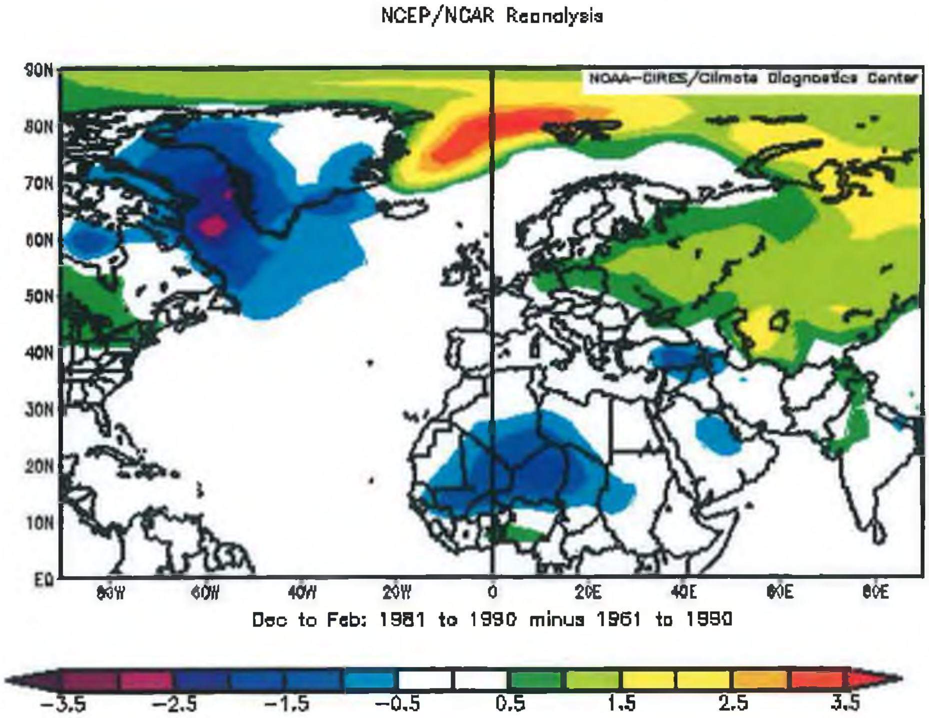


Figure 5.14 Surface air temperature anomaly for winter 1981-1990 from the 1961-1990 anomaly period.

Autumn	U	A	ANE	AE	ASE	AS	ASW	AW	ANW	AN	NE	E	SE	S	SW	W	NW	N	C	CNE	CE	CSE	CS	CSW	CW	CNW	CN
valentia max	-	-*	+	-	-*	(+)	(-)	-	+	+	+	+	-	-	-*	+	+**	+	+	+	(+)	+	-	-	-	-	-
valentia min	-	-	-	-	-	-	(+)	+	+	+	0	(+)	+	-	-	+	+**	+	+	+	-	+	-	-	-	-	-
valentia mean	-	-	+	-	-*	-	0	(+)	+	+	0	+	(-)	-	-	+	+**	+	+	+	-	+	-*	-	-	-	-
shannon max	-	-*	+	-	-*	-	+	+	0	+	+	+	-	-	-*	+	+**	+	+	+	-	+	-	-*	-	-	-
shannon min	+	0	+	-	-	(+)	+	+	+	+	+	+	+	0	-	+**	+**	+**	+*	+	-	+**	-	-	-	+	0
shannon mean	(+)	-	+	-	-	-	+	+	+	+	+	+	+	-	-	+*	+**	+**	+*	+	-	+*	-	-	-	+	-
dublin max	+	-	+	+	-	(+)	+	+	+	+	+	+	-	0	-	+	+**	+	+	+*	-	+	-	-	-	+	-
dublin min	+	-*	-	-*	-*	(-)	0	+	+	+	(-)	(-)	+	-	(-)	+*	+**	+	+	+	-	+*	-	-	-	+	+
dublin mean	+	-	+	-	-*	(+)	+	+	+	+	+	(+)	0	(-)	-	+*	+**	+	+	+	-	+*	-	-	-	+	(-)
malin_max	-	-**	+	-	-**	-	+	+	+	+	0	(-)	-	-	-	+	+*	+	+	+*	-	+	-	-*	-	-	-
malin_min	-	-*	+	-	-**	-	-	-	+	(+)	-	(-)	+	-	-	+*	+**	+*	+	+	-	+*	-	-	-	-	-
malin_mean	-	-*	+	-	-**	-	-	(-)	+	+	-	-	(+)	-	-	+*	+**	+*	+	+*	-	+**	-	-	-	-	-
belmullet max	-	-*	+	-	-*	0	+	(-)	+	+	+	+	-	-	-	+	+*	+	+	+	-	+	-	-	-	-	-
belmullet min	-	-**	-	-	-*	-	-	+	+	-	-	-	-	-	-	+	+**	+	+	+	-	+*	-	-	-	-	-
belmullet mean	-	-**	-	-	-*	-	+	+	+	(+)	-	(-)	-	-	-	+	+**	+	+	+	-	+*	-	-	-	-	-
birr max	-	-**	+	-	-*	-	+	+	+	+	+	+	-	-	-*	+	+**	+	+	+*	(-)	+	-	-	-	+	-
birr min	+	-	+	-*	-*	-	-	(+)	+	(+)	-	(+)	+	(-)	(-)	+*	+**	+	+	+	-	+*	-	-	-	+	+
birr mean	+	-	0	-	-	-	0	(+)	+	+	(+)	+	(+)	-	-	+	+**	+	+	+	-	+*	-	-	-	+	-
kilkenny max	-	-	+	-	-*	-	+	+	+	+	+	+	-	-	-	+	+**	+	+	+	-	+*	-	-	-	+	-
kilkenny min	+	-	-	-	-*	+	0	+	+	+	+	+	+	(+)	(+)	+	+**	+**	+	+	-	+	-	(-)	(+)	+	+
kilkenny mean	+	-	(+)	-	-*	+	+	+	+	+	+	+	+	0	(-)	+*	+**	+*	+	+	-	+**	-	-	-	+	-
mullingar max	-	-**	+	-	-**	-	-	-	-	+	+	+	-	-	-**	+	+*	+	+	+*	0	+	-	-	-	+	-
mullingar min	+	-**	-	-	-**	-	-	+	+	+	-	-	+	-	-	+*	+**	+*	+	+	-	+*	-	-	-	(+)	+
mullingar mean	0	-**	0	-	-**	-	-	-	+	+	0	+	-	-	-*	+	+**	+	+	+	-	+*	-	-	-	+	-
rosslare max	+	-	+	-	-*	-	+	+	+	+	+	+	-	-	-	+	+**	+	+	+**	-	+*	-	-	-	+	-
rosslare min	+	-	+	-*	-*	-	-	+	+	+	+	+	+	-	-	+**	+**	+*	+	+	-	+*	-	-	-	-	+
rosslare mean	+	-	+	-	-*	-	+	+	+	+	+	+	-	-	-	+*	+**	+	+	+	-	+*	-	-	-	+	-

Table 5.10 Direction of trend in maximum, minimum and mean temperature for each circulation type in autumn, 1961-1990.
+ indicates increasing trend; - indicates decreasing trend; 0 indicates no trend; (brackets) indicate very slight increasing/decreasing trend.
** represents trends significant at the 99% level;
* represents trends significant at the 95% level.

Winter	U	A	ANE	AE	ASE	AS	ASW	AW	ANW	AN	NE	E	SE	S	SW	W	NW	N	C	CNE	CE	CSE	CS	CSW	CW	CNW	CN
valentia max	-	+**	-	+**	+	-	+	(-)	-	+	-	+*	-	(-)	+	+	-**	+	+	-	-	-	+	-	0	-	+
valentia min	-	+**	-	+*	+	-	+	+	(+)	+*	+	0	-	-	(+)	-	-**	+	+	+	+	+	0	-	+	-**	(-)
valentia mean	-	+**	-	+*	+	-	+	+	+	+*	+	+	-	-	+	-	-**	+	+	+	+	+	+	-	+	-**	(+)
shannon max	-	+**	-	+**	+	-	+	+	+	+	-	+*	-	-	+	+	-**	+	-	+	+	-	+	-	0	-	+
shannon min	-	+**	+	+**	+	-	+	+	(-)	+**	+	+	+	-	+	-	-	+*	+	+	-	+	(+)	+	+	-*	+
shannon mean	-	+**	+	+**	+	-	+	+	-	+*	+	+	+	-	+	(-)	-	+	+	+	-	-	+	-	+	-*	+
dublin max	-	+**	-	+	+**	-	+*	0	-	+	-	+	-	-	+**	+	-**	+	+	+	-	+	+**	(+)	0	-	+
dublin min	-	+**	+	+	+	-	+	+	(+)	+	+	+	-	-	+	-	-	+	0	+	-	-	+	+	-	-*	-
dublin mean	-	+**	+	+	+	-*	+	+	0	+	-	+	-	-	+*	(+)	-*	+	+	+	-	0	+	+	-	-	(+)
malin_max	-	+**	-	+	+	-	+	-	-	+	-	+	-	-	+	+	-	+	-	-	-	0	+*	+	-	-	+
malin_min	-	+**	-	+	0	-	+	+	+	+	-	+	-	-	+	-	-	+	+	+	-	-	+	+	+	-	-
malin_mean	0	+**	-	+	+	-	+	+	(-)	+	-	+	-	-	+	(-)	-	+	-	+	-	(-)	+	+	(-)	-	(+)
belmullet max	+	+**	-	+*	+	-	+**	-	-	+	-	+	-	-	+*	+	-**	+	-	-	-	-	+	+	0	-	-
belmullet min	-	+**	-	+	+	-	+	+	0	+	+	-	-*	-*	(-)	-**	-*	-	+	+	-	-	-	-	+	-	-
belmullet mean	-	+**	-	+*	+	-	+	+	(-)	+	(+)	+	-	-	+	-	-**	-	-	+	-	-	+	+	+	-	-
birr max	-	+**	0	+**	+	-	+	+	-	+	-	+*	-	-	+	+	-**	+	-	+	-	-	+	-	+	-	+
birr min	-	+**	-	+**	-	-*	+	+	(+)	+	+	+	-	-	(+)	-	-	(+)	(+)	+	-	-	-	+	+	-	-
birr mean	-	+**	-	+**	-	-*	+*	+	-	+	+	+	-	-	+	(-)	-*	+	0	+	-	-	+	-	(-)	-	+
kilkenny max	-	+**	+	+	+	-	+	+	-	+	(-)	+	-	-	+	+	-**	+	0	+	-	+	+	+	+	-*	+
kilkenny min	-	+**	+	+	-	-**	+	+	+	+	+	+	-	-	+	(-)	-	+	(+)	+	-	-	(+)	-	+	-*	+
kilkenny mean	-	+**	+	+*	(+)	-**	+	+	+	+	+	+	-	-	+	(+)	-	+	0	+	-	-	+	+	+	-*	+
mullingar max	-	+**	-	+*	+**	-	+	(-)	-	+	-	+	-	-**	+	+	-**	+	(-)	+	-	-	+*	(-)	(+)	-	+
mullingar min	-	+**	-	+*	+	-**	+	+	+	+	+	+	-*	-	0	-	-	+	+	+	-	-	(+)	+	+	-	-
mullingar mean	-	+**	-	+*	+	-**	+	+	(+)	+	(+)	+	-	-*	+	(+)	-*	+	0	+	-	-	+	(+)	+	-*	+
rosslare max	-	+**	-	+	+	-	+*	+	-	+	-	+	-	-	+**	+	-**	+	+	+	-	+	+**	+	+	-	+
rosslare min	-	+**	+	+*	+*	-*	+	+*	+	+*	+	+	-	-	+	-	-	+	+	+	-	-	+	-	+	-*	-
rosslare mean	-	+**	+	+	+*	-*	+	+	-	+*	-	+	-	-	+	-	-*	+	+	+	-	+	+	+	+	-	+

Table 5.11 Direction of trend in maximum, minimum and mean temperature for each circulation type in winter, 1961-1990.
+ indicates increasing trend; - indicates decreasing trend; 0 indicates no trend; (brackets) indicate very slight increasing/decreasing trend.
** represents trends significant at the 99% level;
* represents trends significant at the 95% level.

Autumn	U	A	ANE	AE	ASE	AS	ASW	AW	ANW	AN	NE	E	SE	S	SW	W	NW	N	C	CNE	CE	CSE	CS	CSW	CW	CNW	CN
Valentia	+	-	+	-	0	+	+	-	-	-	0	-	+	+	+	-	+	-	+	+*	+	+*	-	-	-	+	+
Shannon	+	+	+	+	+	0	-	(+)	-	-	+	-	+	(-)	+*	-	+	-	+	+	+	+	-	0	+	+**	+
Malin Hd	+	-	-	+	(+)	+	+	-	-	+	+	+	-	+	-	-	-	-**	+*	+	+	+	+	+**	+	+*	+
Belmullet	+	(-)	+	+	+	+	+	-	-	+	+	(+)	+	+**	(-)	-	-	-	(+)	+	+	-	-	-	+	+*	+
Clones	+	(-)	+	-	-	+	+*	-	-	+*	+	-	-	0	+	-	-	-	+	+	+	-	-	+**	+	+	+
Rosslare	(+)	+	(+)	+	+	+	-	-	+	-	+	-	+	(-)	+	-	(-)	-	(+)	-	+	+	-	+	+	-	+
Birr	0	-	+	+	+	+	-	+	(-)	-	+	-	+	0	+	(-)	-	-	+	+	+	+	-	+	+	+	-
Kilkenny	+	-	+	+	+	+	+	+	+	-	+	-	(+)	(+)	+	(-)	+	0	(+)	+	+	+	-	+	+	-	+
Casement	-	+	-	+	+	+	-	(+)	+	+	(+)	-	-	-	+	(+)	-	-	+	+	+	+	-	+*	+	-	+

Table 5.12 Direction of trend of precipitation for each circulation type in autumn, 1961-1990.
+ indicates increasing trend; - indicates decreasing trend; 0 indicates no trend; (brackets) indicates very slight increasing/ decreasing trend.
** represents trends significant at the 99% level
* represents trends significant at the 95% level.

Winter	U	A	ANE	AE	ASE	AS	ASW	AW	ANW	AN	NE	E	SE	S	SW	W	NW	N	C	CNE	CE	CSE	CS	CSW	CW	CNW	CN
Valentia	+	0	+	0	+	+	+	-	-	-	-	+	+	+	+	-	(+)	-	+	-	-	+	+**	-	-	+	+
Shannon	-	+	(-)	0	+	+	+	-	-	-	-	+	+	+	0	+	0	-	(+)	0	-	+	+**	(-)	-	+	+
Malin Hd	-	(-)	-	-	-	-	+	-	+	-	-	-	-	+	(-)	+	+	-	(+)	-	-	-	+**	+	-	-	+
Belmullet	+	-	-	-*	+	+	+	-	-	-	-	0	(+)	+	+	+	(-)	-	+	-	+	+	+**	(-)	-	+	+
Clones	-	+	-	-	-	+	+	(-)	+	-	+	-	-	+	-	-	(-)	-	+	0	-	+	+**	+	-	-	+
Rosslare	(+)	-	+	-	-	-	+	-	-	-	+	-	+	+	-	-	(-)	+	(-)	-	-	+	+	-	+	-	+
Birr	-	(+)	-	-	+	+	+	(-)	-	0	+	(-)	+	+	(-)	-	(-)	-	+	+	-	+	+**	-	-	+	+
Kilkenny	+	(-)	+	-	-	-	+	+	+	-	-	(+)	+	+	-	(-)	0	-	(-)	-	-	+	+**	-	-	-	+
Casement	+	-	-	-	-	-	+	+	-	-	-	-	-	+	(+)	-	0	(+)	+	+	-	+	+	-	+	-	+

Table 5.13 Direction of trend of precipitation for each circulation type in winter, 1961-1990.
+ indicates increasing trend; - indicates decreasing trend; 0 indicates no trend; (brackets) indicates very slight increasing/ decreasing trend.
** represents trends significant at the 99% level
* represents trends significant at the 95% level.

5.4.5 Seasonal summary

In terms of the relationship between mean precipitation, mean maximum and mean minimum temperatures and changing circulation types, the seasonal increase in temperature and seasonal changes in precipitation outlined in Chapter 2, are to an extent explained by the above changes:

- The occurrence of southwesterly and westerly CTs has increased (significantly for SW) during the 1961-1990 period in winter. SW maximum and minimum temperatures have increased at all stations while only maximum temperatures on W days are increasing. Maximum temperatures on southwesterly days at Dublin, Belmullet and Rosslare have also increased significantly. This may explain, in some part, the greater rate of increase in maximum temperatures compared to minimum temperatures noted in Chapter 2. CN and AN types also increase in frequency in winter, with temperatures increasing at all stations for AN, and predominantly for maxima and means for CN. Significant temperature increases are also recorded for A and AE days.

- There is an increase in precipitation, especially in the west, in winter. This appears to be related to increases in rainfall at all stations on southerly, cyclonic-southerly, cyclonic-northerly and anticyclonic-northwesterly days. Increased average rainfall on SW days at Valentia and Belmullet and rainfall on W days at Shannon, Malin Head and Belmullet also contributes to this trend.

- In spring, the frequency of unclassified days has increased, with the temperatures on these days increasing also. An increase in frequency of A and W days has been matched by an increase in maximum and minimum temperature on these days. There has been no change in the frequency of SW days, yet maximum temperatures have been decreasing significantly while minimum temperatures increase or have little or no change. This may account to some extent for minimum temperatures in spring increasing more than maximum temperatures. In general, warmer spring temperatures are associated with E, SE and S days, while cooler temperatures occur on SW, W and NW days.

- Rainfall in spring reveals increases in the west of the country with decreases in the east and southeast. There have been decreases in precipitation on anticyclonic days at all stations. However there have been increases in rainfall at all stations on westerly days, except those on the east and southeast – Birr, Kilkenny and Casement. Similarly, rainfall on southwesterly days has also increased in the north and west, but decreased for Rosslare, Birr, Kilkenny and Casement. It appears that A, SW and W are the primary factors contributing to spring rainfall changes.

- Changes in circulation type frequency in summer reveal no significant changes, although temperature increases have been observed on anticyclonic and directional type days. Decreasing temperature trends have been related to cyclonic-type days. Of the major circulation types occurring in summer in Ireland, southwesterlies reveal no change in their frequency of occurrence while westerlies and northwesterlies are decreasing. Temperatures on westerly and southwesterly days are increasing, with minimum temperatures increasing more than maximums on westerly days (significantly for Shannon, Malin Head, Birr, Kilkenny and Mullingar).

- Maximum temperatures in Dublin in summer may be increasing at a greater rate than minimum temperatures because maximum temperatures on a number of CT days are increasing significantly while minimum temperatures are not. Maximum temperatures on unclassified days increase significantly, at the 99% level, while for most other stations it is only minimum temperatures which increase at this level. Temperatures on westerly and southerly days are also similar, with greater increases on maximum days relative to minimum.

- Summertime precipitation has increased everywhere in the period 1961-1990. Rainfall on SW days has increased, significantly at Malin Head, Belmullet, Clones, Birr and Kilkenny. On westerly days there are only increases in mean rainfall at Valentia, Shannon, Malin Head and Clones, while on northwesterly days there is no change at a number of stations and decreases for Rosslare, Birr, Kilkenny and Casement. However, the frequency of W and NW days are decreasing so these CTs may not explain as much of the precipitation as expected. On unclassified days, southerly, anticyclonic-southerly and cyclonic days rainfall is increasing at nearly all stations, with the frequency of these CTs either increasing or unchanged.

- In autumn, only Dublin Airport and Belmullet maximum temperatures display temperature increases greater than minimum temperatures. This may be associated with the fact that on anticyclonic days, while all temperatures are decreasing, minimum temperatures at Dublin and Belmullet are decreasing more significantly. Maximum temperatures at Valentia, Shannon, Birr and Malin Head are decreasing more significantly than minima. Temperatures on AN, W, NW, N, C, CNE and CSE days are increasing for almost all stations. On southwesterly days, while all stations reveal decreasing temperatures or little change, maximum temperatures at Valentia, Shannon, Birr and Mullingar are decreasing significantly more than minima.

- For precipitation, there are greater seasonal increases in the southwest in autumn. There are increases in southwesterly rainfall for most stations, with a significant increase for Shannon. Similarly, there are increases on AS, NE, C, CE, CW and CN days.

The previous section has dealt with Irish climate trends in the period 1961-1990. An investigation of long-term quasi-cyclical changes in circulation is necessary to examine the extent to which this climate variation is representative of longer period trends. The primary mode of atmospheric circulation in the mid-latitude region is the North Atlantic Oscillation (NAO). According to Barnston and Livezey (1987) and Marshall *et al.* (2001), the NAO is the only mode which is present in every month of the year, thus making it a good indicator of long-term trends.

5.5 Relationship with North Atlantic Oscillation Index

This section briefly examines the relationship between atmospheric circulation and temperature and precipitation at selected sites in Ireland. An index of circulation frequently cited in studies on Northern European climate variability is the North Atlantic Oscillation (NAO). This is a mode of natural variability most prevalent during the winter months when pressure gradients are at their strongest. When sea level pressure is lower than normal near Iceland, and/or higher than normal near the Azores, the NAO is said to be in a positive phase, and in a negative phase if the opposite occurs. When the NAO is in a positive phase, the storm tracks moving across the North Atlantic Ocean are stronger, bringing depressions north-eastward into Northern Europe. This mode is also associated with an increase in wind speed from the west and an increase in temperature and precipitation for Northern Europe. The wintertime NAO exhibits significant interannual and interdecadal variability (Hurrell, 1995). The index was in a markedly positive phase at the beginning of the century and has been again since the mid-1970s. The index has been calculated since the middle of the 19th century and is updated at the Climate Research Unit at the University of East Anglia.

As the NAO is also a measure of the strength of the westerlies, Wilby *et al.*, (1997) found significant positive correlations between the Central England Temperature and the Lamb westerly weather type. According to Hurrell (1996), the NAO explains about 30% of the variance of mean winter Northern Hemisphere temperatures. Correlations between the winter phase of the NAO and winter maximum, minimum and mean temperatures at Malin Head and Valentia reveal positive correlations, significant at the 99% level. Malin Head and Valentia have been chosen as they represent the longest surface climate record for the west coast of Ireland (since 1890). The variation in the long-term temperature record (1890-2000) explained by the NAO is approximately 30% for Malin Head and 50% for Valentia. Figures 5.15 and 5.16 outline the relationship between the winter phase of the NAO and winter temperatures at Valentia and winter temperatures at Malin Head. There is a clear agreement between the time series, with positive values of the NAO being associated with higher winter temperatures, and negative phases of the NAO with lower temperatures.

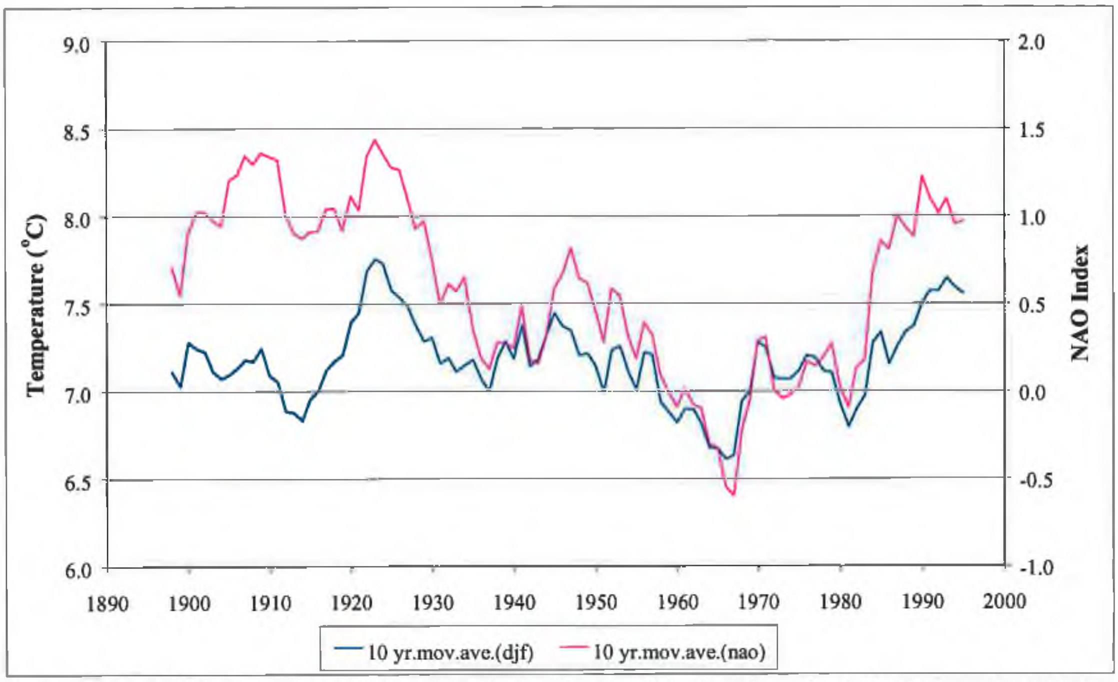


Figure 5.15 Relationship between the winter phase of the NAO and winter temperatures at Valentia, 1890-2000. (10 yr.mov.ave = 10 year moving average)

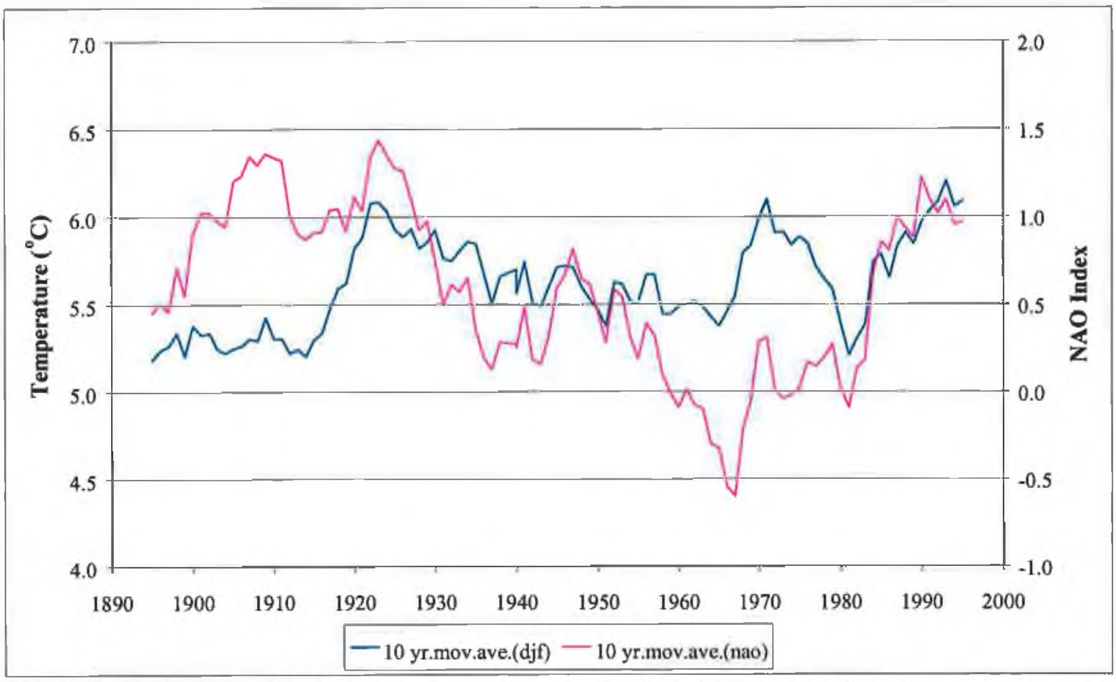


Figure 5.16 Relationship between the winter phase of the NAO and winter temperatures at Malin Head, 1890-2000. (10.yr.mov.ave = 10 year moving average)

Above normal winter precipitation occurs in northern Europe when the NAO is in a positive phase, while the opposite occurs when in a negative phase. In relation to Irish precipitation, again there is a significant correlation, at the 99% level, between winter precipitation and the winter phase of the NAO. Figure 5.17 shows Malin Head winter precipitation in relation to the winter NAO index for the period 1890 to 2000. As with temperature, positive values of the NAO are associated with higher precipitation values, while negative NAO phases are linked with lower precipitation.

Figure 5.17 Relationship between winter phase of the NAO and winter precipitation at Malin Head, 1890-2000.

While the index is most relevant in winter months, in the following section the links between the NAO, the circulation types identified for Ireland and seasonal temperature and precipitation series throughout Ireland are examined. The NAO is positively correlated with westerly circulation in all seasons, with AW in summer, ASW and AW in autumn and with SW and AW in winter. The index, as expected, is significantly negatively correlated with easterly and hybrid-easterly types. For example, in spring it is negatively correlated with easterlies, negatively correlated with northerlies in summer, with ANE, ASE, NE, E and SE in autumn and with E, SE, C and CE in winter.

Maximum and minimum temperatures have significant correlations (at the 99% level) with the winter index of the NAO at all synoptic stations. The seasonal correlations are outlined in Table 5.14. There are also significant correlations between spring minimum temperatures and spring values of the NAO at Valentia, Belmullet, Birr and Kilkenny, and with maximum temperatures at Rosslare. With relation to precipitation, it is apparent that spring rainfall series have generally higher correlation coefficients than winter at most stations (with the exception of Shannon, Malin Head and Belmullet). The statistical significance at these three west coast stations is greater than 95% for both spring and winter. There are negative correlations between the NAO and summer precipitation at all stations except for Valentia and Malin Head. These negative correlations are significant only at Kilkenny and Belmullet. The results are summarised in Table 5.15.

As the NAO is a measure of the strength of the westerlies one would expect there to be greater correlations between the index and westerly and hybrid-westerly circulation types. It is evident that the NAO explains a substantial portion of the variance in temperature and precipitation on the west coast of Ireland in winter. Obviously other modes of atmospheric circulation variability play an important role in the climate of Ireland during other seasons and at other locations.

		Spring	Summer	Autumn	Winter
Valentia	maxT	-0.02	-0.03	0.07	0.64**
	minT	0.37**	0.08	0.18	0.59**
Shannon	maxT	-0.03	-0.02	0.19	0.63**
	minT	0.16	0.09	0.17	0.55**
Dublin AP	maxT	0.23	0.15	0.21	0.66**
	minT	0.13	0.07	0.10	0.47**
Malin	maxT	0.10	0.13	0.18	0.53**
	minT	0.09	0.08	0.01	0.41**
Belmullet	maxT	-0.13	-0.06	0.02	0.64**
	minT	0.29*	0.08	0.27*	0.50**
Birr	maxT	0.01	0.05	0.25	0.65**
	minT	0.30*	0.08	0.20	0.51**
Kilkenny	maxT	0.07	0.13	0.26*	0.67**
	minT	0.32*	0.00	0.03	0.50**
Mullingar	maxT	0.12	0.05	0.21	0.66**
	minT	0.26	0.01	0.02	0.51**
Rosslare	maxT	0.28*	0.24	0.19	0.63**
	minT	-0.02	-0.02	0.03	0.46**

Table 5.14 Seasonal correlation between NAO and maximum and minimum temperatures, 1961-1990

	Spring	Summer	Autumn	Winter
Valentia	0.20	0.02	0.16	0.13
Shannon	0.29*	-0.13	0.25	0.33*
Malin Hd	0.27*	0.03	0.34*	0.30*
Belmullet	0.33*	-0.04	0.29*	0.40**
Clones	0.42*	-0.09	0.17	0.24
Rosslare	0.21*	-0.25	-0.01	-0.02
Kilkenny	0.13	-0.26*	0.08	0.11
Casement	0.13	-0.27*	-0.02	0.01
Birr	0.25	-0.18	0.11	0.22

Table 5.15 Seasonal correlation between NAO and precipitation, 1961-1990.

5.6 Conclusion

This chapter has outlined the relationship between the 27 circulation types, identified in Chapter 4, and temperature and precipitation variables for Ireland. Changes identified in Irish climate in recent decades can be related to large-scale changes in atmospheric circulation. It is recognised that climate in Ireland is being driven by a number of factors, including (i) the change in occurrence frequency of circulation types, (ii) changes in climatic characteristics at the source regions of some CTs, and (iii) changes in the North Atlantic Oscillation. The combination of these, over the period 1961-1990, has led to a number of significant changes. An increasing frequency of westerly and southwesterly circulation, arising from a predominantly positive phase of the NAO since the mid 1970s, has resulted in increased winter temperatures and increases in winter precipitation in the south and west coasts. Similarly, increasing easterly temperatures in winter are related to changes in source regions of easterly CT days coming off the European continent. Other circulation types, which play an important role in determining Irish climate include westerly, northwesterly, cyclonic and anticyclonic types.

The identification of the relationship between circulation and local climatic variables is also essential for the development of statistical and empirical downscaling approaches. Following on from this analysis, Chapters 6 and 7 will outline a circulation type downscaling methodology from which the relationships outlined in this chapter can be used to downscale from large-scale GCM output to the finer resolution local scale. Chapter 6 describes the various downscaling methods before presenting a more detailed summary of the method used in downscaling for Ireland in this case. Seasonal climate scenarios for 2041-2070 for Ireland are revealed in Chapter 7.

Chapter 6

Weather type approach to downscaling

6.1 Introduction

As outlined previously, there are a number of consistent and distinct relationships which exist between surface climate observations in Ireland and large-scale atmospheric circulation types. For example, southwesterly, westerly and cyclonic hybrid types generally have above average mean daily rainfall, and a higher proportion of wet days, in most seasons. As regards temperature, there are increasing temperature trends for anticyclonic types in winter, spring and summer, while northwesterly temperatures are decreasing in these seasons. A link between the North Atlantic Oscillation and westerly circulation types, and also with maximum and minimum temperatures in winter has also been observed.

This study of the connection between the local weather and circulation patterns is a prerequisite for future downscaling studies from Global Climate Model (GCM) output. Climate change scenarios used in impact studies often rely on the results from GCM experiments. GCMs are expected, therefore, to be able to simulate realistic, internally consistent weather and climate patterns at the global scale (Hulme *et al.*, 1993). However, there is a scale mismatch between the requirements of the impacts analyst and the availability of useful information from GCMs. According to Palutikof *et al.* (2002), GCMs are generally only able to satisfactorily reproduce the characteristics of surface climate variables at the hemispheric or global scale, rather than at the local and regional scales which are required. Downscaling is the technique of using large-scale climate information (predictors e.g. atmospheric circulation patterns) to predict local climates (predictands e.g. daily temperature). It is a means of bridging the gap, both temporally and spatially, between what the climate impact analyst wants and what the climate modeller is able to provide. While the downscaling term has only recently become widespread, downscaling techniques are firmly established as a means of relating mesoscale atmospheric circulation patterns to regional surface climate variables (Wilby, 1998b).

This chapter will initially outline the main approaches to downscaling, namely dynamical and statistical methods, with examples of the application of each. There are a number of fundamental criteria which must be satisfied before downscaling can be applied. For example, the link between the large-scale and local climate should be strong in order to explain the local climate variability correctly. These criteria and additional limitations of the downscaling method are subsequently considered. Finally, the application of the weather type approach to downscaling for Ireland is applied. The choice of data and GCM is outlined, followed by a comparison of the observed and modelled circulation type frequencies for the 1961-1990 period, both on a monthly and seasonal basis.

6.2 Downscaling approaches

There are a number of different methods of downscaling, the two main ones being dynamical and statistical. There are also conventional methods and composite methods. Below is a brief description of each method with more detail on the statistical approach.

6.2.1 Conventional and composite downscaling

Conventional methods of downscaling involve the scaling of observed local time series with GCM data. The scaling factor is usually the difference between two GCM runs, the control run for the present day and a future run. An advantage of this method is the fact that the difference between the GCMs performance and the observed present-day climate variable is dispersed. Composite downscaling methods provide a means of constructing multiple scenarios and/or combining results from a number of GCMs. Information from more than one GCM can be averaged. Conventional methods can then be used to obtain information at the local scale.

6.2.2 Dynamical downscaling

Dynamical downscaling involves the development of finer-resolution Regional Climate Models (RCMs) that are driven by boundary conditions such as wind, temperature and humidity variables, and forced by the large-scale features of the GCM. The RCM develops its own climate within the boundary domain. The model should be able to replicate the physical processes operating at regional scales and take into account orographic features that are partially or totally absent in a GCM that may be important for regional climates (Zorita *et al.*, 1995). Information at higher spatial resolutions can be achieved (up to 10-20 km or less) and at temporal scales of hours or less (Hewitson and Crane, 1996). Given that the method is based on physical processes and takes account of local factors makes it more appealing. However, this approach is computationally costly as there is an increase in model resolution. Another problem with this approach is that feedbacks from the regional model back into the GCM are not usually incorporated (Zorita *et al.*, 1995).

6.2.3 Statistical downscaling

Statistical downscaling is sometimes preferred due to its relative ease to use and lower cost (Busuioc *et al.*, 2001a). By using the observed relationships between the large-scale circulation and the local climates, statistical models can be created that are able to translate anomalies of the large-scale flow into anomalies of local climate variables (von Storch, 1995). Once the statistical model parameters are estimated from a training set of large-scale and local observations, the models may be used to infer changes in the local variables due to changes in the large-scale fields simulated by GCMs (Zorita *et al.*, 1995: 1024).

The relationship between the large-scale weather patterns and the local scale can be determined by using statistical (or dynamical) downscaling. There are a number of methods including linear and non-linear regression, canonical correlation analysis, artificial neural networks, singular value decomposition and stochastic weather generators which can be used to determine this relationship. Advantages of statistical downscaling methods include the fact that they are relatively easy to compute and can be applied to a variety of GCM experiments.

They also provide local information, which is needed most in climate change impact studies (IPCC, 2001).

6.2.3.1 Weather generators. Stochastic downscaling, such as use of a weather generator, is primarily aimed at providing daily time series. In most cases the weather generator produces long series of synthetic daily weather data, which is similar to the observations in a statistical sense (Rummukainen, 1997). This method of downscaling is primarily used for daily precipitation in hydrological studies. Most weather generators use first- or second-order Markov chain processes, in which the precipitation occurrence on each day is governed by precipitation occurrence on the previous day.

6.2.3.2 Transfer functions. In this approach, transfer functions are derived from the observational data using statistical methods. A relationship of the form $y = f(x)$ is developed between the large-scale predictors and local scale predictands. Most statistical methods make use of linear regression methods, with relatively few utilising non-linear methods such as neural networks. According to Biau *et al.* (1999) non-linear methods have the disadvantage of being more difficult from the theoretical and numerical point of view and, as such, are rarely used. Multiple linear regression is the least computationally demanding downscaling technique. Schoof and Pryor (2001) use multiple linear regression, with temperature variables as the predictands, and PC scores as predictors. Precipitation however is highly skewed, and as such, is not normally distributed. Therefore, precipitation was modelled using a Poisson regression model by Schoof and Pryor (2001). Hanssen-Bauer and Førland (1998) also use multiple linear regression to establish the relationships between the monthly average geostrophic wind components and absolute pressure (as predictors) and local monthly mean temperature and monthly precipitation totals (as predictands). von Storch *et al.* (1993) used canonical correlation analysis (CCA) to relate local monthly precipitation in the Iberian peninsula to the large-scale sea level pressure field.

6.2.3.3 Weather typing. The synoptic approach to downscaling involves the definition of 'weather classes', either synoptically or by the construction of indices of airflow. Essentially, the frequency distributions of the local climate variables are derived by weighting the climate states with the relative frequencies of the weather classes. Climate change is then determined by the changing frequency of the weather classes (IPCC, 2001). There are a number of methods to derive these weather classes, either subjectively or objectively, and they have been extensively outlined in Chapter 3. The approach, which has been adopted in this study, is similar to that used by Jones *et al.* (1993). This initially involved developing a set of indices from daily grid point mean sea level pressure (MSLP) data for an area over Ireland. The direction (D) and numerical values of strength of airflow (F) and total shear vorticity (Z) were calculated from daily MSLP data. The corresponding circulation types, consistent with the Jenkinson and Collison (1977) UK catalogue, were then defined from a number of rules conditional on the relationship between D, F and Z. This classification, while providing a method of checking the Lamb Weather Type frequencies, can also be easily adapted to validate GCM control simulations and applied to GCM perturbed models (Wilby, 1998a).

According to Huth (2000), any classification method which is to be used to compare GCM simulated climate with observed climate should meet several requirements. These include, firstly, that the classification must be computer-based and not subjective, as it is impractical to classify GCM output manually. Secondly, the method should be able to cope with tens of thousands of days to allow for a classification period as long as possible. Thirdly, the method used should enable the researcher to compare characteristics of the climates, such as cyclones and ridges, the persistence of types and the probability of transition between types.

The weather typing method of downscaling which has previously been applied to observed and GCM data is based on the statistical relationship between large-scale atmospheric circulation and local weather, and as such is based on sensible physical linkages between the two (Wilby, 1997). However, the method is based on the fundamental assumption that the relationships between large-scale climate and local weather will remain the same in a future perturbed climate. This is a serious issue faced in all downscaling procedures - the issue of non-stationarity, and the fact that linkages may not be constant in time.

6.3 Downscaling criteria

Generally downscaling should satisfy 3 main criteria: (i) the link between the large-scale and local climate should be strong in order to explain adequately the local climate variability; (ii) the large-scale climate variable should be well simulated by the GCM; and (iii) the relationship between local and large-scale climate should not change in time and should remain the same in a future perturbed climate. It is the third condition which provides the most uncertainty as it is almost impossible to check in practice. According to Zorita *et al.* (1995), this requirement is in some way equivalent to the assumption that GCMs will also simulate altered climates properly. If the classification period is long however, the model may be able to identify the major factors affecting regional climate, as all situations which may exist in a perturbed climate may have been captured in the natural variability of the observed climate (Zorita *et al.*, 1995). The GCM should be able to simulate past climates, and if so, it is generally assumed to be capable of simulating future climates (Busuioc *et al.*, 2001a). Rummukainen (1997) also highlights the fact that on short time scales (such as up to a few decades) this criterion should not be too big an issue as the anticipated scale of change is still of the order of the natural interannual and interdecadal variability (Rummukainen, 1997).

A number of authors have outlined more general limitations in the use of the downscaling technique. Wilby (1994) identified a number of issues, primarily to do with classification, scale and stability. As regards classification, most weather classification schemes are based on regional and local-scale factors which means that they are not easily transferable to other regions. Features such as topography and land/ocean distributions, which are unique to that area, are naturally included. As suggested by Wilby, if there is to be global application of GCMs to impact analysis such as hydrology, there is also a need for more general classification systems. Secondly, due to the wide range of spatial and temporal scales, it is rare for any downscaling approach to be able to depict climate variability at all these scales. The third major restriction described by Wilby (1994), and identified by authors in the previous section, is possibly considered the most important and most serious obstacle to downscaling for future climate scenario generation. This is the issue of non-stationarity between the circulation weather pattern and the associated climatic variable. In many cases, this relationship is not constant in time and there is a need to acknowledge that a non-stationary relationship exists. This temporal instability is a serious limitation to any circulation-type method of downscaling. Through their analysis of daily rainfall for the UK, with respect to the Lamb Weather Types and the absence or presence of fronts, Wilby *et al.* (1995) highlight the value of subdividing daily rainfall by precipitation mechanism. This inclusion of frontal information led to significant improvements in the rainfall models. The authors were then able to attribute the intra-weather-class variability to simple changes in the dominant precipitation mechanism. Sweeney and O'Hare (1992) found minor changes in temporal variations in mean precipitation yield for the Lamb Weather Types and have suggested that this non-stationarity may be due to changes in sea surface temperatures, and/or shifts in the main depression paths.

There are also concerns pertaining to the characteristics of certain predictors. Precipitation is generally not suitable for statistical techniques such as regression-based downscaling methods due to its discontinuity through time. Similarly, as atmospheric circulation is continuous in time, discrete categories (such as Lamb Weather Types) within precipitation models may also have limitations (Conway *et al.*, 1996). As Conway *et al.* (1996) explain, there is often an 'overlap between the mean precipitation distributions of the most common circulation types and as such they may be statistically indistinguishable' (1996: 170). This limitation however, only appears to be relevant when considering extreme daily precipitation and not mean monthly and seasonal values.

6.4 Weather type approach to downscaling for Ireland

6.4.1 Choice of model

General Circulation Models (GCMs) are complex, gridded three-dimensional computer-based models of the climate system (Goodess, 2000b). They are 'based on the physical laws for atmospheric composition and behaviour and attempt to provide a calculable model of the earth's climate system, including internal and external forcing as well as feedback in the climate system' (Rummukainen, 1997: 1). They represent the atmosphere, ocean, land-surface and sea-ice processes. However, GCMs are limited by their coarse spatial and temporal resolution. Horizontal grid resolutions generally range from 200 to 1000 km. The Hadley Centre for Climate Prediction and Research climate models, HadCM2 and HadCM3, are atmospheric GCMs coupled to a three-dimensional representation of the ocean and a terrestrial biosphere model (Viner, 2000). As they need high performance computing resources, such models can only be run at a few centres around the world. The HadCM3 model has been part of an international model inter-comparison project and it has performed as one of the best models in the world (Hulme *et al.*, 2002). HadCM3 has a horizontal grid resolution of 2.5° latitude by 3.75° longitude, which is still relatively coarse. The model uses 19 vertical levels for the representation of the atmosphere and 20 levels for the representation of the ocean. With advanced computing power and further research, greater resolutions are becoming available. According to Zorita *et al.* (1995) 'GCMs are assumed to simulate realistically the large-scale atmospheric features which give rise to the observed distribution of regional climates, such as subtropical highs, subpolar storms and storm tracks' (Zorita *et al.*, 1995: 1024). This is a requirement of all models and has to be taken as given. However, these models may only satisfactorily reproduce the characteristics of surface meteorological variables, such as temperature or rainfall at the hemispheric or global scale, rather than the required regional or local scale (Palutikof *et al.*, 1997; Goodess and Palutikof, 1998; Palutikof *et al.*, 2002). The final estimation of regional climate change strongly depends on the degree of confidence put on the GCM simulations (Zorita *et al.*, 1995).

6.4.2 Choice of Scenario

The IPCC Special Report on Emission Scenarios (SRES)(2000) identifies a number of 'storylines'. These scenarios are alternative images of how the future might unfold, determined by driving forces such as demographic development, socio-economic development and technological change. Six climate models were used to produce 40 SRES scenarios within 4 broad families – A1, A2, B1 and B2. The A1 family describes a future world with rapid economic growth, a population peak mid-century and rapid introduction of new and efficient technologies. The A2 family describes a future heterogeneous world with self-reliance and preservation of local identities. There is an increasing global population and economic development is regionally oriented. The B1 family describes a future convergent world with a global population peaking in the mid-century but with changes in economy towards service and information economy. The B2 family describes a future world with emphasis on local solutions to environmental, economic and social sustainability. A more detailed description of the main characteristics of the four SRES storylines and scenario families is available in Box 6.1.

The Emission Scenarios of the Special Report on Emission Scenarios (SRES)

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into four groups that describe alternative directions of technological change in the energy system. Two of the fossil-intensive groups were merged in the SPM.

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Box 6.1 The main characteristics of the four main SRES storylines.
Source: IPCC Special Report on Emissions Scenarios (2000).

None of the scenarios can be described as the best or most likely scenario. Instead they are a realistic grouping of a wide range of possible future simulations. Figure 6.1 represents an estimate of how global concentrations of carbon dioxide will change in the future for each of the scenarios. Despite the relatively large differences in emissions between the four scenarios, there is only a slight difference between the global temperature differences they produce until after the middle of the present century. This is partly because much of the change in climate over the next 30 to 40 years has already been determined by historic emissions. (Hulme *et al.*, 2002). Ideally, a number of scenarios should be used in each analysis. In this study, the HadCM3 B2 SRES scenario has been used initially as it dates back to 1860 and as such can be used as a control for the 1961-1990 period. It is also easily accessible and available from the Climate Research Unit (CRU). A number of authors have chosen the A2 and B2 scenarios as they represent a modest guide for future emission increases. As can be seen in Figure 6.1, A2 and B2 scenarios would be considered 'middle of the road' scenarios with respect to total CO_2 emissions. This is also the case for other global greenhouse gas emissions such as methane and nitrous oxide.

6.4.3 Data used and time period chosen

National Centers for Environmental Prediction (NCEP) Reanalysis data are available four times daily and as daily averages. However, HadCM3 MSLP data are available only once daily, an average of all 30-minute timesteps generated (Pope *et al.*, 2000). As there is nothing that can be done with this scale mismatch, in this case, daily MSLP data from NCEP was used. In the future, GCM data are likely to be archived at a higher temporal resolution, which will enable modelling of diurnal climate variables and even single points in time (Palutikof *et al.*, 2002). 1961-1990 was chosen as a baseline and reference period. This period was chosen so as to determine climate change with respect to the present. Also, for this period there are greater data availability, both observational and NCEP Reanalyses. Most climate modelling studies use one of three future time periods: 2020, 2050 and 2100. In this instance, the future period 2041-2070 was chosen as this is representative of mid-century - 2055.

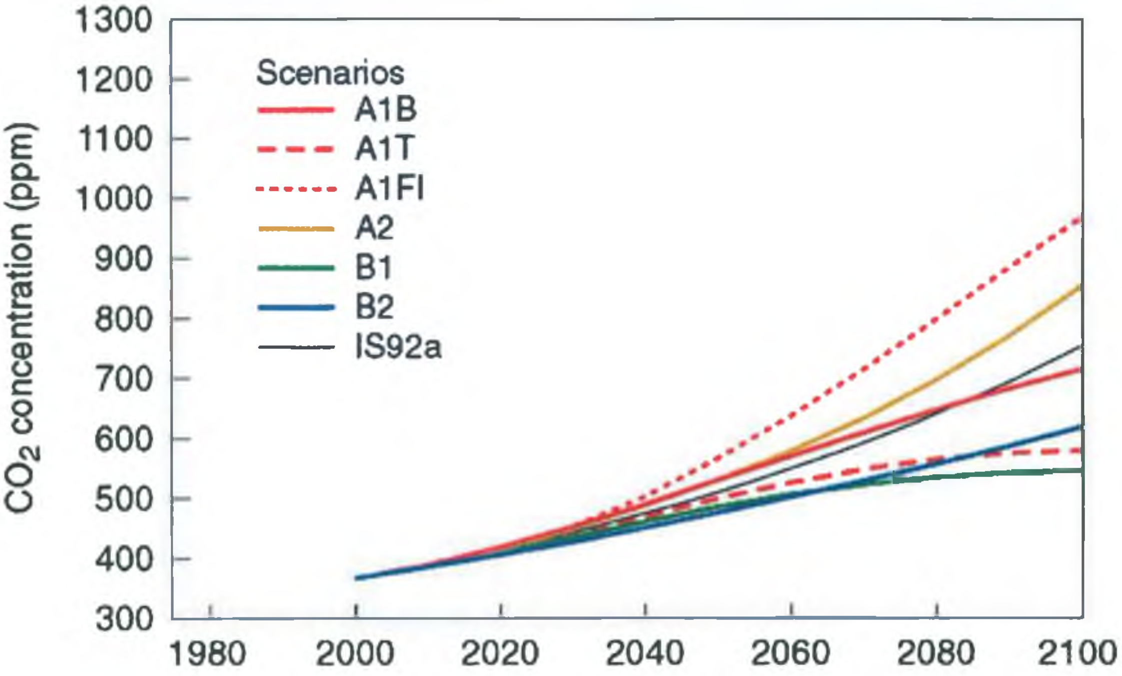


Figure 6.1 Global carbon dioxide concentrations (parts per million) from 1990 to 2100 for each of the four emission scenarios. [Source: IPCC, 2001]

6.5 Observed and modelled circulation type frequencies

It is recognised that there are recurring errors in the GCM which can be traced through to the downscaled series (Palutikof *et al.*, 2002). However, its performance is still satisfactory considering it is the 'control' 1961-1990 time series rather than the observed 1961-1990 series which is used to provide the baseline for the climate change scenarios. This is as a result of the knowledge that the errors are consistent throughout the GCM (Palutikof *et al.*, 2002). According to Wilks (1999), the 'control' GCM will always be different to some extent from the observed climate. Results from future modelled GCM integrations are, therefore, not used in downscaling directly. An adjustment is made to the observed series which reflects the relative change between the control and the modelled future period (Wilks, 1999).

In the following section, the seasonal and monthly frequencies of the 27 circulation types have been calculated from the 1961-1990 control run of the HadCM3B2 model and compared with the observed frequency of CTs for the same period. For the control run, each of the months has 30 days, and each season 90. Therefore, there is a difference between the number of observed cases (which range from 847 in February to 930 in January, March, May, July, August, October and December for the 30-year period) and number of modelled cases (900 in each month over the 30-year period). No allowance has been made for this difference. For each month, the percentage frequencies of the individual CTs have been calculated for both the observed and modelled case.

The Mann-Whitney U-test (also known as the Wilcoxon rank sum test) is used to test for significant differences between the paired values (observed and control-run frequencies). It is a non-parametric test which means that it does not assume the data form any particular pattern of distribution. The test was applied to each of the seasons and months to determine if there is a significant difference between the observed frequency of circulation types and the control run of the GCM circulation type frequencies in the period 1961-1990. Significant differences are identified between the seasonal control and observed frequencies for a number of circulation types. These are presented in Table 6.1. The greatest disparities are found in spring, with smaller differences and fewer significant differences in winter. In all seasons and on an annual basis anticyclonic-westerly and southwesterly circulation types reveal statistically significant differences, with the control model underestimating the frequencies in each case.

	spring	summer	autumn	winter	annual
A	-83*	-59	-33	-47	-222**
AE	+14*	-7	-6	-5	-4
AN	-37*	-31	-9	-1	-78**
ANE	-5	+4	-6**	-11	-18
ANW	-76**	-51**	-18	-3	-148**
AS	+30*	-10	-5	+12	+27
ASE	+57	-4	-3	-4	+46
ASW	+9	-39**	-38*	-14	-82**
AW	-117**	-28*	-34*	-21*	-200**
C	+18	+134**	+101**	+98**	+351**
CE	-18	+11	-2	0	-9
CN	+16	+34	+28*	+18	+96**
CNE	+1	+10	+7	+4	+22
CNW	+28	+52**	+15	+24**	+119**
CS	+3	+10	+28*	+26	+67*
CSE	-16	+12	-2	+1	-5
CSW	-40**	+24*	+30	+34*	+48*
CW	+19*	+28*	+22	+36**	+105**
E	-36*	+12	-12	-50**	-86**
N	+171**	+12	-27	+50	+206**
NE	-34	-5	+17	-13	-35
NW	+79**	-13	-12	+3	+57
S	+228**	-9	+76*	+60	+355**
SE	+55	+8	+26	+5	+94*
SW	-125**	-110**	-136**	-123*	-494**
U	+30	+14	-11	0	+33
W	-231**	-59	-26	-86	-402**

Table 6.1 Actual differences between 1961-1990 observed and 1961-1990 control circulation type frequencies. Significant differences are identified using the Mann-Whitney U test.

** indicates statistical significance at the 99% level

* indicates statistical significance at the 95% level

The main differences between the model and the observed frequency of CTs, for the baseline period, include the underestimation of A, AN, ANW, AW, SW and W types in all seasons and annually, while there is an overestimation of C, CN, CNE, CNW, CS, CW and SE in all seasons and annually. These percentage frequencies can be seen in Table 6.2. The model also underestimates the frequency of CSW in spring, AS and NW in summer and autumn, S in summer and U and N in autumn. It also overestimates AE, ASE, ASW in spring, ANE, CW, E in summer, NE in autumn, NW in summer and autumn and ASE in summer and winter. The greatest percentage differences are in spring, with a maximum of +973% for ASE circulation type. In percentage frequency of cases, this is an increase from 0.22% in observed cases to 2.33% in the control model.

	spring	summer	autumn	winter	annual
A	-22.8	-20.2	-10.6	-18.5	-18.2
AE	67.3	-48.9	-23.2	-26.1	-3.6
AN	-43.4	-41.2	-23.5	-2.8	-33.6
ANE	-7.1	20.8	-25.3	-57.8	-13.9
ANW	-77.1	-49.4	-37.6	-7.8	-51.6
AS	**513.3**	-18.2	-6.0	20.3	16.1
ASE	**973.3**	-31.9	-8.7	-8.1	49.6
ASW	34.0	-53.2	-37.3	-21.3	-29.8
AW	-82.6	-47.1	-45.9	-38.0	-60.6
C	10.2	98.7	84.8	78.2	58.7
CE	-50.4	**127.1**	-14.4	0.0	-12.4
CN	**111.2**	**136.0**	**203.3**	**120.6**	**140.6**
CNE	6.0	56.0	**119.1**	67.1	39.9
CNW	**262.4**	**192.1**	61.8	**104.9**	**140.2**
CS	6.7	36.3	**119.1**	72.7	44.5
CSE	-32.6	**177.5**	-12.4	4.3	-3.9
CSW	-43.2	74.4	67.1	81.4	24.4
CW	79.9	68.8	68.5	**116.7**	82.2
E	-29.8	38.3	-27.8	-62.4	-30.7
N	**210.3**	7.4	-15.0	42.0	35.7
NE	-19.8	-3.5	36.2	-24.3	-8.7
NW	97.2	-2.1	-3.6	1.6	8.1
S	**276.4**	-2.4	25.8	15.8	38.1
SE	83.7	18.6	36.6	4.1	30.9
SW	-33.5	-29.5	-29.2	-25.9	-29.1
U	41.5	10.0	-13.3	0.0	10.4
W	-57.0	-18.3	-7.5	-28.6	-29.9

Table 6.2 Seasonal percentage differences between 1961-1990 observed and 1961-1990 control circulation type frequencies.
Bold indicates differences greater than 100%

On a monthly basis, the differences between the observed frequencies and model frequencies are consistent with the seasonal findings. The model underestimates the frequency of occurrence of A (except in October), AE (from June to December), ANW (except in February), ASW (except February to April), AW (in all months), SW (except April) and W (in all months except September). In terms of overestimation, the model overestimates C (except in March), CN, CNW and CW (in all months), CSW (except March to May) and N (except September to December). The monthly percentage differences between the observed and modelled circulation type frequency can be seen in Table 6.3.

For the 10 main CTs (SW, W, A, S, NW, C, N, U, NE and SE) the observed and modelled monthly percentage frequencies are plotted in Figures 6.2 to 6.11. It becomes clear from Figure 6.2 for southwesterly days that while the model underestimates the observed frequency of SW days in all months (except April), there are large inconsistencies in the range of underestimation. For example, May and December are the months with the largest differences, while February has the least discrepancy. The SW type also has the strongest seasonal cycle with maximum in December and minimum in late spring (April/May). For westerly circulation (Figure 6.3) the model underestimates all months except September, although there are also large differences in some months, such as March and May. For most CTs the annual and seasonal cycle is replicated to some degree by the models, although as noted above, there are cases where certain months are over-/under-estimated to a greater degree. Examples of this include April for anticyclonic days, March for southerly days, June and July for cyclonic days and March for northerly days.

On the occasions when there are large discrepancies (those greater than 100%) it is generally the case that the model is overestimating the CT frequency. It is also for the most part AS, ASE, S, SE and cyclonic-hybrid circulation types (see Table 6.3).

	jan_%diff	feb_%diff	mar_%diff	apr_%diff	may_%diff	jun_%diff	jul_%diff	aug_%diff	sep_%diff	oct_%diff	nov_%diff	dec_%diff
A	-20.32	-15.07	-19.13	-35.62	-4.62	-14.44	-26.91	-20.10	-12.50	10.04	-25.84	-20.70
AE	29.17	9.80	55.00	50.00	**106.67**	-20.00	-58.67	-74.17	0.00	-48.33	-27.27	-77.04
AN	67.92	11.22	-15.80	-72.73	-32.61	-33.33	-77.40	15.49	-46.15	14.81	-26.67	-55.71
ANE	-82.78	-47.72	50.30	-15.79	-25.60	**350.00**	-61.25	-48.33	75.00	24.00	-71.43	-48.33
ANW	-22.50	25.48	-74.86	-86.67	-70.00	-63.64	-67.37	-10.44	-14.29	-36.85	-60.00	-17.33
AS	-40.38	55.28	**235.83**	**1800.00**	**313.33**	-14.29	11.94	-45.29	4.35	-33.33	29.41	77.14
ASE	-36.85	56.85	**2586.67**	**400.00**	**2566.67**	**100.00**	3.33	-87.08	-25.00	-13.89	9.09	-25.37
ASW	-45.10	7.56	**164.07**	0.00	-48.33	-61.11	-55.71	-44.36	-40.48	-39.22	-29.17	-2.11
AW	-41.88	-28.03	-82.03	-89.13	-72.18	-40.00	-61.25	-34.74	-48.15	-46.67	-40.00	-43.64
C	**108.78**	47.89	-13.38	43.94	3.33	96.15	**104.47**	94.65	69.44	**115.05**	73.47	72.22
CE	**158.33**	-52.94	-48.33	-36.36	-59.81	**133.33**	**158.33**	3.33	**100.00**	-13.89	-33.33	-31.11
CN	**148.00**	**182.33**	**175.56**	0.00	**230.67**	**109.09**	75.67	**313.33**	83.33	**150.95**	**1300.00**	77.14
CNE	**261.67**	**-100.00**	-48.33	-71.43	**152.59**	**183.33**	-11.43	3.33	**150.00**	**158.33**	50.00	**566.67**
CNW	**158.33**	**103.91**	**726.67**	**100.00**	**210.00**	63.64	**475.71**	**137.67**	85.71	**106.67**	10.00	60.74
CS	63.61	34.44	-1.83	11.11	10.22	33.33	-17.33	**106.67**	-10.00	**197.08**	**233.33**	**137.67**
CSE	32.86	50.58	-22.50	-60.00	-3.56	**166.67**	**933.33**	-65.56	-80.00	29.17	16.67	-28.46
CSW	47.62	**135.28**	-40.38	-33.33	-49.53	18.18	**141.11**	77.14	41.18	**106.67**	60.00	77.96
CW	**130.51**	41.17	69.09	**220.00**	14.81	18.18	**138.46**	52.28	15.38	66.92	**171.43**	**197.08**
E	-45.29	-70.42	-40.95	-35.19	-17.33	8.70	16.25	**313.33**	28.57	-55.71	-28.57	-63.10
N	57.72	**133.76**	**313.33**	**235.00**	**149.92**	6.76	3.33	13.67	-12.50	-4.18	-25.76	-29.08
NE	19.23	-37.26	-48.33	-30.36	4.90	37.50	-41.44	-32.83	46.67	37.78	26.32	-40.18
NW	-18.35	60.15	**193.33**	34.48	52.93	-39.36	-6.47	41.01	21.95	4.77	-30.39	-19.38
S	16.46	-17.97	**399.44**	**253.13**	**199.31**	-4.55	21.79	-17.86	16.84	-13.29	**113.70**	60.94
SE	-1.47	-40.49	17.42	**129.17**	97.68	4.76	**134.85**	-36.85	37.50	22.12	44.44	**168.67**
SW	-24.35	-19.00	-35.58	3.70	-55.47	-41.60	-25.11	-20.58	-28.08	-27.79	-31.69	-31.49
U	24.00	-33.57	-2.75	38.46	65.33	**109.76**	12.87	-45.68	-18.18	15.26	-44.44	34.33
W	-35.95	-12.00	-53.41	-50.00	-69.18	-38.75	-13.40	-7.09	10.78	-8.63	-23.64	-32.48

Table 6.3 Monthly percentage difference between 1961-1990 observed frequency of circulation types and 1961-1990 control/ model frequency of circulation types. Bold indicates difference greater than 100%.

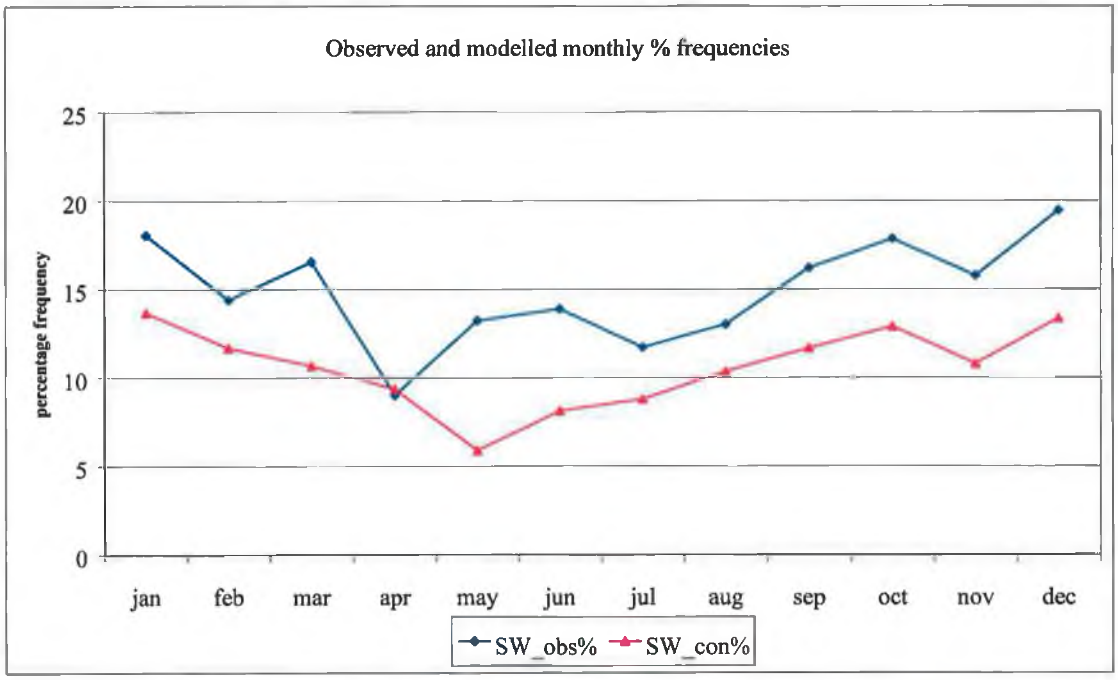


Figure 6.2 1961 – 1990 observed and control/model monthly mean percentage frequencies of southwesterly circulation.

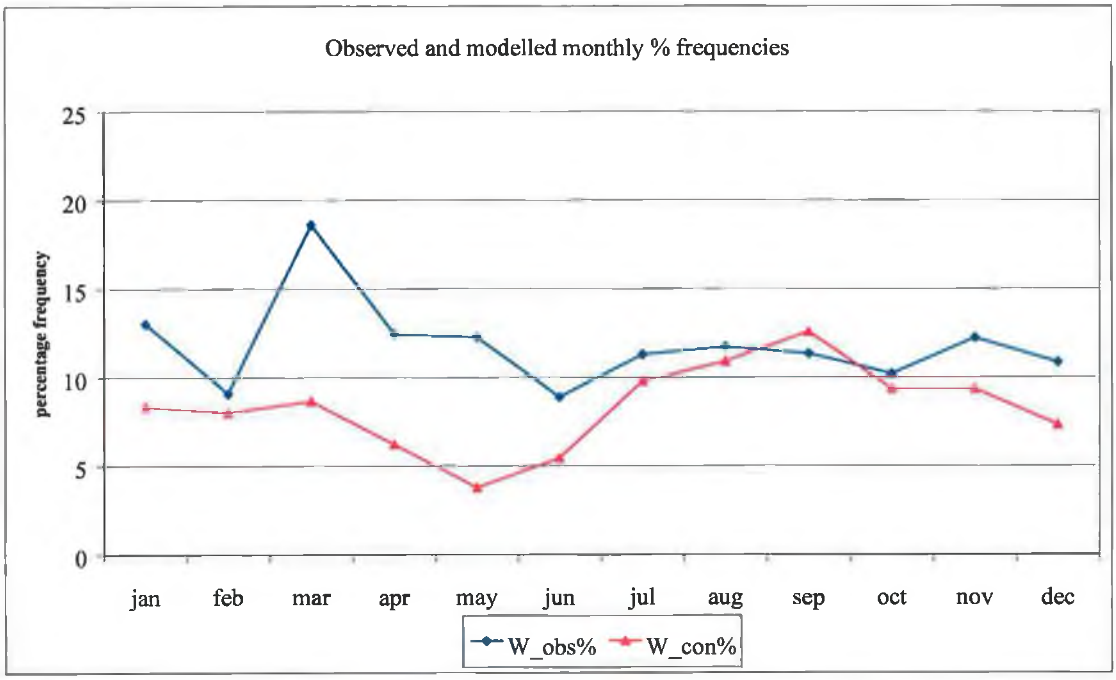


Figure 6.3 1961 – 1990 observed and control/model monthly mean percentage frequencies of westerly circulation.

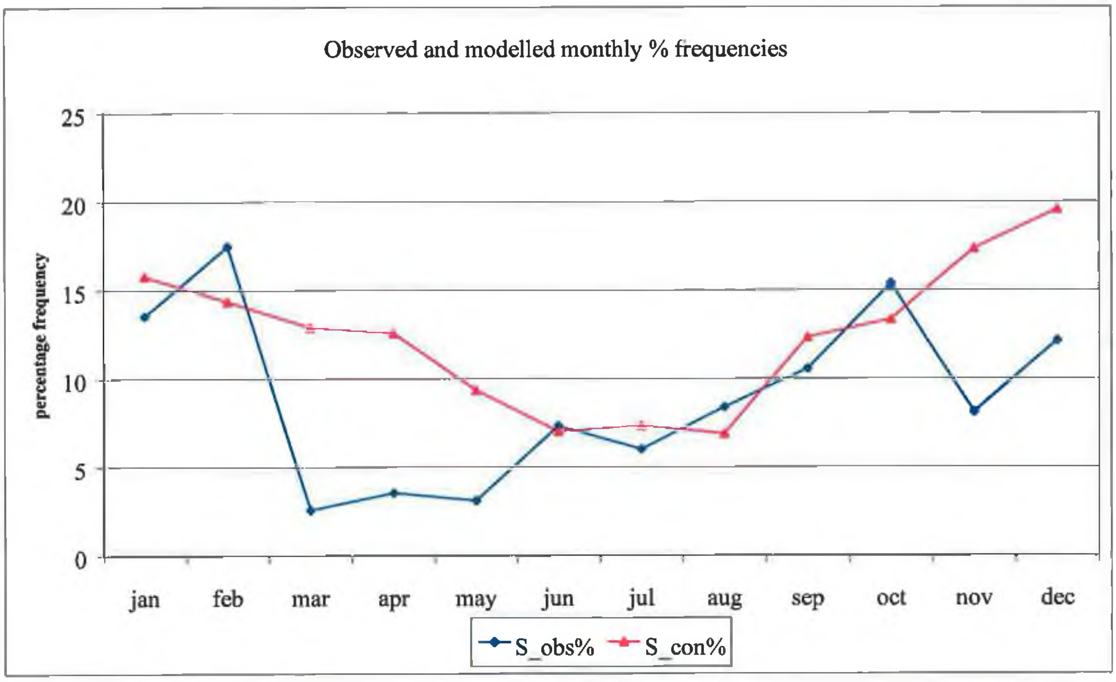


Figure 6.4 1961 – 1990 observed and control/model monthly mean percentage frequencies of southerly circulation

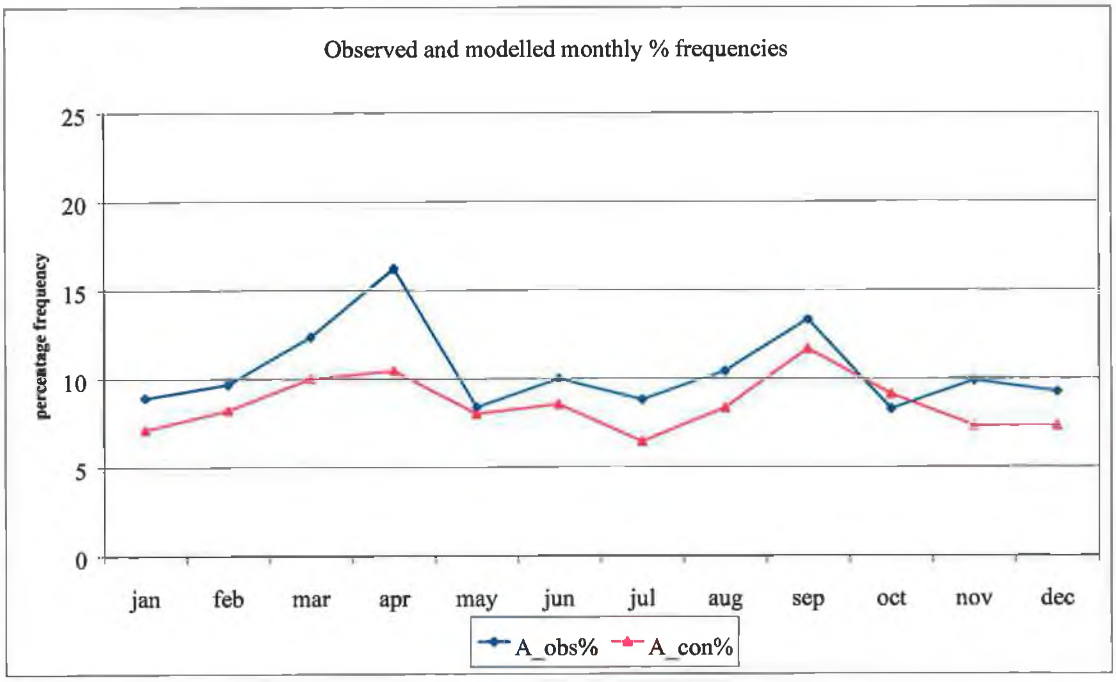


Figure 6.5 1961 – 1990 observed and control/model monthly mean percentage frequencies of anticyclonic circulation.

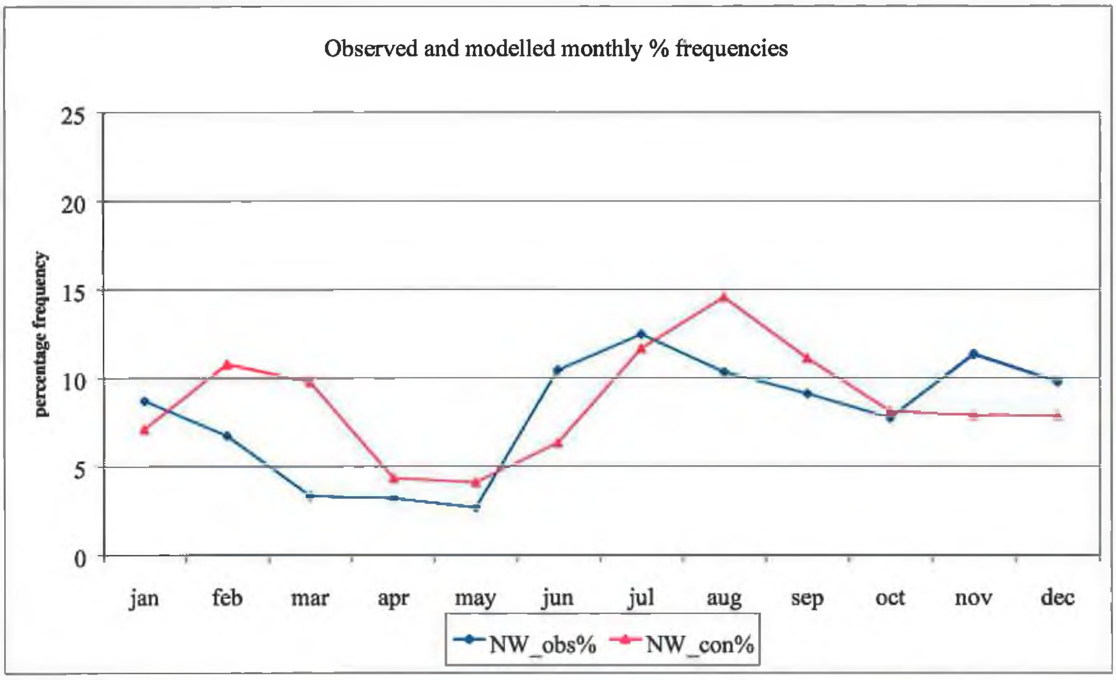


Figure 6.6 1961 – 1990 observed and control/model monthly mean percentage frequencies of northwesterly circulation.

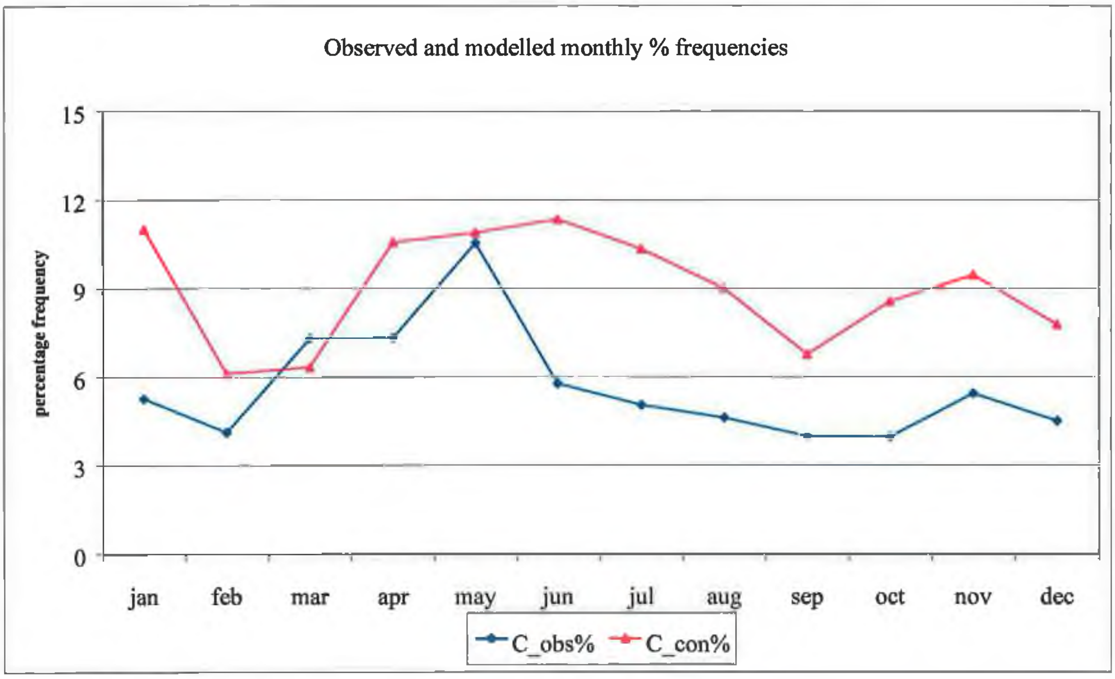


Figure 6.7 1961 – 1990 observed and control/model monthly mean percentage frequencies of cyclonic circulation.

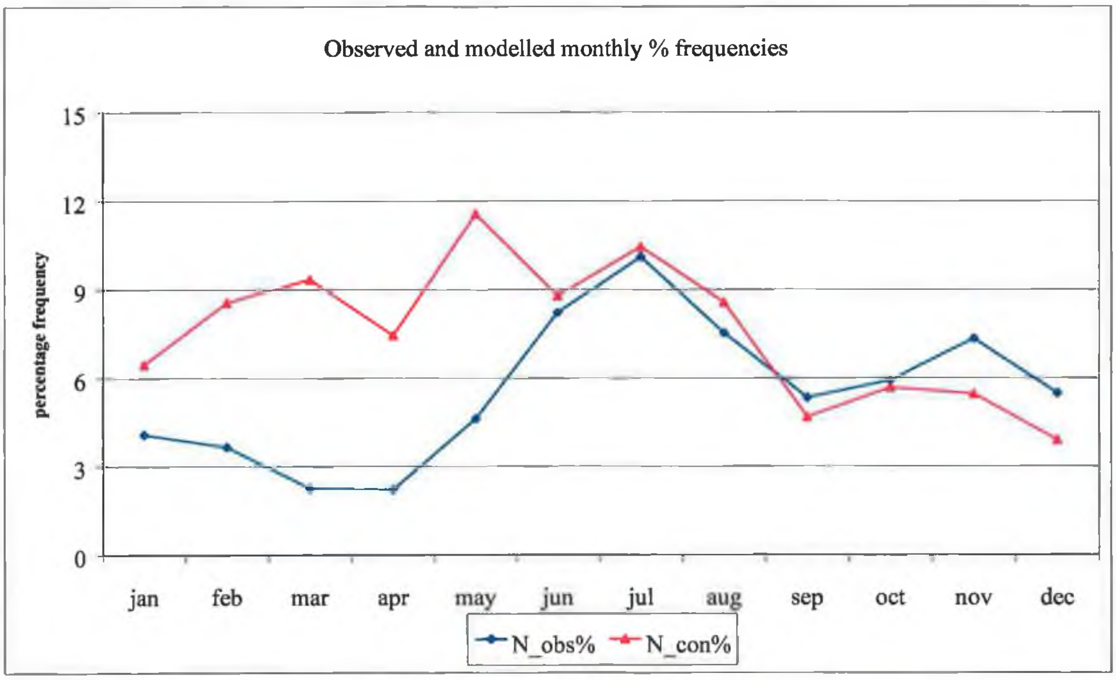


Figure 6.8 1961 – 1990 observed and control/model monthly mean percentage frequencies of northerly circulation.

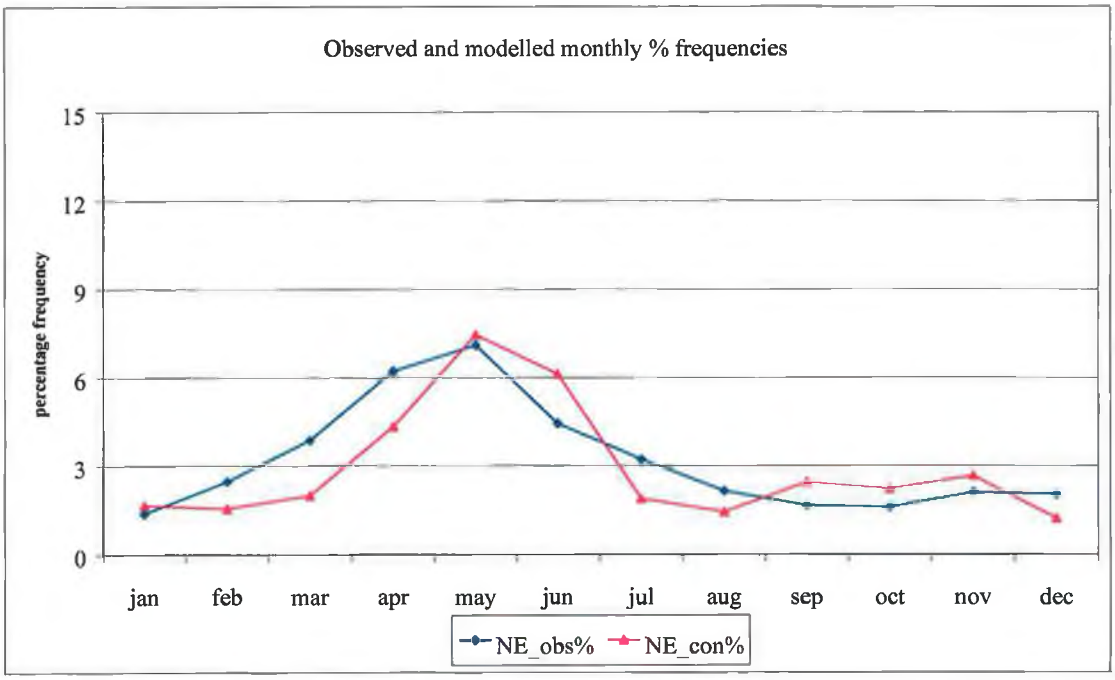


Figure 6.9 1961 – 1990 observed and control/model monthly mean percentage frequencies of northeasterly circulation.

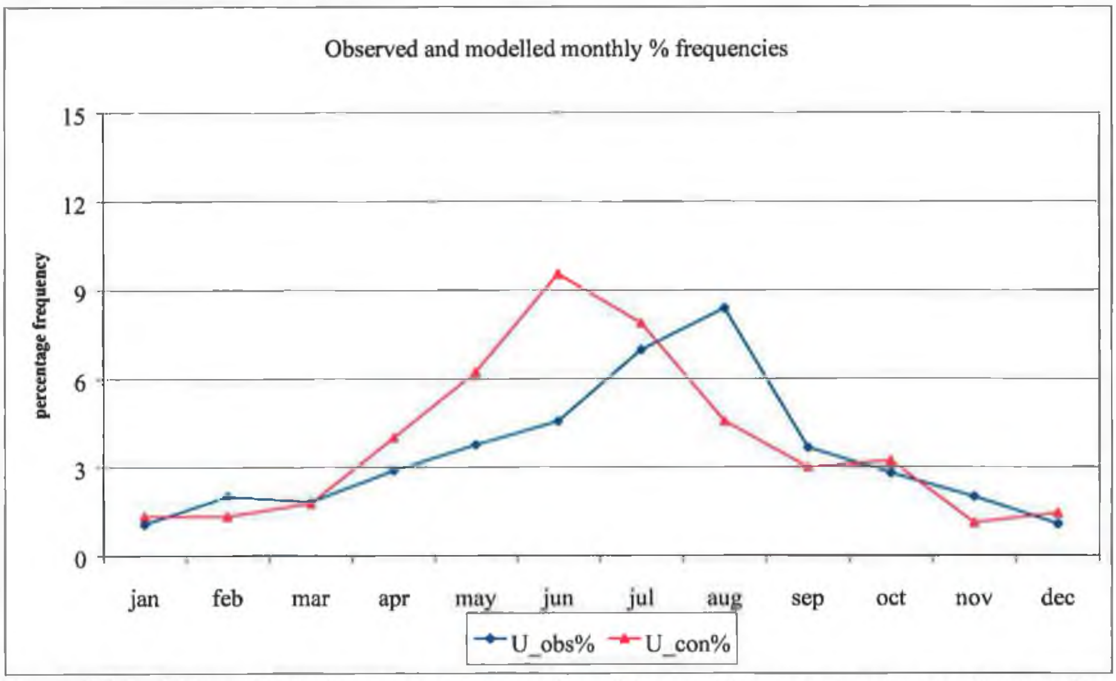


Figure 6.10 1961 – 1990 observed and control/model monthly mean percentage frequencies of unclassified circulation.

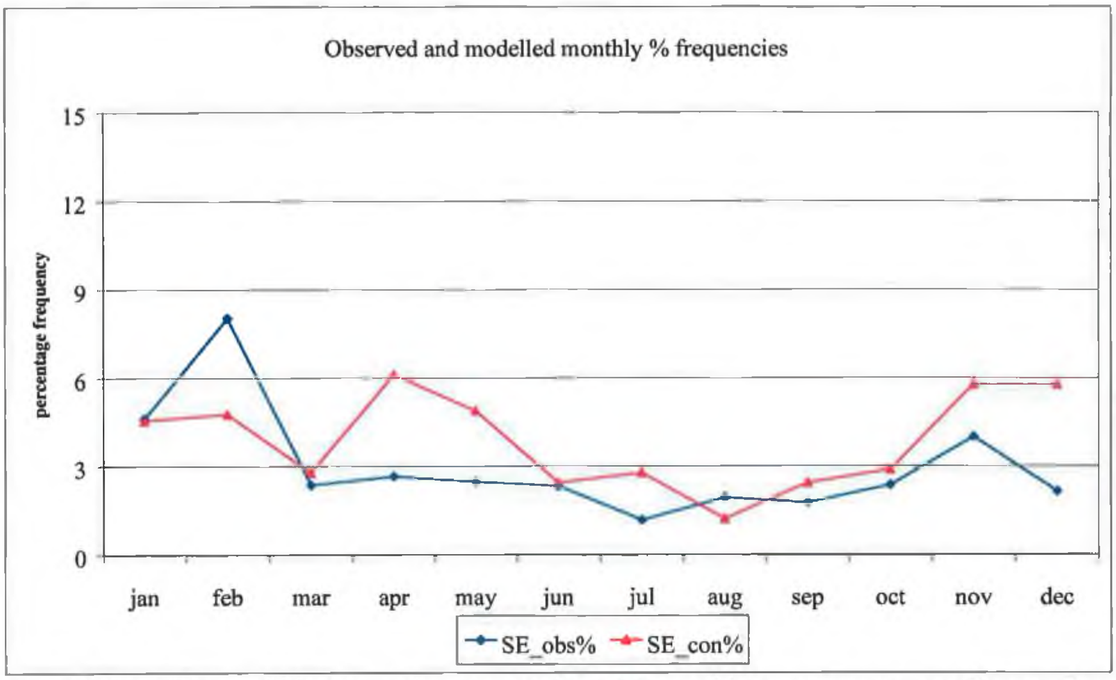


Figure 6.11 1961 – 1990 observed and control/model monthly mean percentage frequencies of southeasterly circulation.

6.6 Conclusion

The classification of circulation patterns and their application to GCM output has been applied by many authors. This can be a form of validating the GCM but also as a means of downscaling from large-scale predictors, such as atmospheric circulation, to local scale predictands such as temperature and precipitation. The weather type approach to downscaling applied here can only represent links that have been observed in the past and relies on the assumption that these links will prevail in a future changed climate. From a comparison of the observed and modelled circulation type frequencies in the 1961-1990 period, a number of consistent results are highlighted. For the ten major circulation types, the model replicates to a certain degree the annual and seasonal cycle although there are some months for certain CTs where there is a greater level of over- or underestimation. In the cases where there are large discrepancies this is generally because the model has overestimated the CT frequency. An application of the Mann-Whitney U-test/Wilcoxon rank sum test has outlined that there are some statistical differences between the observed and control run of the GCM, in particular the underestimation of AW and SW types in all seasons and annually. As noted by Conway and Jones (1998), applying Lamb Weather Types and other classification schemes to GCMs for control run integrations highlights the fact that the frequency of weather types differ from observed. The authors also assert that the relationships in the GCM between the weather types and surface weather differ from those evident in reality. While this may be considered as a flaw in the method, it is still an acceptable approach for the validation of GCM output and is expected to improve as higher resolution GCMs become available (Conway and Jones, 1998). Unfortunately, any inadequacies in the GCM cannot be accounted for by downscaling. Chapter 7 will examine the future changes in weather type frequencies for the period 2041 – 2070. Changes in surface climate variables as a result of frequency changes in the main circulation types will also be modelled.

Chapter 7

Future changes in circulation type frequencies and modelled climate changes for Ireland, 2041-2070.

7.1 Introduction

Future climate scenarios, as required for impact studies, are often constructed from GCM results. Ideally, according to Hulme *et al.* (1993), the GCM should be able to provide a realistic and internally consistent simulation of weather and climate patterns at the local scale. The control run of the GCM (the simulation of the 1961-1990 period) is validated against the observed 1961-1990 period to reveal the extent to which the model can capture the most relevant features of the present day climate. This provides evidence of the validity of the GCM and also determines if there is any inherent bias. Often the bias within the GCM itself is too great, and the spatial resolution too coarse, that some from of downscaling from the GCM to the local or regional level is required. The previous chapter has provided a validation of the HadCM3 model for this purpose. Some of the key findings include a seasonal and annual underestimation of anticyclonic-hybrid, westerly and southwesterly circulation types, with an overestimation of cyclonic-hybrid and southeasterly types. According to the IPCC,

> 'A good simulation of present day climate, however, is neither a necessary nor a sufficient condition for accurate simulation of climate change. It is possible, for example, that a model with a poor simulation of present day climate could provide a more accurate simulation of climate change than one which has a good simulation of present climate, if it contains a better representation of the dominant feedback processes that will be initiated by radiative forcing'
>
> (IPCC, 2001: 760).

Acknowledging the existence of the errors in the GCM, the remainder of this chapter will outline future changes in circulation type frequencies along with future seasonal rainfall scenarios dependent on the CTs.

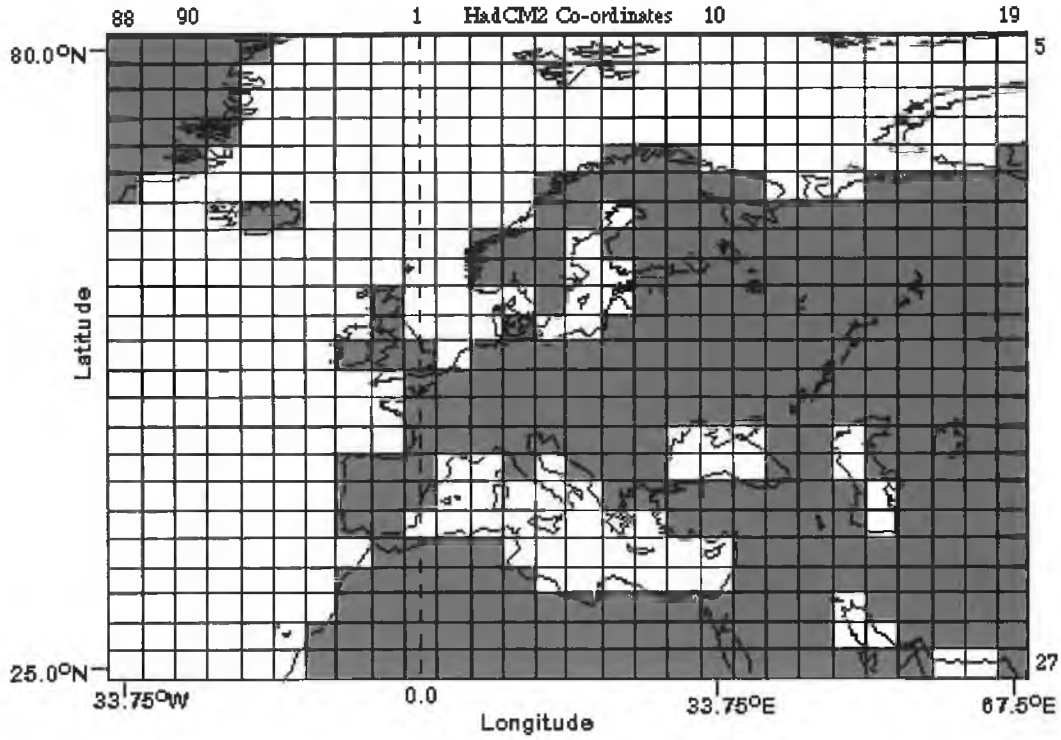


Figure 7.1 HadCM2 and HadCM3 GCM gridded resolution of 2.5° latitude by 3.75° longitude. [Source: CRU Link project. www.cru.uea.ac.uk/link.]

The HadCM3 global climate model provides climate change scenarios on a global scale for a number of variables for different time periods in the future. However, the resolution of the model is coarse, between 250 and 300 km for the grid boxes over the UK and Ireland, with only one grid box for the whole of Ireland (see Figure 7.1). At this resolution, the B2 scenario of the GCM for the 2050s projects an increase in temperature in both summer and winter and an increase in precipitation in winter with decreases in summer. At the smaller RCM grid resolution ($50km^2$), the United Kingdom Climate Impacts Programme (UKCIP) indicates increases of up to 1°C in winter and almost 2°C in summer for Ireland using the B2 scenario in the 2050s. Precipitation increases are greater in the east in winter (up to 10%) while decreases of up to 30% in the south and east in summer are also identified (Hulme *et al.*, 2002). The UKCIP report (Hulme *et al.*, 2002) also outlines results from a variety of global climate models on mean changes in winter and summer temperature and precipitation for the 2080s for the

SRES A2 scenarios. While the magnitude and spatial pattern of warming and wetting varies between models, there is still a clear consensus on warming in both summer and winter, and wetting in winter. There is less agreement for summer rainfall with some models (CCCma (Canada) and CSIRO (Australia)) indicating slightly wetter summers in the north and drying in the south. This comparison of models serves to point out that current state of knowledge and modelling capability ensures that all models are telling a similar story (Hulme *et al.*, 2002). However, for analyses on impacts in Ireland, for example on agriculture and water resources which are so clearly dependent on precipitation, these coarse scale projections need to be further refined to the smaller, local scale.

Goodess (2000a) outlined that systematic errors exist in a number of GCMs and these can be traced through to the downscaled series. Although the GCM performance is considered accurate when developing statistical downscaling methodologies, as asserted by Palutikof *et al.* (2002), it is the control run of the GCM rather than the observed series which is used as a baseline. This is built on the assumption that errors are consistent throughout the GCM run. More confidence is placed on the ability of the GCM to describe climate change than the ability of the GCM to model the climate at a particular time. That is to say, the GCM may be considered reliable for addressing the response of the climate to changing CO_2 emissions, but may not be able to reproduce the features of present day climate (Rummukainen, 1997). Some authors consider aspects of the HadCM3 models representation of the observed European climate to be not as good as they expect. For example, storm tracks over northwest Europe are displaced too far south which results in a strengthening of the winter winds over the south of England (Hulme *et al.*, 2002). This may be seen in an overestimation of cyclonic and cyclonic-hybrid CTs for the baseline period in Ireland, in most seasons and annually. Similarly, Barthelmie *et al.* (2003) found that the HadCM3 model appears to underestimate winter wind speeds in the future over the Baltic basin, indicating a potential bias in the model.

As the GCM is not able to reproduce the present climate accurately, the projections of future climate from the model cannot be used directly. The IPCC (2001) outline a number of ways in which changes in climate can be calculated from model results and applied to baseline data. The modelled climate for the future is compared to the control period of the same model, with the differences then applied to the observed baseline climate. The changes in climate can be either ratios or percentages, on a daily, monthly or seasonal timescale. For temperature the change is usually expressed as the difference between periods, while for precipitation and other variables the change is expressed as ratios or percentages. Each of these periods must be of the same length of record, usually a 30-year period. In this case, the changes in the 2041-2070 future climate are calculated as the changes in 30-year mean climate with respect to the observed climate of 1961-1990. It is acknowledged that

> '...while discrete 30-year periods are a convenient way to show the changes in map form, in reality climate will be continuously changing from year-to-year, both as a result of natural variability but also because of the underlying long-term trends in climate brought about by human influences on the climate system.'
>
> (Hulme *et al.*, 2002: 39).

7.2 Circulation type frequency changes: 1961-1990 control – 2041-2070 model

The difference between the circulation type frequencies of the 1961-1990 baseline and 2041-2070 future run of the HadCM3B2 model scenario are outlined below. These differences can then be applied to the observational baseline data to provide a climate change scenario for the future. The Mann-Whitney/Wilcoxon signed ranks test shows that the actual differences between the two series are not statistically different, with the exception of AE in spring, AW and CSW in autumn. Each of these differences is significant at the 95% level (see Table 7.1). The percentage differences between the control and future CT frequency are shown in Table 7.2. The main variation occurs for easterly and hybrid-easterly types (e.g. AE, CNE). For the larger inconsistencies (greater than 50%) the CTs represent increases in occurrence of airflow from an easterly direction in all seasons except spring. In this season, it is anticyclonic northwesterly and anticyclonic westerly which increase more than 50%. The greatest annual percentage increase is for easterly circulation (+37%) while the smallest annual change is for the westerly type (-1%). In all seasons and annually, there is an increase in easterlies and southwesterlies. It appears that future changes in circulation types will be quite small for the majority of the directional types, with the exception of increases in easterlies in autumn and winter and the decline in northeasterlies in autumn. Figures 7.2 to 7.5 display the seasonal percentage differences between the control and model frequencies.

	spring	summer	autumn	winter	annual
A	-22	+9	+25	-22	-10
AE	-3*	+8	0	+11	+16
AN	-8	+6	+7	+1	+6
ANE	-14	+4	-3	+12	-1
ANW	+14	-2	+10	-7	+15
AS	+9	-17	+4	-6	-10
ASE	-19	+16	+11	-1	+7
ASW	-4	+9	-14	-23	-32
AW	+15	+13	+9*	-8	+29
C	-19	-26	+12	+10	-23
CE	-6	-8	-2	+8	-8
CN	+3	+8	+14	0	-3
CNE	-14	+3	0	-3	-14
CNW	+5	-22	+13	-3	-7
CS	-9	-10	+4	-8	-23
CSE	-5	-8	+7	+8	+2
CSW	+15	-5	-30*	-3	-23
CW	+5	-25	+4	-27	-43
E	+7	+2	+22	+37	+68
N	-45	+36	-6	-7	-22
NE	-6	+17	-27	-1	-17
NW	+24	+10	-1	-12	+21
S	+28	-32	-13	-27	-44
SE	+19	-5	-7	+16	+23
SW	+31	+6	+39	+17	+93
U	-22	+6	+9	+14	+7
W	+21	+7	-59	+24	-7

Table 7.1 Actual differences between 1961-1990 control and 2041-2070 model circulation type frequencies. Significant differences are identified using the Mann-Whitney U test.

* Indicates statistical significance at the 95% level

	spring	summer	autumn	winter	annual
A	-8.6	4.3	9.9	-10.8	-1.08
AE	-8.3	**114.3**	0.0	**78.6**	21.05
AN	-17.4	14.3	25.0	3.1	4.05
ANE	-28.0	15.4	-17.6	**150.0**	-0.99
ANW	**63.6**	-4.0	34.5	-20.6	11.11
AS	25.0	-42.5	6.1	-8.3	-4.67
ASE	-30.2	**200.0**	39.3	-2.3	4.90
ASW	-10.5	27.3	-22.6	-45.1	-17.39
AW	**62.5**	43.3	23.1	-23.5	22.83
C	-7.6	-9.4	5.4	4.5	-2.36
CE	-35.3	-40.0	-18.2	**88.9**	-14.04
CN	9.7	13.3	-33.3	0.0	-1.81
CNE	**-50.0**	10.3	0.0	-30.0	-17.50
CNW	12.8	-27.5	32.5	-6.4	-3.40
CS	-12.7	-25.0	7.7	-12.9	-10.22
CSE	-16.1	-42.1	**53.8**	30.8	2.25
CSW	30.0	-8.6	-39.5	-3.9	-8.85
CW	11.4	-35.2	7.3	-40.3	-18.14
E	8.9	4.3	**73.3**	**123.3**	36.76
N	-17.6	14.4	-4.2	-4.1	-2.69
NE	-4.8	20.0	-40.9	-2.5	-5.40
NW	14.6	3.4	-0.4	-5.2	2.25
S	8.9	-16.8	-3.4	-6.0	-3.29
SE	15.3	-8.6	-7.0	11.8	5.50
SW	13.3	2.4	12.3	4.9	8.13
U	-20.4	3.0	13.6	37.8	1.71
W	12.5	3.0	-21.0	11.3	-0.78

Table 7.2 Seasonal percentage differences between 1961-1990 control and 2041-2070 model circulation type frequencies.
Bold indicates differences greater than 50%.

7.3 Modelling precipitation change

To determine the change in rainfall in a future modelled climate by means of circulation type frequencies, the percentage difference between the control and modelled frequencies are added onto the observed baseline CT frequencies. The seasonal mean precipitation is calculated for each CT and station and weighted by its frequency of occurrence to yield total precipitation. By calculating the mean seasonal rainfall within the baseline period for each CT and at each station, this method can then be applied to the future modelled CT frequency.

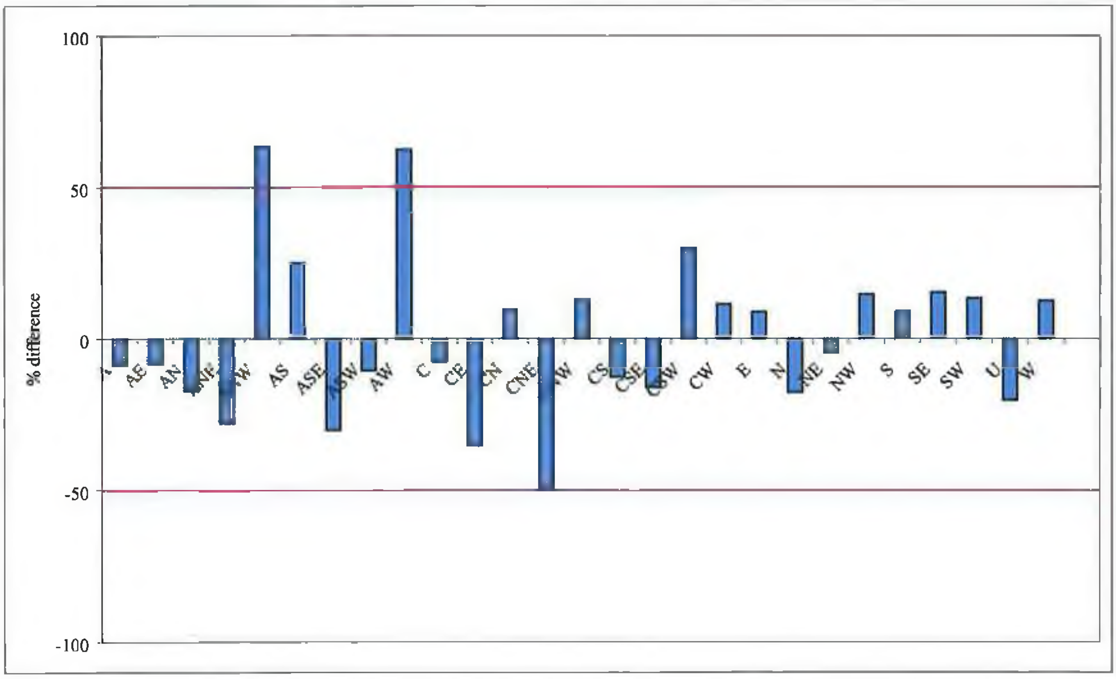


Figure 7.2 Percentage difference between 1961-1990 control and 2041-2070 model circulation type frequencies for spring

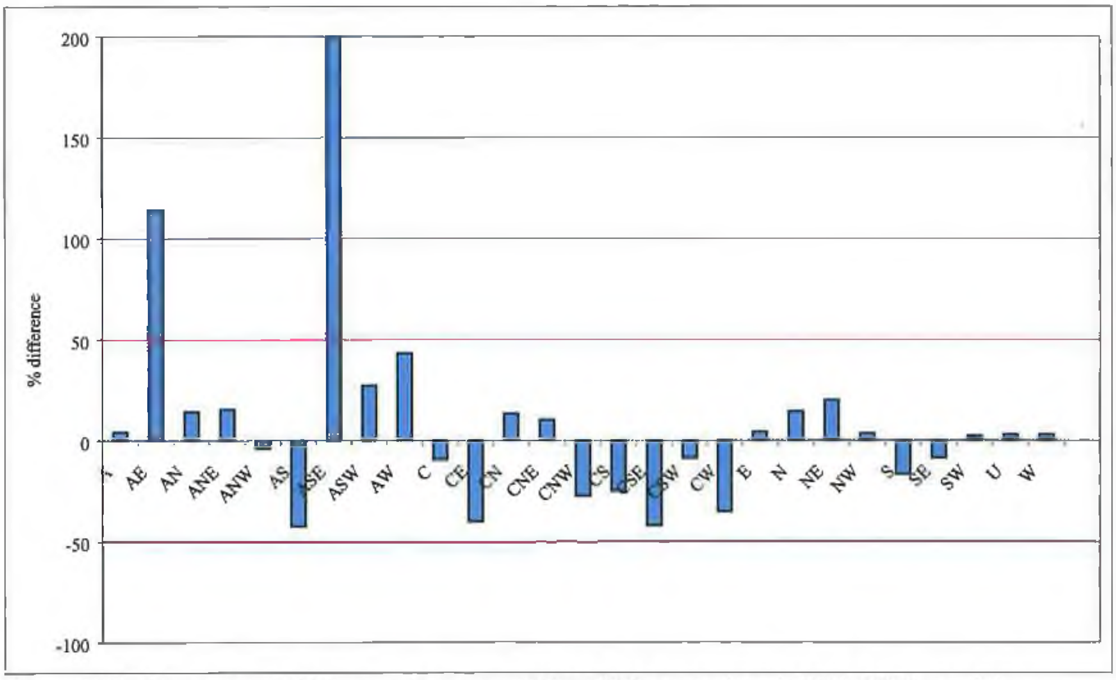


Figure 7.3 Percentage difference between 1961-1990 control and 2041-2070 model circulation type frequencies for summer

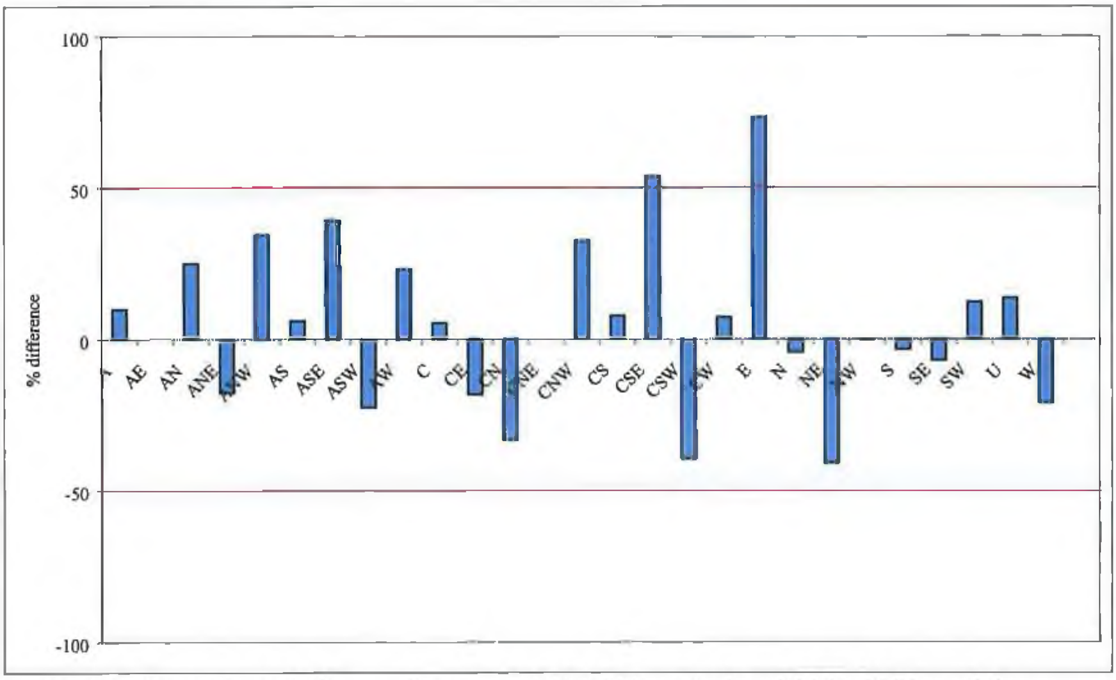


Figure 7.4 Percentage difference between 1961-1990 control and 2041-2070 model circulation type frequencies for autumn.

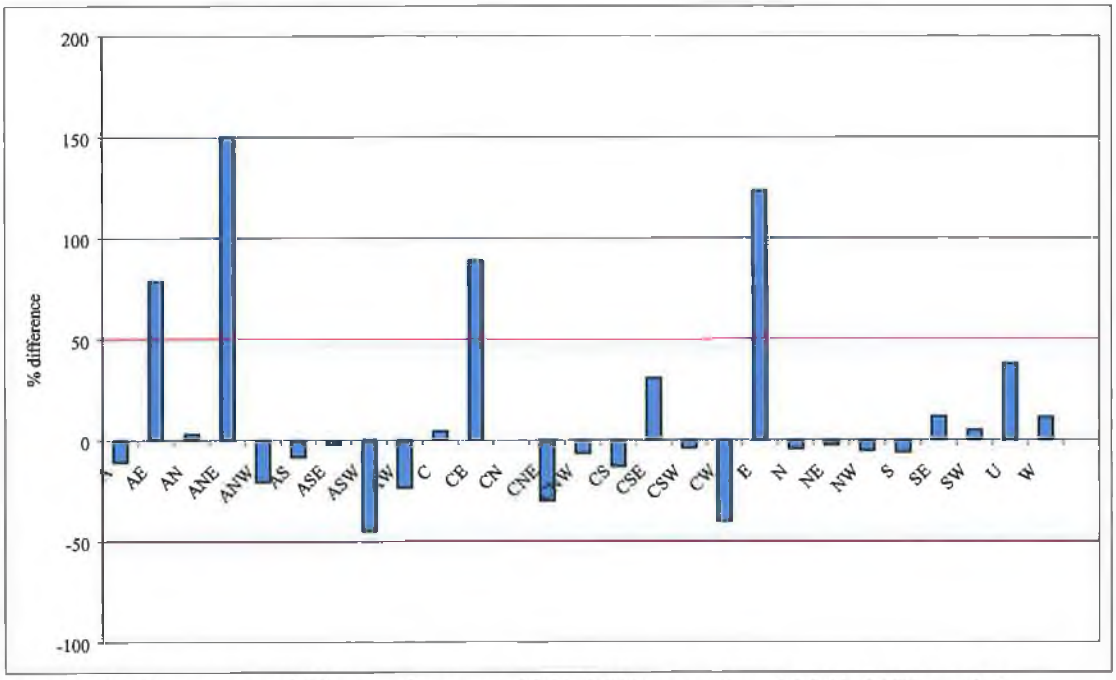


Figure 7.5 Percentage difference between 1961-1990 control and 2041-2070 model circulation type frequencies for winter.

7.3.1 The role of specific humidity

The majority of statistical downscaling models have included only the large-scale atmospheric circulation. However, it has been acknowledged that the inclusion of humidity in statistical downscaling models of precipitation is imperative for scenarios of future climate with an enhanced greenhouse effect (Crane and Hewitson, 1998; Murphy, 1999, 2000; Hellstrom *et al.*, 2001). Wilby and Wigley (1997) recognise that circulation changes may not be enough to derive realistic precipitation changes (1997). Murphy (1999; 2000) compared an RCM over Europe with a regression based statistical downscaling model. Each of the techniques produced significantly different predictions of climate change. The two main reasons for a disparity between projections, outlined by Murphy are: differences between the strength of the simulated predictor/predictand relationships, and omission from the regression equations of variables which represent climate change feedbacks, but which are weak predictors of natural variability. In particular, the exclusion of specific humidity is highlighted as a basis for the difference between the dynamical and statistical predictions of precipitation change (IPCC, 2001). Specific humidity is a measure of the mass of water vapour contained in a given mass of air. Because warm air can contain more moisture than cold air, changing temperature as well as atmospheric circulation will have an effect on precipitation. However, Beckmann and Buishand (2001) found that the correlation between precipitation and atmospheric moisture is generally stronger than that between precipitation and temperature (2001). Obviously, it will also be necessary for the GCM to simulate accurately specific humidity, as well as the CWTs.

In line with the methodology for use of GCM circulation types and the intrinsic GCM bias, the difference between the specific humidity means for each circulation type from the 1961-1990 control and 2041-2070 model are added onto the 1961-1990 observed means to determine the future specific humidity. The specific humidity is represented by the values from the HadCM3 model at the grid box centred on 52.5°N, 7.5°W. Specific humidity increases in the future in all seasons and scenarios (Hulme *et al.*, 2002). To take account of this increased specific humidity, and projected increase in mean rainfall, the 2041-2070 mean rainfall yield for each station, season and circulation type is calculated from the linear relationship between specific humidity and rainfall for the season and CT at each station in the baseline period, and then computed using specific humidity values for the future. That is,

$$\text{Precipitation}_{2041\text{-}2070} = m\,(\text{shum}_{2041\text{-}2070}) + c$$

where m and c are the slope and constant derived from the precipitation and specific humidity relationship in the 1961-1990 period. In the next sections, seasonal precipitation scenarios are outlined for Ireland based on this method.

7.4 Seasonal precipitation scenarios

7.4.1 Spring

Spring precipitation increases over the whole country for the period 2041-2070, with a southeast - northwest gradient (see Figure 7.6). The increased precipitation occurs when the frequency of southwesterly, westerly, northwesterly types along with cyclonic and anticyclonic hybrids of these circulation types increase. For the stations of Malin Head, Belmullet and Shannon on the north and west, where there are large percentage increases in total precipitation yield, this can also be accounted for by the fact that the largest 2041-2070 mean rainfalls occur on SW, W, CSW and CW days at these stations. Surprisingly however, the mean precipitation difference between 1961-1990 and 2041-2070 at nearly all stations on AW, W and CSW days has decreased, but the overall precipitation increase is made up by the large increases in frequency of these types.

7.4.2 Summer

A reduction in summer rainfall is predicted, with rainfall decreasing westwards as can be seen in Figure 7.7. Reductions are only of about 1-2% on the east coast and midlands. This is primarily due to a decline in the frequency of cyclonic circulation types but also the cyclonic-hybrid categories and southerly and anticyclonic-southerly types. A greater decrease in precipitation is observed at

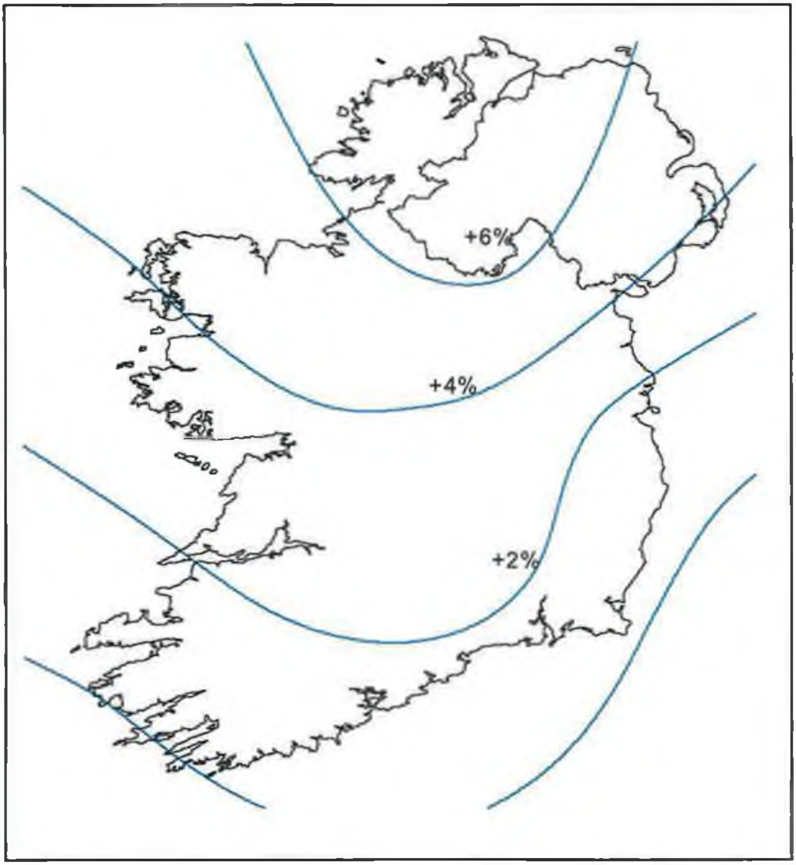


Figure 7.6 Spring precipitation change, 2041-2070

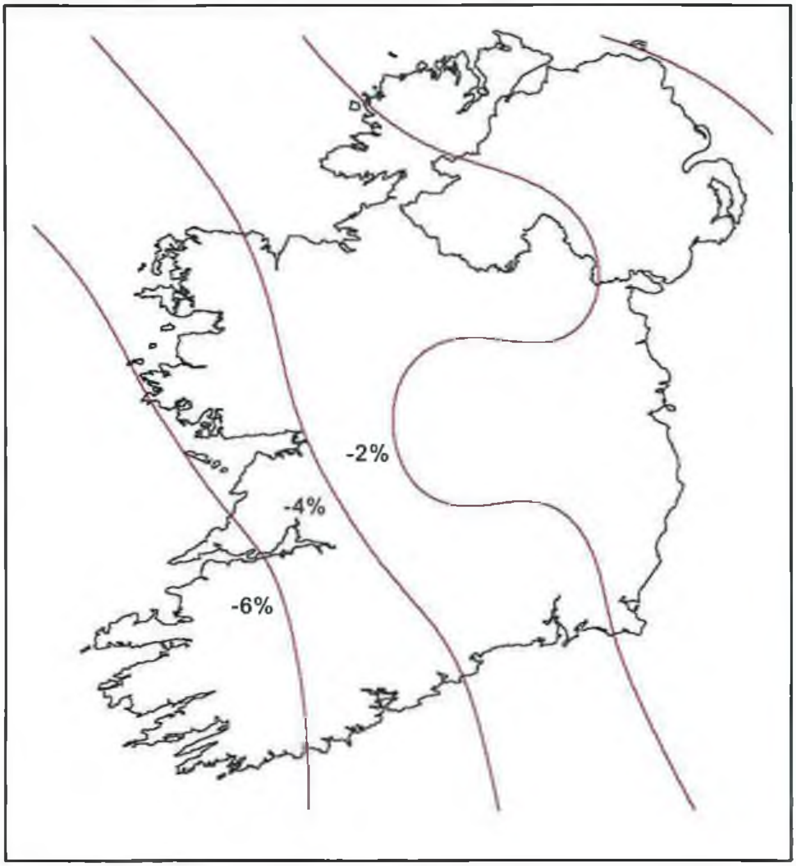


Figure 7.7 Summer precipitation change, 2041-2070

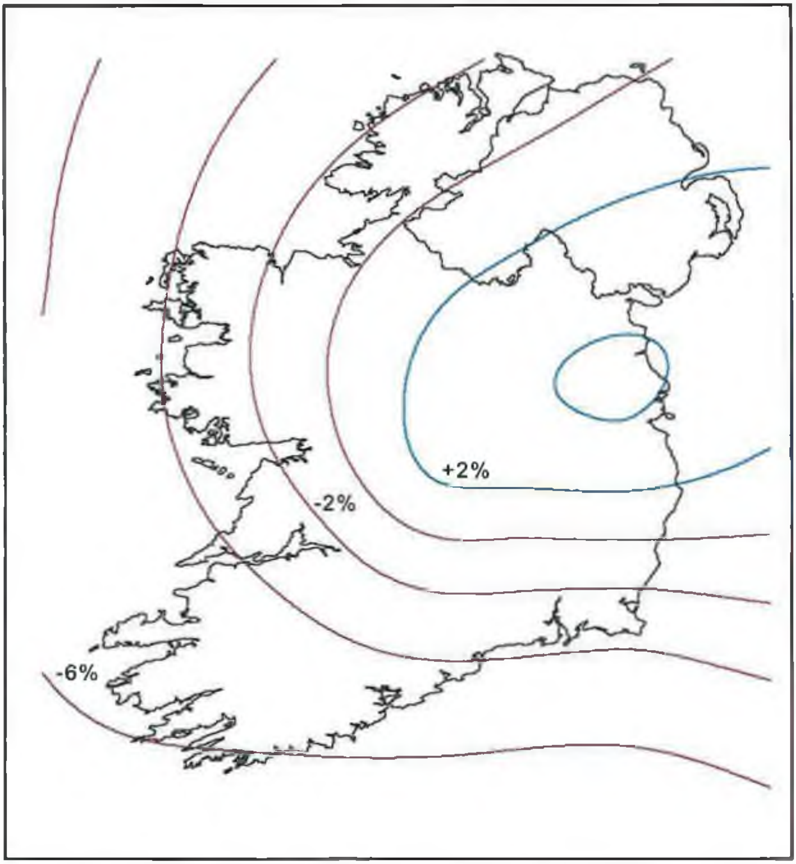


Figure 7.8 Autumn precipitation change, 2041-2070

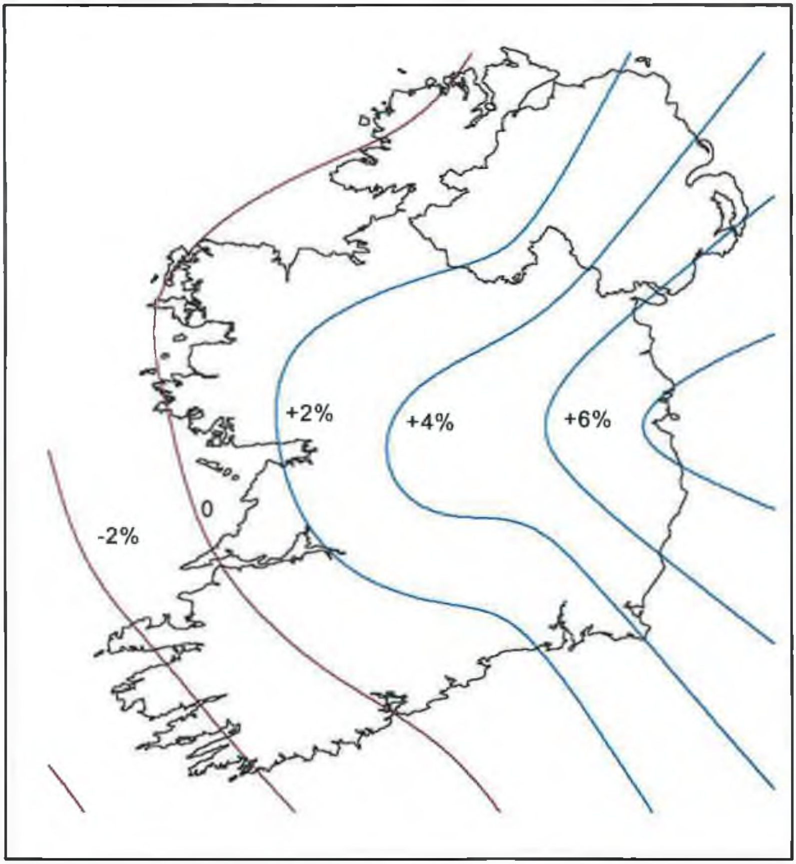


Figure 7.9 Winter precipitation change, 2041-2070

Valentia, due to the decline in southerly circulation, and the fact that this is the second largest mean daily rainfall category (after CS), with a mean daily rainfall of 6.76mm (9.46mm - CS) in the 2041-2070 period. C, CS and CW circulation types also contribute towards large decreases in seasonal rainfall at Valentia in summer. The spatial pattern for summer rainfall - an east-west gradient - is dissimilar to the UKCIP scenario for summer. The authors of UKCIP02 reveal a decrease in summer rainfall, but with greatest reduction in the southeast and least reduction in the northwest.

7.4.3 Autumn

Precipitation increases in autumn in the north and east of Ireland, with decreases in the south and west. These range from +4% at Casement on the east coast to -6% at Valentia in the southwest (see Figure 7.8). The decrease in westerly, cyclonic southwesterly and anticyclonic southwesterly ensures that rainfall on the west and southwest coast decreases substantially. The decrease in mean rainfall on northwesterly days at Valentia also ensures a significant decrease in precipitation, even though the frequency of this circulation type changes very little (-0.4%). The increase in frequency of easterly and cyclonic southeasterly circulation patterns ensures an increase on the east coast, particularly when the highest mean rainfall for east coast stations fall primarily on cyclonic and cyclonic south-easterly days.

7.4.4 Winter

Winter precipitation displays an east-west pattern, with greater increases on the east of the country and little change and even decreasing precipitation on the west coast (as shown in Figure 7.9). There is a 2% decrease in rainfall at Valentia on the southwest coast, with increases of over 7% at Casement Aerodrome. The decreasing rainfall at Valentia is due primarily to a decrease in the frequency of southerly, anticyclonic-southwesterly, northwesterly, cyclonic-westerly and cyclonic-southerly CTs. Of these, rainfall means within the CTs also decrease (with the exception of southerly). At Malin Head, where there is only a 0.4% increase in rainfall, the slight increase in yield is due to an increase in frequency of westerly, southwesterly and cyclonic circulation types. There is a smaller decrease in yield due to the decrease in northwesterly and cyclonic-westerly circulation. For the east coast stations of Casement (+7%) and Rosslare (+4%), the large increases in winter rainfall can be attributed to the large increase in occurrence of easterly circulation, as well as cyclonic, southeasterly and cyclonic-southeasterly CTs. The estimated increase in mean winter rainfall for these stations is comparable with that in the simulated rainfall of the HadCM3 model. This spatial pattern is consistent with the most recent UK Climate Impacts Programme (Hulme *et al*., 2002) scenarios for the United Kingdom. Analogous to Ireland, it revealed that the largest percentage changes in precipitation in winter are experienced in eastern and southern parts of the country (2002).

7.5 Conclusion

The HadCM3 B2 scenario has been validated and utilised to provide climate change scenarios based on a weather type downscaling methodology. While there are errors in the GCM, the performance of the GCM for model development is considered appropriate when the difference between model-baseline and model-future is applied to observed data. Errors consistent throughout the GCM are therefore incorporated. Only scenarios for future precipitation, and not temperature, are presented in this work. Plausible precipitation scenarios can be derived, as both changes in circulation type frequency and changes in the moisture content of the atmosphere are taken into account. For example, spring precipitation increases on the north and west coast of Ireland are primarily a consequence of an increasing occurrence frequency of SW, W and NW types, but also an increase in total precipitation yield on these days. However, the temperature scenarios do not take into account within-type circulation variability. They are based solely on changes in frequency of CTs. Temperatures on easterly days are generally less than those on other CT days in winter and autumn. Thus, a large increase in easterlies at the expense of other 'warmer' types (S, NW in winter; W, N in autumn) would mean a greater reduction in temperature. For the temperature scenarios constructed for Ireland (but not included), temperature changes in all seasons are within ± 0.5°C. With the exception of spring, these temperatures are all decreasing. This is inconsistent with all predictions of temperature change for the mid-latitudes, from both GCMs and downscaling studies. Obviously temperature scenarios in Ireland need further analysis. Perhaps the inclusion of additional predictands, such as sea surface temperatures, may improve the temperature model.

In terms of the precipitation scenarios presented, the changes identified are primarily as a result of changing circulation type frequencies, but in some cases changes within the activity of weather classes also. This is a similar to a finding by Widmann and Schär (1997), who revealed that seasonal precipitation changes are not solely due to changes in the frequency of circulation types. Within the rain producing types there was also a tendency to wetter conditions. The spatial pattern is reasonably well reproduced for precipitation in winter, with increases in precipitation in the east and south comparable with the UKCIP scenarios. As observed by Saunders and Byrne, winter is the time when most precipitation occurs so this is encouraging (Saunders and Byrne, 1996).

Chapter 8

Conclusions and further recommendations

8.1 Introduction

This thesis set out to determine if climate change in Ireland is occurring, and if so, what are the possible driving forces of this change. In order to place Ireland's climate in the global context, the spatial and temporal characteristics of temperature and precipitation, on a variety of time-scales from annual to daily, were examined. An automated, daily, objective atmospheric circulation classification scheme was subsequently developed. The atmospheric circulation mechanisms steering Irish climate change were identified using this scheme, which is derived for Ireland based on indices of airflow.

The thesis was also concerned with the prediction of future climate change, based on the relationships between circulation types and surface climate variables observed in the present. A major advantage of the methodology developed, is its ability to be applied and transferred to Global Climate Model output in different time periods, as opposed to other circulation classification techniques. Ensuing from the derived relationships in the present, seasonal climate scenarios for the future were generated.

8.2 Main Research Findings

A detailed spatial and temporal analysis of the Irish meteorological record provides evidence that Irish climate is changing, in line with global trends. Irish temperature records are comparable with the global record, with increases of 0.5°C over the course of the 20th century. Similarly, precipitation records reveal increases in the north and west of the country and decreases in the south, which appear to confirm global climate model predictions for the mid-latitudes. There are other notable changes in Irish climate, including a decrease in frequency of frost and cold days, and an increase in rain and wet days in certain periods of the year.

An objective, daily, automated atmospheric circulation classification system has been developed. This provides a means of deriving frequencies of circulation types for Ireland, and subsequently, determining relationships between circulation types and surface climate variables. Changes identified in the observed climate record in the present can be related to changes in circulation types. For example, an increase in frequency of southwesterly and westerly circulation type days in winter, coupled with increasing temperatures on these days produces a seasonal increase in winter temperatures. An increase in maximum temperatures on westerly days also ensures maximum temperatures increase at a greater rate than minimum temperatures in this season. Similarly, increased precipitation in the west of Ireland, in the 1961-1990 winter period, may be related to an increase in frequency of westerly, southwesterly and cyclonic- and anticyclonic-southwesterly days. An increase in rainfall yield on southwesterly days at Valentia and Belmullet enhances this increased rainfall.

Likewise in spring, the most persistent circulation types are anticyclonic, westerly and southwesterly. On anticyclonic and westerly days, both maximum and minimum temperatures increase, which, when combined with an increase in frequency of W and A types, corresponds to increasing temperatures. Southwesterly days reveal no change in occurrence frequency, although a decrease in maximum temperatures and little or no change in minimum temperatures are evident on SW days. It may be this CT predominantly, in conjunction with the others, which provides the explanation for the greater increase in minimum temperatures in the observed spring record rather than maxima. It is apparent therefore, that circulation patterns are strongly linked to observed changes in temperature and precipitation.

It is clear that particular circulation types play a major role in steering Irish climate, and some, such as westerlies and southwesterlies are more important than others in deriving Irish weather patterns. The North Atlantic Oscillation Index, an important mechanism in North Atlantic and North and West European climate variability, is characterised by W and SW winds, and may hold the key to explaining major changes in Irish climate. The NAO accounts for a large proportion of variance in European temperature and precipitation, and this is also found to be true for Ireland. The index is highly correlated with the frequency of W and SW circulation types in winter and spring in Ireland. By determining the relationships between circulation weather types and local surface climate variables in the present, this provides the key to future climate change prediction and scenario construction for impact analyses.

The weather type approach to downscaling, from Global Climate Model output, is one method of predicting future climate change. A verification of the GCM, in the baseline period, revealed a number of over- and under-estimations by the HadCM3 model. However, even though CTs are not simulated accurately in the present does not mean that the model cannot correctly predict CTs for the future. An accurate simulation of the present climate does not ensure an accurate prediction of future climate change, nor does a poor simulation of present climate mean that there will be a poor simulation of the future. Inherent in using any GCM is that there are uncertainties.

Future changes in circulation types highlight only small changes in the majority of directional types, with larger percentage changes in cyclonic- and anticyclonic-hybrid types. Large increases in easterly-type circulation, coupled with large increases in anticyclonic-northeasterlies and cyclonic-easterlies in winter, appear to detect a shift in the dominant phase of the North Atlantic Oscillation. The future scenario for winter climate may be a move away from the mild, wet winters of recent years, to somewhat colder, drier winters. This would be associated with a shift from a positive phase of the NAO to a negative phase of the NAO. The scenarios presented in Chapter 7 reveal this trend, with increased winter rainfall in the east of the country, associated with CE days, but decreased rainfall on the west coast. In producing this scenario, it is assumed that natural forces alone produce changes in climate, with human-induced changes in greenhouse warming not taken into account. Within-type variability in CTs needs to be factored into scenario development for the future, as changes in source regions of air-masses, and the path over which they develop may be influenced by anthropogenic activities. The incorporation of additional variables may minimise the problem that CTs are not the only forcing factor for changes in temperature and precipitation. Sea surface temperature data may be one variable which could be used to supplement the data.

A reversal in the NAO Index would not be uncommon, and would merely accentuate the cyclical nature of this coupled atmosphere/ocean phenomenon. There have been other shifts in the past, with a predominantly positive phase from the beginning of the century to about 1930, a downward trend from the 1940s to the 1970s and a strongly positive phase in the last 30 years. This shift in phases of the NAO also corroborates the trend in long-term temperature identified in Chapter 2. The cycles in the NAO will, in the short-term, influence local climate, but this must be placed in the longer-term context of an anthropogenic influence upon climate variation. However it is more difficult to single out an anthropogenic warming signal, in a system of natural noise which is always changing on different time scales.

8.3 Further Developments and Recommendations

A number of issues were raised while completing this research. The following section will focus on some of these, including ways in which the methodology could be further refined and providing recommendations for the future.

The issue of GCM reliability is inherent in all downscaling methodologies and studies based on climate model output. This is due to the uncertainties throughout the model, from the initial representation of the model to the effects of emissions and their impact on climatic elements. Climate modellers are faced with the difficulty of understanding how the climate system works and how best to model it. Ideally, due to differences in model development and physics, a range of GCMs would be utilised to provide a more consistent comparison, both for observed and future climates. The application of alternative climate models, such as ECHAM4/OPYC3 or CCCma1 may also be beneficial in providing future climate scenarios.

A possible drawback of the method outlined here is the use of only one SRES scenario (B2). This would be considered inadequate were this a detailed study on future climate change. Additional scenarios (such as A2 and B1) should be used in future research, particularly if there are to be policy implications derived from them.

A further limitation was that of data availability and reliability. While climate records in Ireland are updated regularly and are well maintained and homogenised, it is important to stress the value of this network. Further analysis of a broader suite of climatic variables could have been considered if more complete records were available. As regards large-scale data, the recent availability of ECMWF ERA-40 data offers the possibility of comparison with NCEP Reanalysis data, and may provide a better representation of mean sea level pressure patterns for Europe and Ireland.

8.4 Final Conclusions

The analysis of circulation weather types has provided a useful approach to detect changes in Irish climate. The circulation patterns developed are well related to temperature and precipitation characteristics, and their changing frequencies have played a major role in steering Irish climate. This thesis has revealed several important relationships between surface climate and large-scale circulation patterns. It is of paramount importance to understand these changes before attempting to predict what will happen in the future. Clearly the NAO is the key source of Irish climate variability. Variations in the NAO Index are important to human activity, with the NAO having a direct impact on a number of sectors, including agriculture, water availability and energy. This raises the question: are the changes in surface climate the result of change in the natural mode of the NAO, or are anthropogenically-induced changes responsible for certain modes of the NAO being dominant? Future climate change will be manifest in natural climate oscillations, as evident in this research, but must also be taken together, and in collaboration, with anthropogenic influences.

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Appendix A

Daily automated atmospheric circulation catalogue for Ireland,

1961-1990

1961	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	W	W	SW	W	CSW	N	U	AN	S	CW	SW	CNW
2	CW	CW	W	E	W	ANW	AN	ANW	CN	S	NW	NW
3	CN	NW	SW	SE	W	AW	NW	SW	N	SW	N	SE
4	N	W	SW	C	CSW	SW	N	W	U	SE	A	C
5	W	SW	SW	C	W	SW	AN	W	N	S	SW	NW
6	NW	W	SW	E	SW	W	ANW	W	NW	C	W	NW
7	SW	W	SW	AE	W	W	AW	SW	NW	CNW	SW	S
8	W	SW	SW	S	AW	NW	NW	CNW	AS	SW	W	S
9	CS	W	SW	CS	A	W	NW	W	S	SW	NW	SW
10	CNE	SW	W	C	ASW	C	U	N	SW	SW	CNW	SW
11	ASW	W	SW	SW	ASW	NW	CS	N	W	SW	NE	SW
12	SW	SW	W	SW	S	C	C	SW	SW	AS	ANE	SW
13	U	S	W	CSW	CS	AN	NW	NW	SW	AS	NE	SW
14	A	SW	SW	NW	W	SW	CNW	NW	SW	AS	ANE	S
15	AS	AS	SW	ASW	U	SW	N	NW	SW	AW	ANE	S
16	SE	S	SW	SW	SE	SW	NW	NW	CSW	NW	AE	S
17	S	S	ANW	A	E	W	U	ANW	ASW	NW	ASE	S
18	S	SW	AN	S	AE	ANW	NE	NW	A	N	SE	S
19	CSW	SW	A	CS	ANE	ANW	N	NW	CS	N	SE	ASE
20	SW	S	A	CSW	NE	A	U	W	A	N	E	ASE
21	CS	AS	A	CSW	AE	ASW	U	W	ASW	SW	SE	ASE
22	SE	S	A	C	ANE	NW	NE	NW	S	CSW	U	SE
23	S	S	A	C	A	AW	AN	W	SW	W	W	SE
24	S	S	AW	SW	A	AW	A	U	AW	SW	W	SE
25	CS	S	AW	C	NE	W	SW	SW	SW	SW	W	E
26	S	SW	A	CN	ANE	N	W	SW	SW	CSW	C	E
27	SW	SW	A	CS	A	ANW	NW	ASW	SW	C	NE	AE
28	SW	W	AW	CSE	W	ASW	N	S	CW	N	W	A
29	SW		W	SW	C	SW	A	SW	SW	ANW	W	E
30	W		NW	SW	E	S	U	A	CSW	AW	W	NE
31	W		AW		NE		ANW	AS		W		N

1962	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	N	NW	A	AW	SE	A	A	W	S	SW	SW	S
2	A	ANW	NE	SW	SE	A	ANW	W	SW	SW	C	S
3	A	W	NE	CNW	CS	AS	N	CW	S	ASW	C	S
4	A	W	NE	CW	S	AS	N	W	C	S	SW	S
5	SW	AW	A	NW	CS	AS	N	NW	CW	ASW	C	S
6	SW	SW	S	AW	SW	S	U	N	C	ASW	CSE	S
7	SW	CNW	S	W	SW	AS	SW	N	NW	S	C	S
8	SW	NW	C	NW	CSW	A	S	ASW	AW	S	U	SW
9	SW	AW	C	ANW	CSW	NW	SE	W	SW	CE	NE	NW
10	SW	ANW	C	W	CNW	AN	C	W	CSW	U	NE	NW
11	CW	AW	SE	AW	N	SW	C	W	C	SE	E	NW
12	CW	NW	E	A	ANE	SW	N	ANW	CN	ASE	U	N
13	NW	N	A	S	A	SW	SE	A	S	A	A	N
14	W	AN	S	S	ANW	SW	C	SE	S	A	NW	NW
15	SW	AW	CS	SE	AW	ASW	CN	CW	NW	A	N	NW
16	SW	NW	CS	NE	W	A	U	W	NW	A	CW	NW
17	CW	ANW	S	CNE	AW	S	S	NW	N	A	N	NW
18	W	A	SE	CNE	W	CSW	S	SW	A	A	N	NW
19	W	ASW	AE	C	N	W	SW	S	A	A	AN	AW
20	SW	AS	E	CSW	CS	W	SW	W	A	A	CSW	W
21	SW	AS	AE	W	CNW	SW	CW	W	A	AS	N	A
22	NW	SE	ANE	S	W	W	NW	W	A	ASE	W	S
23	SW	SE	NE	SW	A	SW	U	SW	ASW	ASW	SW	S
24	CSW	E	A	SW	A	NW	SE	W	S	SW	CNW	ASE
25	W	E	W	SW	ANE	ANW	NE	W	CS	CW	U	A
26	AW	E	NW	A	ANE	N	NE	W	NW	N	A	N
27	ASW	E	A	E	NE	AN	A	W	S	W	A	NE
28	A	NE	CS	E	ANE	NW	A	CW	CW	NW	A	NE
29	AS		C	SE	N	N	ASW	A	S	W	A	E
30	SW		A	SE	A	AN	W	A	SW	W	AS	E
31	W		ANW		A		W	A		NW		CE

1963	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	E	NE	S	W	AN	CE	C	NE	N	NW	C	CS
2	E	E	S	A	ANW	E	C	NE	N	NW	C	CE
3	NE	N	S	A	ANW	E	C	U	NW	W	CE	E
4	C	CS	SW	ANE	W	NE	C	CNW	CNW	NW	CE	E
5	CSE	CS	SW	NE	W	NE	C	N	N	NW	C	E
6	SE	CS	SW	E	W	CE	CN	ANW	ANW	W	C	E
7	SE	C	SW	E	SW	SE	N	W	W	W	CW	SE
8	SE	S	C	E	W	SE	ANW	NW	W	W	W	AS
9	SE	CSE	C	E	SW	E	NW	W	W	AW	S	A
10	SE	E	C	CNE	CNW	U	NW	CW	U	AW	CSE	S
11	SE	E	C	NW	W	U	CW	NW	A	ASW	C	CS
12	A	A	SW	W	SW	U	C	NW	A	SW	NW	CSE
13	A	S	CS	W	W	N	U	N	A	ANW	AW	SE
14	A	S	CSW	SW	W	U	SW	NW	A	SW	SW	AE
15	AN	CS	SW	CSW	ANW	AW	SW	W	A	SW	C	AE
16	C	CS	CSW	CS	W	W	NW	CN	SW	SW	NW	ASE
17	SE	SE	CSW	C	ANW	SW	W	N	U	SW	S	ASE
18	E	SE	NW	W	ANW	NW	W	NW	U	SW	CW	AE
19	SE	E	CS	SW	AW	SW	W	NW	S	SW	C	AE
20	CSE	AN	N	C	W	SW	A	NW	AS	SW	AW	ANE
21	SE	U	U	C	N	W	SW	W	A	SW	SW	A
22	SE	ASW	AS	SW	ANW	W	A	W	ASW	AS	W	ASW
23	AS	S	SW	CSW	SW	SW	CS	SW	S	SW	S	S
24	AS	S	W	U	CS	SW	NW	W	W	ASW	CSW	S
25	A	S	W	SW	SW	CW	NW	SW	W	AS	C	SW
26	A	S	W	SW	W	NW	A	W	W	S	NW	A
27	A	S	W	W	ANW	N	AS	NW	ANW	S	ASW	SW
28	A	S	W	W	A	N	AS	SW	AW	S	NW	SW
29	A		C	ANW	ANE	N	S	SW	NW	S	A	SW
30	NE		CN	W	NE	CN	S	CSW	ANW	CS	S	SW
31	NE		SW		C		U	C		C		W

1964	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	S	W	S	E	AW	E	AN	NW	SE	AE	SE	N
2	S	SW	S	NE	SW	NE	ANW	NW	S	A	AE	NW
3	S	W	SE	NE	W	E	N	ANW	U	S	AE	NW
4	S	ANW	SE	NE	W	CS	N	A	A	S	E	N
5	S	A	SE	A	W	S	N	SW	W	U	ANE	AW
6	AS	A	AE	N	SW	S	NW	NW	NW	SW	A	SW
7	AS	A	AE	AW	SW	CNW	W	NW	W	W	ASE	CSW
8	AS	A	A	W	W	ASW	NW	NW	W	NW	S	SW
9	AS	A	E	W	SW	S	NW	NW	SW	CNW	AS	W
10	AS	A	E	W	W	SW	W	U	SW	CNW	S	W
11	ASE	A	SE	W	SW	SW	W	AS	W	CN	SW	SW
12	ASE	S	C	W	SW	SE	NW	SE	AS	NW	W	SW
13	E	S	CS	W	AW	N	S	E	S	NW	SW	W
14	SE	CS	C	W	A	W	SW	U	SW	CN	W	AW
15	SE	S	CW	SW	SW	NW	SW	U	SW	N	W	SW
16	SE	SE	CS	CS	SW	W	S	S	C	ANW	W	CNW
17	S	E	C	C	S	NW	U	C	NW	SW	SW	N
18	S	E	CS	C	CW	N	N	CN	W	SW	SW	A
19	SW	SE	C	C	W	N	W	N	NW	S	ASW	A
20	ASW	S	C	C	SW	AN	U	A	NW	ASW	ASW	NE
21	A	S	C	C	SW	ANW	U	A	S	U	ASW	NE
22	AS	S	C	C	C	NW	N	ASW	SW	NW	SW	E
23	A	S	CSW	U	NE	ANW	ANW	SW	S	N	AW	E
24	A	S	C	S	NE	A	W	SW	CS	NW	W	N
25	A	S	ANW	SW	NE	A	W	SW	SW	AW	ASW	N
26	A	S	SW	SW	CE	ASW	A	S	SW	SW	SW	W
27	SW	S	SW	CSW	CSE	W	W	U	A	S	NW	CN
28	NW	SW	CS	W	CS	NW	NW	NW	A	AS	NW	ANW
29	W	S	C	W	SE	ANW	W	AN	A	S	N	W
30	NW		CS	AW	SE	NW	W	A	AE	S	NW	W
31	W		CSE		E		NW	ASE		SE		W

1965	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	NW	ASE	NE	SW	C	NE	AN	W	A	N	W	SW
2	N	SE	AW	SW	C	A	N	C	A	SW	N	W
3	ANE	ASE	CW	SW	C	A	N	C	N	S	N	NW
4	A	A	CNE	CSW	C	SW	AN	CS	N	S	AN	W
5	ASW	A	ANE	U	ANW	SW	NW	CW	N	U	A	W
6	SW	A	AW	W	SW	U	C	NW	C	U	E	NW
7	SW	ANE	ASW	W	SW	CN	N	NW	C	C	CSE	N
8	NW	ANE	SW	W	W	N	N	U	CN	SE	S	W
9	W	A	S	SW	AW	A	NW	S	NW	SE	C	W
10	SW	A	S	W	SW	S	SW	S	NW	ASE	S	NW
11	SW	A	CS	W	SW	S	SW	S	N	ASE	SE	NW
12	W	W	CS	W	S	SW	C	S	C	ASE	E	W
13	CW	NW	C	AW	S	ASW	C	S	U	AS	S	W
14	W	A	CSW	W	SW	SW	C	CSW	SW	NW	SE	S
15	NW	A	SW	AW	SW	CSW	U	U	SW	ANW	SE	SW
16	W	A	W	AW	C	W	AS	A	SW	A	SE	SW
17	W	A	NW	ANW	NE	SW	AS	SW	C	A	CSE	SW
18	NW	A	N	ANW	N	W	S	SW	NW	A	C	W
19	SW	NE	SE	AN	A	SW	C	W	SW	AS	C	ANW
20	C	E	CSE	AN	SW	SW	CN	SW	SW	S	CE	A
21	SW	E	C	SW	SW	SW	NW	CNW	SW	S	NE	ASW
22	W	NE	CSE	A	CSW	W	U	N	SW	S	N	SW
23	SW	NE	C	W	C	SW	C	N	SW	S	W	CNW
24	ASW	NE	W	W	C	SW	NW	NW	CS	S	AW	C
25	A	E	CSW	NW	CSW	W	N	ANW	C	S	C	NE
26	AE	ANE	CW	NW	NW	NW	NW	CW	C	SW	SW	A
27	E	N	SW	N	N	ANW	SW	SW	C	SW	NW	ANE
28	E	NE	SW	NE	NE	ANW	W	W	CSE	W	W	SW
29	E		S	CSE	NE	A	NW	NW	N	W	N	SW
30	E		SE	CSE	ANE	N	N	AW	N	W	N	W
31	E		S		NE		NW	N		SW		SW

1966	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	W	S	SW	U	SW	AN	AW	NW	SW	CW	N	CW
2	W	S	SW	NE	U	A	NW	SE	CW	U	NE	N
3	W	S	W	SE	SW	ASW	U	C	SW	CE	ANW	N
4	S	SW	AW	SE	CSW	SW	U	NW	W	NE	C	A
5	S	SW	W	C	CW	W	NW	NW	SW	S	C	W
6	S	SW	SW	C	N	CSW	N	U	AW	SW	NE	NW
7	S	S	SW	CSE	W	SW	NW	NW	A	C	N	AW
8	S	C	AW	CSE	C	SW	NW	W	A	N	NW	NW
9	S	CS	AW	C	NW	N	AW	CSW	SW	S	ANW	NW
10	S	CSE	AW	C	SW	N	W	W	SW	W	A	NW
11	SE	CS	A	C	CSW	NE	NW	CS	SW	SW	SW	CSW
12	ASE	S	A	CSE	NW	CE	NW	C	W	S	SW	CNW
13	SE	SE	ANW	SE	SW	C	NW	C	NW	SE	W	NW
14	ASE	S	A	CSE	W	S	NW	N	W	E	NW	SW
15	AE	S	A	CSE	W	S	NW	A	NW	N	NW	SW
16	AE	SE	ASW	CSE	SW	S	N	SW	A	S	N	AW
17	ASE	SE	AW	SE	W	CS	N	ASW	CSW	CS	N	W
18	SE	S	ASW	CE	W	CSW	A	A	U	C	ANE	W
19	SE	S	SW	CNE	W	C	AN	U	A	C	A	W
20	CE	CS	AW	NW	AW	C	NE	CE	A	CNW	C	N
21	SE	CSE	A	SW	SW	CW	NE	CNE	A	NW	NE	ANW
22	E	C	A	CSW	NW	C	AN	NE	ASE	A	ANE	NW
23	SE	W	A	CSW	A	CW	NW	A	ASE	N	U	NW
24	SE	SW	A	NW	W	NW	NW	AS	SE	NE	NW	NW
25	CSE	S	A	W	W	W	NW	AS	SE	N	NW	ASW
26	C	SW	W	SW	ANW	SW	CN	SE	SE	N	NW	S
27	SW	W	NW	W	SE	NW	AN	SE	SE	N	W	W
28	S	NW	A	W	SE	ANW	NW	SE	U	ANE	NW	SW
29	SW		A	SW	SE	A	NW	C	U	A	W	W
30	SW		A	SW	SE	ANW	NW	CN	U	A	NW	SW
31	AS		A		A		NW	ANW		NW		NW

1967	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	A	W	AW	SW	N	S	SW	W	CSW	SW	C	A
2	A	SW	AW	W	AN	SW	W	NW	W	W	CN	AS
3	A	W	AW	AW	C	SW	W	NW	W	W	NW	A
4	SE	A	SW	AW	C	AW	W	NW	W	NW	N	A
5	ANE	A	W	A	C	SW	SW	SW	CNW	SW	N	NW
6	NW	W	SW	ANE	C	W	SW	S	NW	SW	NW	N
7	N	NE	SW	NE	C	NW	CSW	CSE	ANW	SW	CNE	N
8	NE	A	AW	NE	C	N	NW	C	AS	SW	A	N
9	A	A	C	NE	ASW	A	ASW	C	ASW	SW	NW	N
10	N	A	W	NE	A	A	ASW	N	W	ASW	SW	AN
11	N	S	W	NE	NE	A	A	NW	N	SW	W	ANW
12	ANW	S	AW	ANE	NE	AS	C	NW	N	SW	SW	A
13	A	S	W	A	NE	A	C	SW	A	SW	SW	A
14	A	S	W	A	NE	A	C	C	A	SW	W	A
15	S	S	A	A	NE	A	S	W	A	W	N	AW
16	S	SW	AW	A	NE	A	S	CW	SW	C	AN	A
17	CSW	SW	AW	A	NE	AN	SW	W	CNW	NW	A	AS
18	S	SW	A	A	AW	AN	SW	CSW	SW	S	A	S
19	CS	SW	A	AW	W	W	W	U	CW	SW	SE	SE
20	S	W	AW	ANW	W	W	W	A	NW	SW	U	S
21	W	W	AW	AN	CSW	W	U	S	N	NW	AE	SW
22	S	CSW	AW	W	C	W	NE	S	S	W	SE	SW
23	CS	NW	A	W	CW	ASE	AW	U	S	W	AS	W
24	CSW	S	W	W	C	CSE	SW	S	S	SW	SW	NW
25	SW	CSW	W	AW	W	C	SW	S	SW	SW	N	N
26	S	W	W	W	W	CN	SW	AW	CS	W	NW	NW
27	S	SW	NW	A	CSW	U	W	U	S	CW	W	NW
28	S	W	AN	A	C	SW	W	SW	S	NW	W	N
29	S		A	A	SW	W	SW	NW	SW	NW	W	N
30	SW		AN	A	C	ASW	SW	AW	W	W	W	NW
31	W		A		S		SW	W		NW		NW

1968	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	NW	NW	NE	W	NE	SW	U	NE	CSW	SW	C	S
2	NW	NW	AN	N	NE	U	N	U	C	SW	NE	S
3	NW	NW	A	AN	CN	SW	NW	A	NW	SW	ANE	S
4	SW	SW	A	ANE	NE	W	A	U	ASW	S	S	S
5	CNW	C	A	A	NE	W	A	U	SW	S	S	S
6	NW	C	AN	A	N	W	AE	NE	ASW	A	S	S
7	A	C	ANE	A	U	SW	NE	NE	S	AS	SE	SE
8	SW	C	A	A	NE	U	CNE	NE	S	U	SE	AS
9	C	C	A	SW	W	A	U	NE	S	S	S	SW
10	A	SE	A	SW	NW	A	NE	ANE	S	SW	S	C
11	A	SE	A	S	AN	AS	N	ASW	SW	SW	S	AS
12	S	S	AW	S	W	A	U	CS	U	SW	S	SW
13	SW	SE	AW	SE	W	A	C	NW	U	W	S	C
14	SW	E	W	SE	SW	NE	CN	NW	NE	W	SE	SW
15	W	AE	ANW	CSE	W	NE	NW	CW	NE	W	SE	CSW
16	CSW	A	W	CSE	A	AS	N	C	NE	AW	AS	C
17	NW	A	W	CSE	ANE	SW	AN	NW	A	AS	AS	C
18	W	ASE	AW	CS	NE	W	A	ANW	S	S	AS	NE
19	ASW	ASE	W	S	AE	W	A	SW	S	S	S	SW
20	ASW	SE	W	SW	ANE	W	A	SW	C	SW	S	CSW
21	SE	E	CW	CS	NE	W	A	SW	W	AS	S	S
22	U	E	SW	CS	S	C	A	SW	SW	S	SW	SW
23	AN	ANE	SW	W	S	NW	AN	U	W	S	SW	ANW
24	AN	AN	SW	SW	CS	SW	A	NE	NW	SE	W	CSW
25	NW	AE	W	SW	C	SW	A	AE	S	A	SW	C
26	ANW	A	W	SW	C	SW	A	AE	SW	S	ASW	ANE
27	W	A	W	CSW	C	C	A	ANE	SW	S	C	AN
28	A	S	SW	C	SW	C	A	NE	W	CSW	CNE	N
29	SW	S	N	C	SW	S	AE	NE	NW	SW	E	N
30	SW		ANW	C	SW	SW	NE	W	W	S	E	N
31	W		AW		SW		N	W		C		AN

1969	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	A	W	E	AN	U	AW	SW	U	NE	A	W	NW
2	A	N	NE	A	C	SW	NW	A	A	W	W	NW
3	A	AN	A	AW	C	NW	A	S	AN	ASW	CW	NW
4	NW	A	ANE	A	C	A	W	S	A	AS	N	N
5	CN	ASW	E	A	CSE	A	ANW	SW	A	SW	A	NW
6	E	NW	AE	E	C	A	N	S	A	ASW	ASE	N
7	CNE	N	U	C	C	A	NW	S	A	SW	NW	N
8	C	AN	A	SW	C	A	NW	S	ASW	SW	NW	N
9	S	AN	SE	SW	W	E	ANW	U	SW	S	NW	A
10	S	NW	CSE	W	CSW	E	AW	S	C	SE	W	SW
11	S	NW	CSE	W	SW	AE	ANW	CSW	C	SE	C	NW
12	CSE	N	C	ANW	SW	A	A	N	CN	S	CNW	SW
13	C	NE	C	A	SW	N	A	A	U	S	NW	SW
14	C	N	C	W	CSW	AS	AS	S	E	SW	C	CW
15	C	NE	CSE	ANW	C	S	U	U	AE	SW	NW	NW
16	NW	AE	C	A	NW	CS	NW	A	SE	S	C	SW
17	C	A	CE	U	N	C	A	ASW	CE	S	N	C
18	NW	ASE	C	S	AN	CNW	SW	SW	NE	S	NW	S
19	A	E	C	CS	A	CW	SW	W	A	U	NW	SW
20	S	E	CSW	CS	SW	CNW	ASW	NW	W	U	W	SW
21	SW	E	S	C	U	C	SW	N	W	AS	C	CSW
22	SW	CE	SE	CN	SE	C	SW	N	AW	SW	C	NW
23	S	C	SE	CW	C	U	AW	N	SW	SW	E	SW
24	SW	C	A	C	C	U	A	NW	SW	AW	NE	CSW
25	SW	C	ANE	W	C	A	SW	NW	AW	W	N	N
26	S	U	U	NW	C	SW	ASW	NW	W	A	N	N
27	SW	ASE	A	ANW	CSE	ANW	ASW	N	AW	A	NW	ASW
28	C	E	A	AN	SE	A	N	N	W	U	N	S
29	NW		AW	ANE	E	ASW	ANW	AN	A	AN	N	SE
30	W		AW	A	NE	ASW	S	A	ANW	A	ANW	E
31	NW		NW		AN		S	ANE		A		NE

1970	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	AN	SW	A	AN	SW	AW	NW	SW	AW	W	ASW	NW
2	NW	W	AN	A	SW	AS	NW	S	C	NW	SW	W
3	N	AW	AN	A	SW	S	NW	C	NW	ANW	W	SW
4	ANE	C	N	AN	CSW	SE	W	C	W	W	W	W
5	N	CNE	AN	ANW	CSW	SE	SW	NE	AW	W	ANW	W
6	N	U	A	NE	C	E	SW	CNE	ASW	NW	C	NW
7	S	NW	AN	NE	CNE	NE	SW	U	S	N	N	AN
8	SE	W	N	NE	C	CE	CSW	N	CW	N	W	A
9	C	NW	NE	NE	CE	U	NW	W	CW	A	NW	A
10	U	NW	NW	CNE	CE	U	W	NW	CNW	A	W	ASE
11	C	U	NW	CSE	E	U	AW	U	W	S	W	S
12	NW	CNE	NE	C	NE	U	W	SW	N	S	NW	C
13	SE	NE	NE	U	E	U	W	W	CW	S	W	A
14	C	N	A	SW	NE	NE	NW	W	U	S	N	S
15	CW	N	A	SW	N	NE	AN	S	NW	S	A	SW
16	S	W	AW	SW	ANW	NE	ANW	N	SW	S	W	SW
17	S	NW	AW	W	W	CE	ANW	ANW	SW	A	SW	ASW
18	SW	W	ANW	W	AW	U	W	U	ASW	AW	C	SW
19	S	W	AW	W	AW	U	CNW	NE	S	NW	NW	SW
20	S	W	W	W	AW	SW	N	N	ASW	N	C	A
21	SW	W	W	W	A	S	NW	N	S	AN	W	A
22	S	W	U	SW	AW	CSW	SW	N	S	A	SW	A
23	C	NW	NE	AW	SW	SW	CS	A	S	ASW	C	N
24	S	NW	ANE	ASW	SW	W	C	AS	S	W	C	NE
25	SW	N	A	CN	AW	AW	NW	ASE	S	W	CSE	E
26	AW	AN	A	N	AW	S	CW	A	S	AW	S	NE
27	S	E	A	AN	W	C	CSW	A	AS	SW	S	NE
28	S	A	ANW	ANW	AW	NW	CW	A	S	W	C	NE
29	CSE		W	ANW	W	NW	AW	A	SW	SW	C	NE
30	N		NW	W	AW	W	SW	SW	W	SW	N	NE
31	S		NE		AW		SW	W		SW		AN

1971	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	NW	ANE	W	C	AW	S	SW	C	W	S	SW	NW
2	A	A	A	E	SW	SE	S	CS	SW	S	SW	CN
3	A	A	SW	E	SW	E	S	C	ASW	U	SW	A
4	S	A	SW	E	S	E	U	C	A	S	SW	ASW
5	S	ASE	A	NE	SE	NE	A	C	AS	S	CNW	ASW
6	S	A	E	NE	CSE	NE	A	N	S	SW	N	A
7	SW	A	A	ANE	CS	NE	AS	W	AS	SW	NW	A
8	SW	ASW	A	ANE	SW	CN	U	W	S	AW	N	A
9	SW	S	A	NE	SW	NE	A	W	SE	AW	N	A
10	S	SW	A	A	SW	NE	A	N	S	SW	A	A
11	S	SW	AW	A	W	N	AN	W	S	W	A	AW
12	S	W	AW	SE	A	C	NE	C	A	U	ANW	SW
13	SE	W	W	SE	E	CE	ANE	C	AS	E	N	SW
14	SE	W	NW	E	U	NE	AN	CNE	AS	A	A	SW
15	S	CW	NW	A	AN	N	AN	N	A	SW	AW	SW
16	S	NW	W	A	AN	NW	N	A	AS	SW	NW	SW
17	S	CW	SE	AW	N	ANW	N	AE	SW	SW	W	SW
18	SW	NW	CNE	AW	A	CSW	U	NE	U	W	CNW	S
19	W	SW	NE	AW	A	CNW	ANW	NE	ANW	W	AN	SW
20	CS	SW	NE	AS	A	NW	A	A	A	W	SW	SW
21	C	NW	ANE	CSW	W	W	S	A	A	SW	N	W
22	SW	AS	W	C	NW	ANW	CS	N	A	SW	N	A
23	SW	ASW	W	C	N	U	CS	N	C	SW	N	AW
24	SW	AS	W	C	CNE	SW	C	A	C	U	AN	SW
25	C	S	AW	C	NE	SW	C	A	S	AS	NW	SW
26	C	S	ANW	E	ANW	CW	C	W	CSW	S	W	C
27	CNW	SW	W	AE	NW	W	U	W	CNW	S	W	CE
28	C	A	SW	A	NW	W	S	W	SW	S	NW	E
29	N		W	A	CSW	SW	S	W	SW	SW	SW	ANE
30	CN		U	U	C	SW	S	W	SW	SW	NW	AE
31	N		U		SW		CW	W		ASW		E

1972	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	E	S	W	W	CN	ANW	W	N	A	C	ASW	SW
2	U	CS	CSW	W	N	W	W	N	A	CSE	ASW	CW
3	ASE	SW	C	W	AN	W	W	A	NE	ASE	W	W
4	A	S	W	CW	NE	SW	CW	W	NE	ASE	SW	CW
5	AS	CSE	W	W	CNE	C	W	SW	ANE	SE	SW	SW
6	S	C	C	W	C	C	W	SW	AW	SE	SW	SW
7	S	S	CNE	C	CSW	CN	W	CSW	NW	S	NW	CW
8	S	CSW	N	NW	C	CW	W	C	E	S	A	C
9	S	SW	C	W	CSW	CN	W	NW	N	CSW	SW	W
10	S	SW	NE	W	W	N	W	ANW	NW	CN	NW	W
11	SW	SW	ANE	N	CSW	C	W	SW	NW	NE	NW	SW
12	SW	NW	E	ANW	C	CNE	SW	S	ANW	A	C	SW
13	CSW	NW	CSE	AW	NE	NE	AS	U	N	AE	NW	SW
14	S	ASW	CSW	ANW	NE	AN	A	N	NE	E	N	S
15	CS	C	SW	A	ANE	N	A	AN	A	E	A	S
16	CS	CN	SW	AW	AW	ANW	A	AW	A	ASE	E	S
17	C	N	CS	A	SW	SW	NE	NW	AN	E	ANE	S
18	SW	ANE	SW	A	C	NW	E	ANW	AN	E	S	S
19	W	AS	U	A	C	NW	NE	A	ANE	AE	C	S
20	W	S	A	A	C	SW	NE	ANW	A	ANE	CNW	S
21	AW	SE	A	A	CS	W	CNE	A	ASW	AN	NW	A
22	SW	ANE	A	NE	CSW	NW	C	A	A	ANW	NW	S
23	SW	E	A	AE	CSW	W	U	A	ASE	NW	AN	W
24	W	SE	SW	E	SW	W	N	A	ASE	AW	A	S
25	W	S	W	A	SW	SW	U	A	ASE	ASW	A	S
26	CNW	S	W	A	W	SW	A	ASE	AS	S	A	S
27	N	S	NW	A	ANW	NW	A	AE	A	CSW	SW	CSE
28	ANE	SW	ANW	W	W	W	U	ASE	AS	SW	W	CN
29	ASE	SW	AW	NW	W	SW	ANW	SE	S	SW	W	A
30	ASE		W	CN	NW	SW	CSW	ANE	S	SW	W	SW
31	S		W		ANW		N	ANE		A		SW

1973	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	SW	N	W	AW	A	W	SW	SW	W	A	S	CSE
2	SW	A	W	N	AE	W	S	W	SW	A	S	A
3	ASW	SW	W	W	CE	W	SW	NW	SW	AE	S	ANW
4	A	S	W	W	C	A	AS	SW	SW	E	C	ANW
5	A	AW	W	AW	W	A	SW	W	U	E	N	AW
6	ASE	W	ANW	A	W	A	N	CW	SW	C	A	NW
7	AS	W	ASW	AN	N	A	A	W	ASW	U	ASW	CNW
8	AS	W	SW	ANE	ANW	ANW	S	SW	AS	SW	W	N
9	AS	NW	S	AN	W	NW	SW	SW	AE	W	SW	ASW
10	S	NW	S	AN	ANW	NW	W	A	E	C	NW	SW
11	S	W	S	AN	AW	AW	NW	A	SE	SE	ANW	NW
12	S	W	SE	AN	W	SW	NW	AS	SE	SE	W	NW
13	S	NW	S	A	A	ANW	W	S	E	E	NW	NW
14	S	CNW	AS	A	A	AS	C	SE	SE	CE	W	NW
15	CW	N	A	A	A	S	CNE	U	SE	C	NW	AW
16	A	A	A	A	S	SW	CNE	U	SW	NE	NW	NW
17	A	SE	A	A	CSE	W	N	AN	SW	N	AS	NW
18	S	AW	A	A	CSE	SW	NW	A	C	AW	SW	S
19	S	ANW	A	ANE	CE	NW	W	CSW	N	NW	A	C
20	C	AW	ASW	AN	CE	ANW	CNW	C	N	W	AS	C
21	NW	NW	SW	NE	CE	A	N	SE	NW	ANW	AS	CNW
22	SW	NW	SW	NE	C	A	NW	S	N	W	ASW	C
23	SW	NW	SW	NE	C	A	U	U	AN	A	A	C
24	SW	N	CSW	E	S	A	C	AS	U	ASW	NW	NE
25	SW	W	ANW	E	S	U	N	U	A	ASW	N	A
26	W	U	SW	A	S	A	AN	S	W	S	A	AW
27	NW	SW	SW	A	CSE	A	A	U	SW	S	A	SW
28	NW	SW	A	ANE	C	AW	A	A	W	AN	NW	SW
29	ASW		W	A	C	SW	AN	W	NW	A	N	SW
30	W		AW	CNE	N	SW	A	ANW	N	AS	U	ANW
31	NW		AW		AN		SW	W		S		AS

1974	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	S	C	NW	C	NW	SW	NW	NW	CW	A	SW	SW
2	S	CW	ANW	C	SE	W	C	ANW	C	N	SW	SW
3	S	SW	AN	U	CNE	A	NW	A	CNW	NE	CNW	SW
4	S	CW	U	SE	NE	ASW	CW	A	W	N	A	W
5	S	W	S	SE	E	W	NW	S	CSW	N	SW	ANW
6	SW	NW	SW	S	U	NW	AW	S	W	NW	U	AW
7	SW	ANW	SW	SE	SW	AW	SW	S	C	N	SW	AW
8	SW	SW	SW	E	SW	N	SW	W	W	N	SW	W
9	SW	SW	CS	U	CS	NW	AW	SW	W	N	W	W
10	SW	SW	CE	NE	C	NW	W	NW	SW	N	W	W
11	SW	C	C	CNE	C	ANW	W	SW	SE	N	W	NW
12	SW	W	CSE	CNE	CS	A	NW	W	CS	A	W	NW
13	CSW	CNW	U	E	CSW	AS	N	AS	W	A	CS	ANW
14	SW	S	SW	AE	SW	ANE	W	S	S	ASW	C	W
15	W	C	CW	A	S	N	C	SW	C	U	W	W
16	C	N	W	S	CSW	U	N	W	SW	NW	AW	W
17	W	A	W	U	CSW	NW	N	U	AN	AW	U	NW
18	W	U	W	A	SW	SW	AW	AN	A	W	A	ANW
19	ASW	N	C	S	SW	SW	AW	ASW	AW	NW	S	SW
20	SW	AW	N	S	SW	S	ANW	SW	W	NW	CE	SW
21	S	AW	SW	A	W	SE	AW	W	W	N	E	SW
22	SW	NW	SW	A	W	SE	W	SW	W	N	C	SW
23	SW	A	E	A	N	SE	NW	SW	C	AN	CW	S
24	W	A	CE	A	NE	E	NW	SW	NW	ANW	W	W
25	SW	A	CE	U	A	E	W	SW	NW	NW	NW	SW
26	SW	A	E	U	A	E	W	NW	NW	NW	W	SW
27	SW	AS	U	E	A	E	W	ASW	CN	NW	NW	W
28	W	SW	U	NE	ANW	U	W	SW	N	N	NW	W
29	SW		SW	C	A	U	W	C	N	N	AW	NW
30	CSW		SW	CSW	SW	CSW	W	NE	A	AN	W	ASW
31	S		SW		SW		C	C		NW		SW

1975	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	W	SW	CS	A	W	NW	A	A	A	W	NW	CSW
2	SW	S	CS	N	A	N	A	A	AW	C	SW	N
3	ANW	S	C	NE	A	NW	AN	A	N	W	AW	AN
4	AW	SE	C	NE	ASW	S	N	S	W	W	SW	ANW
5	AW	ASE	W	NE	A	S	U	S	NW	W	SW	ANW
6	W	SE	W	AN	NE	S	SE	S	CW	A	ANW	A
7	NW	SE	W	AN	NE	S	E	S	U	A	A	AN
8	W	SE	W	AN	NE	S	CE	U	SW	AS	A	A
9	SW	SE	N	A	N	U	C	N	W	A	AE	A
10	SW	S	NE	NW	N	A	C	U	W	N	E	A
11	SW	SE	NE	ANW	A	A	W	S	CW	A	SE	A
12	SW	C	E	W	CW	AN	S	U	NW	A	SE	N
13	S	W	U	SW	C	ANW	S	U	CNE	S	SE	AN
14	SW	S	NE	CSW	E	NW	CSW	SW	N	CSW	S	A
15	CSW	S	NE	CNW	E	NW	W	W	AN	C	CW	A
16	SW	SW	SE	SW	A	CNW	U	W	AW	N	N	AN
17	CW	SW	ASE	SW	A	NW	U	C	SW	A	N	NE
18	N	A	SE	SW	SW	SW	SW	SW	NW	S	AN	A
19	SW	S	SE	W	SW	SW	SW	SW	S	S	NW	A
20	W	ASW	S	SW	A	S	W	W	W	S	NW	A
21	W	ASW	SW	CSW	E	ASE	W	NW	ASW	S	A	AW
22	W	S	NW	A	AE	A	W	NW	SW	S	SW	ASW
23	W	S	ANW	A	ANE	A	NW	W	W	S	CSW	W
24	SW	S	A	A	NE	N	NW	AW	SW	SW	W	NW
25	NW	S	A	A	E	A	AW	ASW	CNW	S	W	NW
26	SW	SE	E	A	E	NE	AW	ASW	NW	S	W	A
27	CNW	S	NE	A	E	NE	A	AS	C	S	W	ASW
28	W	S	AN	W	E	AE	ASW	U	S	S	NW	SW
29	SW		ANE	NW	E	A	SW	N	S	S	NW	SW
30	SW		AN	W	E	A	AN	N	CSW	S	NW	W
31	SW		AN		AE		ANE	A		SW		W

1976	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	CSW	SE	A	W	W	NW	SE	ANW	N	NE	W	CW
2	N	SE	SW	N	W	A	SE	ANW	NE	U	W	NW
3	AN	E	SW	W	NW	A	S	ANW	AN	SW	NW	C
4	ANW	NE	SW	AW	A	SW	S	A	N	W	W	N
5	ANW	SE	SW	AW	E	SW	S	A	A	S	SW	SW
6	A	S	CS	A	U	SW	AE	A	A	SW	CSW	CSW
7	AN	S	CSE	AN	W	S	CE	A	A	W	CSW	C
8	A	SW	S	A	W	S	CS	A	NW	S	CSW	NW
9	A	SW	SW	AW	W	SW	SW	A	N	ASW	W	ANW
10	A	W	SW	W	W	SW	S	A	W	S	NW	A
11	A	NW	CSW	NW	W	S	S	SW	N	C	U	A
12	N	W	C	ANW	NW	SW	S	U	N	NW	U	S
13	AN	N	N	W	W	SW	SW	A	N	SW	S	S
14	A	SW	CSW	AN	SW	AW	SW	A	N	CN	SW	CS
15	A	U	C	AN	W	ASW	SW	A	N	NW	SW	S
16	AN	AS	C	AW	SW	U	AW	A	U	S	U	S
17	NE	S	U	A	SW	AW	SW	S	S	C	S	CSE
18	A	S	SE	ASW	CW	W	SW	SE	S	C	U	SE
19	A	S	CSW	S	C	W	W	ASE	S	C	A	E
20	A	S	SW	SE	NW	W	N	ASE	S	SW	A	U
21	AW	S	W	SE	SW	SW	ANW	ASE	SW	SW	A	S
22	ASW	S	W	SE	SW	S	ANW	SE	S	SW	AN	CS
23	W	SW	SW	E	SW	SW	AN	CSE	SE	C	A	SE
24	NW	ASW	W	AE	CSW	SW	AN	CSE	SE	AS	A	SE
25	NW	ASW	W	E	W	S	AN	U	CSE	U	ASW	AE
26	A	ASW	W	E	W	A	N	ANE	CSE	S	SW	A
27	ASW	AS	AW	E	SW	A	N	ANE	CSE	CSE	SW	N
28	SW	S	AW	ASE	CS	A	N	E	C	NE	W	N
29	SW	AW	AW	A	C	AE	AN	NE	C	NE	W	SW
30	W		AW	AW	CSW	E	N	N	C	NE	CNW	C
31	W		W		SW		N	N		S		C

1977	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	N	SW	SW	NW	NE	A	SW	ASW	SW	NW	SW	ASE
2	A	SW	SW	A	NE	A	SW	U	W	ANW	W	S
3	ASW	W	AW	NE	NE	AN	S	NW	ASW	SW	W	S
4	SW	S	AW	A	NW	ANW	S	SW	SW	W	W	S
5	W	SW	AW	A	AW	NW	U	U	ASW	CW	SW	S
6	A	SW	SW	A	AW	CNW	NE	U	W	CNE	SW	CSE
7	A	W	SW	ANE	A	N	N	U	A	CNE	SW	CSE
8	A	SW	SW	AN	ANW	N	N	U	ANW	C	SW	C
9	NW	S	SW	N	W	NE	NE	A	ASW	NW	SW	S
10	N	C	CSW	ANW	SW	NE	NE	AS	SW	A	SW	S
11	N	C	W	W	W	N	E	S	AW	S	SW	CSW
12	C	C	SW	AW	N	U	NE	S	A	SW	NW	W
13	C	C	C	A	A	N	NE	S	A	S	NW	SW
14	N	NW	W	A	S	NE	U	S	A	S	NW	ASW
15	N	SW	SW	A	CE	NE	U	C	A	S	NW	AS
16	A	SW	SW	SW	NE	E	ASW	CNE	SE	S	NW	S
17	S	C	CSW	E	A	E	SW	NE	ASE	S	N	U
18	S	CNW	CW	CSW	SW	NE	NW	NE	A	S	AN	U
19	SW	W	N	SW	U	N	NW	U	ASE	S	W	AS
20	CS	CS	NE	W	U	U	NW	N	ASE	S	N	S
21	C	C	NE	W	ANE	A	SW	N	A	S	N	S
22	SW	C	NE	W	A	A	SW	N	AS	CSW	N	S
23	SW	CNE	CE	W	E	S	SW	S	S	SW	NW	SW
24	S	CNE	SE	SW	E	SW	NW	C	CS	SW	N	W
25	C	U	SE	W	E	NW	N	C	SW	ASW	A	AW
26	SW	ASE	CSE	W	CE	ANW	N	CN	S	S	AS	W
27	C	SE	E	W	C	SW	NW	N	S	SW	S	N
28	CE	S	A	NW	U	NW	N	ASW	W	ASW	ASE	N
29	A		ASW	N	NE	NW	ANW	SW	W	SW	A	NW
30	SW		SW	AN	U	W	NW	SW	W	SW	A	NW
31	U		SW		A		A	SW		W		ANW

1978	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	AW	NW	C	C	CE	S	W	N	N	A	SW	S
2	AW	NW	W	C	CE	S	NW	N	A	W	SW	S
3	NW	SW	ANW	CSE	CE	SE	NW	NW	A	ANW	SW	CS
4	W	SW	A	E	NE	CS	N	W	S	AW	SW	SW
5	ASW	W	S	E	AN	CS	N	CNW	SW	ASW	S	S
6	SW	NW	SW	AE	CSW	W	N	CNW	CSW	AS	S	S
7	ASW	U	SW	A	CSW	W	ANW	N	W	S	S	S
8	ASW	SE	AW	A	C	NW	W	N	SW	S	W	S
9	W	E	SW	ANE	U	AN	W	A	W	C	ASW	SW
10	W	A	SW	AN	W	AN	U	S	W	C	S	S
11	N	C	SW	AN	AW	A	U	S	NW	S	S	S
12	AN	NE	W	N	ANW	A	U	U	ASW	AS	SW	CSW
13	A	N	SW	N	ANW	A	A	SW	W	U	SW	CW
14	A	A	CW	A	NW	SW	ANE	SW	AW	C	SW	C
15	A	SE	W	SW	U	C	ANE	CW	AW	N	W	C
16	N	SE	N	S	W	N	ANE	NW	ASW	NW	W	NE
17	N	SE	AN	S	SW	NE	U	ASW	A	N	SW	A
18	SW	SE	SW	C	U	AN	NW	S	A	ANW	SW	S
19	CNW	SE	W	C	U	NW	NW	SW	A	AW	W	S
20	NW	SE	W	C	SW	W	NW	SW	A	AW	W	E
21	SW	S	AW	CW	SW	C	SW	SW	A	AW	W	C
22	W	S	W	S	C	C	SW	NW	ASW	ANW	W	CSE
23	C	S	NW	S	N	N	SW	A	SW	ASW	SW	SE
24	NW	SW	W	CSE	A	NW	AW	A	W	AW	NW	C
25	W	S	W	E	W	N	S	A	AW	AW	NW	CSW
26	NW	C	W	NE	AW	NW	SW	A	W	A	NW	CS
27	C	CSW	W	CNE	W	W	SW	A	NW	A	U	CSE
28	CN	S	SW	C	SW	W	SW	A	W	A	A	C
29	N		W	CE	SW	NW	SW	AN	NW	ASW	S	C
30	A		SW	CE	S	ANW	N	AN	NW	SW	AS	E
31	W		C		CS		N	ANW		AW		E

1979	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	A	C	W	W	N	AS	ANW	CNW	SW	S	W	SW
2	AS	A	W	NW	AN	ASE	ANW	N	W	S	S	SW
3	SE	A	W	NE	AN	S	A	N	NW	C	SW	SW
4	NE	SE	AW	NE	A	U	A	SW	ASW	NW	W	SW
5	A	SE	W	N	AN	CNW	A	SW	S	S	NW	SW
6	W	SE	W	CN	W	NW	ASW	SW	SW	S	NW	S
7	W	CE	W	CNE	W	CNW	W	NW	S	S	NW	CSW
8	W	SE	W	CE	U	C	W	W	CN	S	NW	SW
9	W	SE	W	CE	SE	C	ANW	NW	AN	S	NW	SW
10	NW	SE	W	NE	CSW	SE	ASW	W	AW	S	ANW	W
11	NW	SE	W	CNE	W	U	ASW	W	W	SW	CW	NW
12	U	SE	A	C	SW	U	ASW	SW	W	CS	AN	SW
13	S	CE	NE	W	SW	NW	NW	SW	ANW	CE	SW	SW
14	S	E	NE	NE	SW	NW	U	CNW	ANW	U	CNW	SW
15	S	ANE	NE	A	AW	NW	A	W	A	NE	N	NW
16	U	ASE	NE	SW	C	ANW	AW	CSW	ASW	AN	N	SW
17	NE	S	NE	SW	C	A	W	NW	SW	W	W	NW
18	E	S	E	W	N	AS	NW	NW	W	SW	NW	NW
19	E	S	AE	W	SW	S	NW	N	W	W	U	N
20	C	S	N	AW	CSW	SW	NW	W	NW	A	ASW	AN
21	S	U	NW	AW	W	W	NW	NW	N	AS	SW	A
22	SE	A	A	W	CSW	W	ANW	NW	A	S	SW	S
23	NE	A	A	NW	C	W	NW	NW	NW	S	W	SW
24	NW	AS	CS	N	CW	NW	W	W	ASW	S	ASW	ASW
25	N	AS	CNE	AN	C	NW	ASW	C	SW	C	SW	SW
26	N	SW	NW	A	C	U	AS	N	W	U	SW	SW
27	NW	SW	NW	A	S	SW	S	A	A	U	SW	C
28	C	NW	N	ANW	C	W	SW	A	A	NW	SW	W
29	C		N	ANW	CSW	NW	W	AS	S	AW	S	NW
30	N		ANW	A	U	N	SW	S	S	SW	SW	N
31	ASW		ANW		CS		CW	S		W		A

1980	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	U	SW	A	ANW	E	ASW	N	S	SW	AW	S	A
2	S	CW	A	A	E	SW	U	S	SW	A	CE	N
3	SW	C	ASW	ASW	E	S	SW	CS	SW	SW	SE	AN
4	W	CSW	SW	SW	E	S	W	CSW	SW	A	ASE	N
5	NW	C	CW	ASW	SE	CSW	ANW	W	W	W	AE	NW
6	A	C	CW	A	E	NW	U	CS	SW	W	E	N
7	S	S	N	A	E	N	CNE	CNE	SW	NW	NE	A
8	S	S	NW	A	U	C	N	U	NW	NW	NE	ASW
9	C	CSW	W	A	SW	E	N	S	W	NW	E	SW
10	A	AW	W	A	S	CNE	N	S	W	C	A	SW
11	AS	SW	W	SW	CS	CNE	NW	CW	SW	N	AN	SW
12	A	SW	W	SW	C	CNE	NW	SW	NW	A	AN	SW
13	ASW	SW	ANW	CSW	CSW	C	C	SW	W	CSW	AW	W
14	N	SW	U	AN	CS	C	CNE	S	SW	C	SW	W
15	NE	S	SW	U	CS	SW	N	C	SW	NE	W	NW
16	A	SW	SW	ANW	S	C	A	S	SW	NE	SW	SW
17	A	SW	NE	A	S	W	SW	W	SW	N	CSW	W
18	S	CSW	CE	A	CSW	SW	W	NW	S	AN	NW	NW
19	CSW	U	E	A	U	W	CNW	AW	C	SW	SW	SW
20	SW	S	ANE	A	N	NW	N	W	CSE	S	SW	NW
21	C	S	NE	A	NE	NW	ASW	N	CNE	S	SW	NW
22	CNW	W	C	A	NE	CW	SW	AN	CSW	C	SW	W
23	CNW	A	C	A	A	CNW	SW	A	W	NW	SW	W
24	NW	S	C	U	A	NW	S	A	ASW	NW	W	W
25	A	U	C	W	AN	N	CS	ASE	S	SW	N	W
26	SE	A	CSW	W	N	N	CN	SE	SW	S	NW	NW
27	S	A	C	ANW	NE	W	C	S	W	SW	NW	ANW
28	S	A	C	AN	NE	CNW	CSE	SW	A	W	N	AW
29	S	AN	NW	ANE	A	N	C	CSW	AW	ANW	A	ASW
30	SW		S	E	SW	NW	C	NW	A	AS	A	SW
31	C		C		NW		SW	A		S		W

1981	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	ANW	ASW	C	SW	U	S	W	ANE	S	CN	SW	AN
2	W	SW	C	A	A	CS	CW	ASW	S	N	SW	A
3	NW	NW	NE	U	W	SW	W	SW	S	N	SW	A
4	N	NW	AS	AE	N	SW	SW	ASW	SW	N	A	NW
5	NW	NW	CS	E	CSW	SW	SW	U	ASW	CN	ASE	NW
6	NW	W	CSW	SE	W	SW	SW	NE	U	CW	S	NW
7	A	W	SW	SW	C	S	SW	A	S	W	S	NW
8	ASW	CW	W	SW	CE	C	SW	U	W	CSW	S	CN
9	NW	N	SW	SW	E	NW	ANW	A	S	CNW	A	NW
10	N	A	SW	S	E	S	SW	ASW	CSW	NW	AW	U
11	A	SW	W	C	C	C	W	SW	SW	ANW	NW	NE
12	N	S	SW	NE	C	S	W	S	SW	N	N	A
13	NW	SE	CNW	E	C	SW	NW	CSW	SW	A	A	CS
14	NW	AS	N	SE	CS	SW	W	U	S	AE	A	NW
15	NW	U	A	E	CS	NW	NW	ANW	W	ANE	SW	C
16	W	A	A	U	C	ANW	NW	A	S	A	SW	C
17	NW	S	A	E	C	AN	NW	A	SW	ANE	SW	CSE
18	W	S	A	E	C	A	NW	ANW	W	ASW	W	A
19	NW	S	W	E	SW	N	NW	NW	SW	W	SW	S
20	W	S	SW	AE	C	N	W	NW	W	N	W	CSW
21	W	CSW	C	ANE	C	A	NW	NW	CW	N	SW	C
22	ASW	C	A	AN	CSW	A	N	ANW	NW	N	SW	U
23	ASW	N	C	U	CSW	AN	N	A	SW	NW	NW	SE
24	AW	S	SW	CNE	CSW	N	N	A	SW	NW	ANW	U
25	AW	S	SW	NE	C	N	W	A	CSW	NW	ASW	S
26	ASW	S	SW	NE	N	NE	NW	A	C	W	SW	S
27	AS	S	CS	ANE	CNW	N	A	AS	NW	W	NW	S
28	S	CS	CSW	A	CS	U	A	S	NW	W	NW	SE
29	S		ANW	A	CSW	NW	AN	C	S	W	AW	CSE
30	A		W	ANW	S	NW	ANE	SE	CSW	SW	NW	C
31	ASW		SW		CSW		NE	SE		AW		CW

1982	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	S	SW	W	C	A	S	SW	U	NW	SW	SW	AS
2	S	S	W	SW	W	S	NW	U	ANW	SW	A	AS
3	S	S	W	S	ANW	S	ANW	U	AW	S	AS	S
4	CSW	S	ANW	C	A	S	W	C	U	CNW	S	SW
5	C	SW	SW	CSE	ANE	S	SW	N	C	N	SW	A
6	SE	SW	W	CSE	NW	S	W	N	NW	N	SE	ASE
7	SE	W	W	C	CW	S	ASW	AW	W	N	CSE	CS
8	CSE	SW	W	ANE	W	AS	S	W	AW	N	C	W
9	SE	SW	W	A	SW	SE	C	W	SW	N	W	SW
10	SE	SW	NW	A	CS	S	U	ASW	ASW	U	SW	W
11	E	SW	W	A	SE	CS	NE	SW	AS	CW	SW	W
12	A	S	W	A	SE	C	NE	W	SW	CS	W	C
13	AS	SW	W	A	CS	N	U	NW	ASW	C	W	N
14	AS	AS	W	AW	CS	U	N	S	AS	N	NW	W
15	S	AS	W	AW	CS	CS	N	W	ASW	AS	ANW	W
16	S	AS	NW	A	SW	U	W	W	A	CS	NW	NW
17	S	SE	AN	ASE	SW	S	U	SW	U	CSW	W	NW
18	S	S	A	ASW	SW	C	A	NW	U	NW	W	NW
19	S	S	C	SW	SW	SW	A	NW	U	SW	W	W
20	SW	S	W	AW	U	S	NE	NW	W	W	SW	NW
21	SW	S	W	W	SW	SE	NE	AW	NW	ASW	SW	N
22	NW	U	A	AW	W	C	NE	W	SW	SW	SW	N
23	SW	A	SW	A	NW	C	ANE	NW	SW	ASW	C	W
24	AW	SW	SW	A	W	S	U	W	SW	SW	CSW	W
25	W	W	SW	A	SW	CSE	AN	W	CS	S	CNW	SW
26	NW	W	SW	A	W	C	A	CW	C	SW	N	SW
27	AN	SW	U	A	W	SW	A	NW	CSW	SW	U	AW
28	NW	SW	NE	A	SW	W	A	SW	SW	S	ANW	ASW
29	ANW		AN	A	SW	W	A	SW	SW	S	ASW	S
30	AW		A	A	SW	SW	U	NW	S	S	S	SW
31	ASW		A		SW		NE	NW		SW		SW

1983	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	W	NW	SW	NE	CNE	CNE	SW	NW	SW	S	W	S
2	SW	NW	SW	AN	NE	C	ANW	NW	C	SW	SW	S
3	SW	AS	W	W	SE	CS	A	ASW	NW	SW	U	SW
4	SW	SW	AW	NW	CSE	C	ASW	AW	SW	SW	A	SW
5	SW	NW	AW	CNW	CS	NE	ASW	A	AW	W	A	A
6	W	N	A	CW	C	SE	S	A	A	SW	S	A
7	W	N	AW	CSW	CN	SE	S	U	S	W	S	SW
8	SW	NE	ASW	U	W	U	SE	U	CSW	W	CS	W
9	W	N	AW	A	W	NW	SE	E	C	W	S	CN
10	SW	N	ASW	NE	C	SW	SE	ANE	N	W	SE	AN
11	SW	NE	SW	NE	C	SW	SE	AN	N	AW	S	SW
12	W	NE	SW	A	C	SW	AE	N	A	SW	SE	AW
13	NW	E	SW	AW	C	SW	U	A	CSW	SW	SE	SW
14	NW	AE	W	A	W	NW	A	ASW	SW	SW	SE	SW
15	NW	E	AW	AW	CS	A	U	SW	C	CSW	ANE	S
16	ANW	SE	W	W	CE	AS	CNE	CSW	NW	NW	ANE	C
17	W	E	W	NW	CE	AS	N	S	W	W	ANE	CS
18	NW	SE	W	E	NE	AS	N	S	W	W	A	CSE
19	AN	SE	W	NE	NE	A	N	SE	W	ANW	A	C
20	A	SE	W	ASE	NE	AE	A	C	SW	SE	A	C
21	A	SE	W	E	N	U	A	CN	A	SE	AE	CNW
22	AS	S	ANW	CNE	SW	N	U	ANW	S	AS	A	CSW
23	S	SE	CNW	C	C	NE	C	U	S	A	S	SW
24	SW	S	AN	E	CSW	ANE	C	U	U	A	S	SW
25	ASW	S	ANW	CE	W	ANW	N	A	S	A	SW	W
26	SW	CW	ANW	CE	A	NW	U	A	SW	ASW	SW	W
27	W	W	N	E	ANE	N	N	N	AS	ANW	NW	W
28	W	ANW	A	E	NE	ANW	AN	ANE	S	AN	NW	W
29	W		W	E	E	NW	ANW	A	SE	A	S	ASW
30	NW		NW	U	E	N	A	ASW	S	W	S	ANW
31	SW		N		CSE		N	SW		AW		W

1984	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	W	CW	ANW	SE	E	CS	ANE	S	SW	SW	CSW	U
2	W	NW	AN	SW	NE	C	AN	C	SW	C	NW	S
3	NW	W	A	CS	C	C	A	C	CW	C	A	CSW
4	NW	SW	A	C	CE	CS	AS	N	N	NE	A	SW
5	W	W	A	U	E	CN	S	U	AN	N	E	CSW
6	W	W	A	NE	E	C	SW	NW	A	A	E	SW
7	NW	NW	A	E	E	NE	ASW	N	U	W	CE	SW
8	N	NW	A	A	A	N	S	ANW	W	W	C	U
9	ASW	A	A	A	A	U	S	AN	NW	AW	C	A
10	SW	A	A	AW	AN	A	CS	A	NW	ASW	SW	A
11	W	A	ANW	ANW	SW	ASW	SW	U	NW	ASW	S	AS
12	W	S	NE	AW	ASW	SW	CW	U	SW	SW	SW	S
13	W	AS	E	AW	A	W	W	A	SW	SW	SW	C
14	W	A	E	W	NW	AW	NW	U	NW	ASW	C	CNW
15	W	S	E	ANW	N	A	N	U	A	S	CS	C
16	W	SW	E	A	N	A	ANW	A	U	SW	NE	S
17	NW	SW	E	SW	N	A	A	S	NW	SW	ASE	W
18	A	S	A	SW	ANE	A	AN	S	NW	W	E	W
19	ANE	S	AW	SW	ANW	A	U	S	NW	CW	N	W
20	AS	CS	SW	SW	N	ANW	E	SE	NW	NW	CSW	W
21	S	C	SW	AW	N	ANW	AE	SE	NW	SW	SW	A
22	W	N	CSW	ASE	N	NW	E	C	NW	CW	SW	SW
23	CNW	A	C	S	NE	NW	E	U	N	AW	W	SW
24	NW	A	C	S	AN	NW	E	C	N	C	W	NW
25	S	A	C	SE	AN	ANW	NE	S	U	NW	W	W
26	C	AE	C	SE	NE	A	A	U	S	AW	ASW	C
27	N	A	C	SE	N	AN	A	A	SW	S	SW	S
28	SW	A	CN	U	U	N	AW	SW	CS	SW	SW	S
29	W	ANW	N	CS	ANW	N	SW	AW	SW	SW	S	S
30	W		SE	C	SW	AN	CW	W	W	SW	CS	SW
31	W		SE		CSW		U	SW		SW		A

1985	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	A	AW	C	C	A	A	ASW	ASW	NW	S	AN	S
2	AS	AW	CW	SW	AN	E	S	W	CS	S	AN	S
3	ASE	ASW	C	SW	ANE	E	S	W	NW	SW	ASW	SW
4	ASE	AS	NW	CS	U	CNE	S	C	C	SW	S	SW
5	ASE	SE	SW	CSW	CN	NE	NW	N	N	SW	NW	NW
6	A	S	SW	CSW	N	NE	A	NW	A	SW	W	SW
7	ANE	S	W	C	W	N	ASW	W	SW	SW	SW	W
8	A	S	SW	CN	ANW	NW	A	SW	SW	W	CS	CNW
9	A	S	SW	N	N	NW	ANW	SW	ASW	W	C	S
10	A	SE	A	W	AN	NW	AW	SW	AS	SW	N	SW
11	AS	SE	A	NW	U	W	SW	C	S	A	N	SW
12	S	SE	AW	W	U	NW	SW	CSW	W	AS	A	SW
13	SE	SE	A	W	CNE	N	U	CS	AW	AS	S	SW
14	ASE	SE	ANW	ANW	C	AN	N	C	W	A	NW	SW
15	A	SE	AN	SW	C	A	SW	CW	NW	AS	ASW	SW
16	SE	SE	AN	SW	SW	ASW	W	W	W	A	SW	ASW
17	E	AS	U	ASW	U	SW	SW	S	W	A	ASW	SW
18	C	S	SW	S	NE	ASW	W	SW	SW	A	AS	W
19	SE	SW	C	A	NE	SW	W	SW	W	AS	ASE	SW
20	CSE	S	CSW	A	CNE	S	W	SW	S	S	AE	SW
21	C	S	C	NE	CNE	C	SW	SW	SW	AS	E	SW
22	NW	SW	NE	E	U	CNW	CW	W	SW	A	ANE	SW
23	NW	SW	N	E	CSE	CW	SW	SW	SW	S	AE	SW
24	SW	S	NW	A	C	W	SW	NW	S	ASE	AE	S
25	C	S	U	A	S	SW	C	NW	S	E	AE	C
26	U	S	NE	A	CS	NW	CNW	SW	S	AS	ANE	E
27	CS	S	ANE	AN	W	NW	U	SW	S	A	N	E
28	W	S	A	AW	W	W	C	SW	S	A	A	A
29	W		S	NW	ASW	SW	CN	SE	S	A	SE	S
30	SW		CSW	NW	S	SW	N	SW	S	ANE	S	S
31	W		SW		ASW		N	CW		NE		W

1986	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	CS	NE	E	ANW	SW	NW	S	CS	W	ASW	NE	SW
2	C	NE	A	AN	CN	NW	SW	CW	W	A	AS	SW
3	N	NE	W	NE	NE	NW	SW	U	N	AS	ANW	SW
4	SW	NE	W	AE	C	NW	W	CNW	A	S	A	SW
5	NW	NE	W	E	C	N	U	S	A	SW	W	W
6	S	CE	AW	NE	C	N	NW	C	A	ASW	A	SW
7	C	E	SW	NE	C	ANW	W	NW	A	ASW	SW	SW
8	C	A	SW	E	W	SW	NW	A	A	SW	AW	CN
9	SW	S	W	E	SW	CSW	AW	U	AE	SW	SW	W
10	SW	S	W	E	W	C	ANW	U	AE	W	SW	S
11	W	S	SW	A	SW	AS	U	U	E	ASW	W	SW
12	NW	S	SW	ANW	C	SW	U	S	E	S	S	SW
13	W	SE	SW	CNW	W	SW	AW	SW	E	S	S	W
14	NW	SE	SW	C	W	AS	ASW	CSW	NE	AW	CS	SW
15	NW	SE	SW	CNE	ANW	SE	SW	W	NE	A	SW	SW
16	AW	SE	SW	NE	AS	C	SW	NW	AN	A	SW	W
17	W	E	SW	N	CS	NW	ANW	U	N	SW	SW	W
18	W	E	W	NW	SW	S	ANW	N	A	W	CSW	W
19	W	ASE	SW	W	SW	CSE	W	ANW	A	W	NW	NW
20	SW	SE	W	W	CSW	E	NW	AS	A	W	W	NW
21	W	ASE	W	C	W	E	NW	S	A	W	SW	N
22	W	SE	W	C	W	SE	N	C	A	W	W	AN
23	NW	E	AW	NE	W	SE	NW	CNE	A	NW	NW	A
24	N	E	NW	NE	SW	C	W	U	A	SW	W	SW
25	ASW	SE	ANW	ANW	SW	S	W	C	AS	NW	SW	W
26	SW	SE	SW	W	W	SE	W	N	A	SW	W	NW
27	NW	E	W	W	W	SE	SW	N	ASW	SW	SW	NW
28	W	E	W	W	ANW	SE	C	N	ASW	W	SW	W
29	CN		NW	W	A	U	NW	N	ASW	SW	ASW	SW
30	NE		W	SW	W	CS	C	N	AS	W	SW	SW
31	NE		NW		NW		NW	AW		SW		W

1987	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	CW	S	CSW	NW	ANW	ASW	AW	NW	A	SE	A	ASE
2	NW	S	A	NE	AN	S	ASW	NW	S	E	A	E
3	ASW	A	SW	CE	AN	C	ASW	NW	SW	E	A	E
4	W	SW	W	CE	A	C	ASW	AN	SW	SE	SE	E
5	NW	SW	SW	CE	A	C	ASW	A	W	U	SE	E
6	AN	W	SW	C	ASW	C	ANW	U	W	NW	S	E
7	A	SW	C	C	ASW	N	AN	N	AW	C	S	E
8	S	SW	CSW	C	A	N	A	N	ASW	NW	C	ASE
9	C	C	CSE	W	A	N	SW	ANW	SW	CW	U	A
10	C	W	CSE	W	A	CN	SW	S	W	N	SW	ASE
11	SE	CNW	SE	ANW	NW	CN	W	SW	S	SW	SW	SE
12	SE	U	A	W	N	N	ASW	SW	W	SW	W	S
13	NE	CSE	W	W	ANW	N	S	W	ASW	CW	NW	SE
14	NE	U	A	W	N	CN	S	A	W	SW	AW	SE
15	NE	U	A	A	AN	N	SW	ASW	SW	U	SW	S
16	AS	AE	ANW	A	W	NW	CSW	ASW	ASW	W	W	S
17	S	ANE	ANW	S	NW	NW	N	SW	U	S	ASW	SW
18	S	AN	AN	SW	N	CSW	N	AS	A	CSW	SW	W
19	S	A	AN	W	ANE	N	CN	S	S	S	ANW	SW
20	SW	A	A	AW	ANE	NW	N	S	SW	C	ANW	SW
21	A	A	W	SW	ANE	W	N	U	SW	NW	ANW	SW
22	A	A	W	S	NE	W	NE	N	SW	AW	N	AS
23	AE	SE	C	SW	E	W	N	N	SW	A	N	S
24	ASE	S	C	S	E	U	N	AN	NW	A	NE	S
25	A	S	W	CSE	CSE	C	N	ANW	AN	SW	NE	SW
26	ASE	S	SW	A	CSE	S	NW	N	AN	SW	AN	SW
27	ASE	SW	C	ASW	U	SW	NW	AN	A	U	A	SW
28	ASE	SW	AN	S	ANW	SW	NW	AW	AS	S	S	SW
29	SE		A	CS	SW	SW	NW	A	AS	S	N	SW
30	ASE		W	U	W	SW	NW	A	S	SE	A	S
31	S		W		W		NW	S		U		W

1988	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	W	C	AN	W	CSE	SW	CW	U	C	SW	A	NE
2	W	W	AW	NE	CE	SW	C	AN	NW	SW	SE	C
3	NW	CSW	AN	A	CNE	CW	C	AW	W	SW	S	SW
4	CW	CNW	AN	A	CNW	N	CN	ASW	SW	CSW	S	NW
5	S	W	ANW	A	W	A	CN	SW	SW	NW	A	NW
6	N	N	ANW	A	SW	SW	CNW	AS	S	W	A	NW
7	ASW	W	ANW	ANE	CS	N	W	AS	S	NW	S	A
8	SW	W	AW	NE	N	NE	W	S	U	W	S	AW
9	SW	W	AW	A	ANW	NE	SW	SW	ASW	NW	SW	AW
10	SW	NW	A	A	SW	E	SW	SW	SW	S	SW	A
11	SW	NW	AW	A	C	NE	W	SW	ANW	CE	ASW	AW
12	S	ASW	ANW	E	C	NE	SW	W	NW	CN	AW	A
13	SW	SW	W	S	C	NE	CNW	SW	N	C	A	A
14	SW	CS	SW	SW	CSE	NE	N	CW	A	E	A	A
15	AW	W	CSW	SW	CE	AN	A	A	A	A	S	S
16	ASW	A	CN	CSW	NE	N	W	AS	A	ASE	S	A
17	U	A	C	S	NE	ANE	NW	S	A	S	CSW	A
18	S	A	CSW	C	NE	A	SW	SW	A	CSE	N	W
19	CSW	A	SW	CS	ANE	A	W	CW	A	CS	A	NW
20	CW	A	SW	SW	A	A	ASW	NW	ASW	S	NE	W
21	W	A	W	S	S	NW	CS	N	SW	S	A	AW
22	N	A	W	CS	S	A	CSW	U	SW	S	A	SW
23	SW	AN	W	CS	C	A	CSW	AW	NW	SE	A	W
24	SW	AN	W	U	CSW	A	SW	NW	W	S	A	W
25	C	N	W	A	SW	AN	SW	NW	SW	S	ASE	SW
26	C	N	ANW	U	CW	NE	W	SW	W	SW	A	SW
27	SE	N	W	C	W	NE	SW	W	SW	W	AS	SW
28	CS	N	W	CS	C	N	C	W	NW	E	SW	SW
29	C	N	NW	C	C	U	W	W	NW	AE	SW	SW
30	NW		N	CSE	CW	C	W	SW	A	ASE	C	ASW
31	SW		NW		W		U	SW		ASE		S

1989	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	S	SW	AN	C	SW	N	NW	NW	ANW	A	SW	ASE
2	S	SW	C	C	SW	NW	A	ANW	A	A	CSW	A
3	S	SW	CW	CE	SW	CN	AS	A	ASW	S	NW	ASE
4	W	W	W	NE	A	N	A	A	ANW	S	NW	SE
5	SW	SW	SW	C	A	N	A	SW	A	NW	N	ASE
6	NW	SW	SW	CN	A	N	NE	U	AW	NW	SW	AE
7	A	SW	W	NW	A	AN	N	AW	U	NW	W	AE
8	SW	S	SW	ASW	A	SW	N	SW	NE	N	NW	ASE
9	W	S	SW	SW	A	S	AN	CW	NE	N	SW	ASE
10	A	AW	W	W	A	S	ANW	SW	NE	ANW	CSW	S
11	SW	SW	W	C	NW	S	ANW	W	NE	NW	SW	S
12	W	AW	CSW	AW	N	S	N	W	U	NW	E	S
13	SW	W	ANW	NW	W	SW	N	SW	W	NW	AS	CSE
14	W	AW	SW	U	SW	A	N	SW	SW	ANW	AS	C
15	SW	NW	A	A	SW	ASW	AN	SW	SW	SW	SE	E
16	SW	A	NE	N	W	A	A	SW	AW	SW	SE	CSE
17	A	SW	W	ANE	SW	AS	A	W	AS	SW	S	C
18	ASW	SW	W	ASE	ASW	A	U	ASW	SW	S	SE	U
19	SW	W	W	AE	S	AE	S	SW	SW	SW	SE	S
20	SW	W	W	E	CS	N	S	SW	SW	SW	SE	CS
21	NW	SW	W	E	CSE	AN	CS	SW	SW	SW	E	CSW
22	SW	W	W	E	C	A	U	AW	NW	SW	E	ANW
23	SW	W	W	ANE	U	AN	U	AW	SW	W	A	SW
24	S	CN	AW	A	NE	AW	S	W	S	SW	A	SW
25	S	CN	SW	A	NE	SW	SW	NW	ASW	W	E	SW
26	SW	NW	SW	NW	ANE	CW	W	NW	AW	A	A	A
27	SW	NW	W	N	A	NW	AW	AN	AN	CE	A	ASE
28	AW	NW	A	SW	A	W	W	SW	A	CNW	SE	SE
29	ASW		SW	W	A	U	W	SW	A	W	SE	S
30	A		SW	SW	ANE	SW	N	W	A	SW	ASE	S
31	AS		SW		A		NW	ANW		SW		S

1990	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	S	SW	ANW	CSE	S	W	NW	S	A	SW	N	A
2	S	W	A	N	S	NW	ANW	S	ASW	SW	N	A
3	S	SW	W	AN	U	NW	ASW	U	NW	NW	N	A
4	S	SW	AW	A	U	W	CSW	ANW	A	W	A	A
5	S	SW	AW	SW	A	W	NW	N	W	W	A	A
6	SW	S	W	S	A	CW	W	AN	NW	CNW	ASE	A
7	SW	CSW	AW	E	AN	NW	W	A	N	N	SE	CN
8	SW	W	W	A	N	N	W	AW	A	A	SE	N
9	SW	SW	W	AW	NW	N	NW	AW	A	W	S	N
10	SW	SW	W	AW	U	N	ANW	SW	A	W	SW	N
11	SW	CW	AW	W	U	N	A	W	A	SW	S	ANW
12	W	NW	SW	W	SE	ANE	A	W	ANE	S	S	N
13	SW	W	SW	W	SE	A	ASE	W	A	S	SW	A
14	W	W	SW	W	SE	AS	S	SW	ANE	SW	NW	AS
15	W	ANW	SW	ANW	C	S	U	CNW	AE	CSW	AW	AS
16	SW	S	SW	W	C	S	A	NW	A	ASW	W	A
17	W	SW	SW	NW	U	S	A	W	NW	NE	W	S
18	SW	SW	SW	W	E	SW	S	CW	W	N	NW	U
19	SW	SW	W	N	E	CSW	S	CNW	NW	SE	NW	ANW
20	ASW	SW	W	NE	E	C	AN	ANW	NW	S	NW	W
21	SW	SW	W	NE	ANE	C	NE	ASW	NW	SE	N	W
22	SW	SW	AW	NE	ANW	NW	E	U	NW	SE	A	SW
23	W	SW	W	U	A	W	SE	U	N	CSE	CSW	SW
24	W	SW	ANW	AW	A	SW	S	U	NW	CS	C	SW
25	C	SW	A	W	SE	SW	S	U	AE	CS	N	W
26	W	W	AW	AW	SE	U	S	SW	AE	C	NE	W
27	CW	NW	W	A	S	NW	C	S	A	CW	ANE	NW
28	W	NW	AW	W	SW	SW	S	S	ASW	NW	A	SW
29	S		AW	ASW	W	S	S	W	U	W	A	W
30	SW		A	SW	SW	C	SW	W	N	CW	A	SW
31	CSW		AS		SW		AS	SW		NW		SW