Key Meteorological Indicators of Climate Change in Ireland

Environmental Research Centre Report

Prepared for the Environmental Protection Agency
by
Irish Climate Analysis and Research Units (ICARUS)
Department of Geography,
National University of Ireland, Maynooth

Authors:

Laura McElwain and John Sweeney

ENVIRONMENTAL PROTECTION AGENCY

An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
E-mail: info@epa.ie Website: www.epa.ie

LoCall 1890 33 55 99

ACKNOWLEDGEMENT

This report has been prepared through the Environmental Research Centre, a measure of the ERTDI Programme which is financed by the Irish Government under the National Development Plan 2000–2006. It is administered on behalf of the Department of the Environment, Heritage and Local Government by the Environmental Protection Agency which has the statutory function of coordinating and promoting environmental research.

DISCLAIMER

Reports produced through the Environmental Research Centre are intended as contributions to inform policy makers and other stakeholders to the necessary debate on the environment.

ENVIRONMENTAL RESEARCH CENTRE PROGRAMME 2000–2006

Published by the Environmental Protection Agency, Ireland

PRINTED ON RECYCLED PAPER

ISBN: 1-84095-222-9
Price: Free

04/07/300

Details of Project Partners

Laura McElwain,
Irish Climate Analysis & Research Units,
Department of Geography,
Rhetoric House,
Co. Kildare,
Ireland
Tel. +353 1 708 6469
E-mail: Laura.C.McElwain@nuim.ie

John Sweeney,
Irish Climate Analysis & Research Units,
Department of Geography,
Rhetoric House,
Co. Kildare,
Ireland
Tel.: +353 1 708 3684
E-mail: John.sweeney@nuim.ie

Table of Contents

List of Figures

List of Tables

Executive Summary

Evidence for an anthropogenic influence on climate change is now stronger than ever before, with the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report assertion that 'It is *very likely* that anthropogenic greenhouse gas increases caused most of the observed increase in globally averaged temperatures since the mid-20th century' (IPCC, 2007a). Global average temperature has increased by 0.74°C over the past 100 years with the rate of warming almost doubling over the last 50 years. Precipitation patterns have also changed with an increase in the number of heavy precipitation events being observed globally.

In order to determine if global trends are reflected in changes in climate at the regional and local level in Ireland, a number of potential indicators of climate change have been investigated. Based on existing observational data, indicators can provide an early warning system, which may point to a critical environmental problem in the future. Climate indicators for Ireland are based primarily on daily synoptic station temperature and precipitation data from Met Éireann's monitoring network. Some of the key findings include:

- Mean annual temperature records closely resemble global trends, with warming evident in 2 periods, 1910 to the mid-1940s, and 1980 to 2004. The warming in the latter period occurred at a much greater rate than the global temperature increase.
- Nearly all stations reveal increases in annual and seasonal mean maximum and minimum temperatures.
- For the 1961 to 2005 period, the majority of stations recorded minimum temperatures increasing at a faster rate than maximum temperatures in spring, summer and autumn. In winter, 6 of the 11 stations have maximum temperatures increasing at a faster rate than minimum temperatures, and these are predominantly on the east coast.
- With minimum temperatures increasing, the number of frost days has decreased significantly at all stations, especially in the midlands, while the length of the frost season also decreased at all stations, except Valentia.
- Heat waves are a cause for concern because of their impact on, for example, human health,

agriculture and water supply. With global warming, it is thought that heat waves may increase in severity, frequency or duration in the future. The number of heat waves has increased at a number of stations annually, with greater increases in winter, spring and summer heat waves. Similarly, cold waves have also decreased at a number of stations. Cold waves generally occur in autumn and winter.

- Changes to precipitation patterns are more spatially and seasonally variable than temperature changes. There are increases in precipitation to the north of the country, with 4 out of 5 of the wettest years on record at Malin Head occurring since 1990. No significant trends are found at the long-term station of Birr.
- The greatest increases for maximum number of consecutive wet days occur at the west coast stations of Belmullet, Claremorris, Malin Head and Valentia.
- Rainfall intensity is an important indicator of climate change. The number of days where daily precipitation is greater than or equal to 10 mm reveals significant annual increases on the west coast and non-significant decreases at the east coast.

The trends identified are largely consistent with global trends. The majority of the indicators do not, as yet, reveal significant change, although those that do are important. Ireland is warmer, with warmer nights and fewer cold days. The west, southwest and north are wetter, with more frequent rainfall and also more intense rainfall. More frequent and intense rainfall is important for river flood management and the engineering and infrastructure industries, while in summer, water shortages will impact upon reservoirs and soil management. It is imperative therefore to maintain and monitor key climate variables in order to identify trends which may be an important guide for future change.

Introduction

Climate change as a consequence of the build up of greenhouse gases in the atmosphere will alter the climate norms in Ireland. 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. Ireland's oceanic position however, may moderate this increase. Annual precipitation increases would also be likely for Ireland as a consequence of a warmer atmosphere maintaining more moisture.

In recent years there has been an increased awareness of the potential impacts of climate change on a variety of sectors in society (2007b). 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 regularly examine trends in Irish climate related data.

Within this context, the following report will outline the spatial and temporal variation in the observational surface climate record, including temperature, precipitation and extreme events, based on daily synoptic station data from the Met Éireann database. Temporal and spatial variability of these climatic indicators is studied to determine whether the model projections from the latest Intergovernmental Panel on Climate Change (IPCC), (2007a) report can already be seen in the Irish observational record (See Appendix 1 for model projections). This work reviews and develops analysis in *Climate Change: Indicators for Ireland* (2002).

Data and Methodology

Long-term observations of temperature and precipitation in Ireland began in the 19th century, and some have continued up to the present. The records are considered reliable from about 1890 onwards.

Eleven synoptic stations for which there are nearly complete records (*e.g.* Claremorris is missing some months in 1997) are used in this analysis (see Figure 1). For a number of stations (Valentia, Birr, Malin Head and Armagh for temperature, Malin Head and Birr for precipitation) monthly records extend back to 1890. These are used for the indices of mean annual temperature and total annual precipitation. In all other indices, the daily data are from start of record for each station, which can be seen in Table 1. Indices are calculated for each standard season and year, for each station. The magnitude of trends is estimated using the linear regression method, while the statistical significance is evaluated using the Kendall-Tau test (Tomozeiu *et al.*, 2003). Apart from a small number of indicators, there are few statistically significant trends. Anomalies are from the baseline period of 1961 – 1990, the baseline used by the World Meteorological Organisation.

Figure 1 Location of weather stations in Ireland which are used in the report

Table 1 Start and end date of daily data for temperature and precipitation

	Start Date		End Date
	Temperature	Precipitation	Temperature/Precipitation
Valentia	1940	1941	March 2005
Shannon	1945	1941	March 2005
Malin	1955	1957	March 2005
Belmullet	1956	1956	March 2005
Phoenix Park	1961	1941	March 2005
Clones	1950	1950	March 2005
Rosslare	1957	1957	March 2005
Claremorris	1950	1944	March 2005
Kilkenny	1957	1957	March 2005
Casement	1961	1954	March 2005
Birr	1955	1955	March 2005

A number of the indices have been calculated using STARDEX (Statistical and Regional Dynamic Downscaling of Extremes for European regions) extremes www.cru.uea.ac.uk/cru/projects/stardex/ indices software.

This was a European Commission funded project created to improve methodologies for downscaling extreme rainfall and temperature from climate models. There are a number of categories for investigating extremes including:

- percentile based indices (*e.g.* 10^{th} or 90^{th} percentile of minimum/ maximum temperature);
- absolute indices (*e.g.* maximum 5 day precipitation);
- threshold indices (*e.g.* days with precipitation greater than 10 mm);
- duration indices (*e.g.* heat wave duration);
- and, others which have a significant societal impact (*e.g.* intensity of daily rainfall) (Sillmann, 2005).

A change in the mean or the intensity or frequency of extreme events can affect substantially ecosystems, society and the economy of a region. Extreme events are severe, rare and intense. They are determined by their spatial scale (thunderstorm, river flooding, heat wave); temporal scale (hours, days, weeks); complexity (1 or more variables) (Sillmann, 2005). Economic losses due to extreme events have increased in the last decades. Problems however can arise when investigating daily extremes with issues of data availability and homogeneity. In terms of future modelling of extremes there are also issues with the accuracy of daily temperature and precipitation data from Global Climate Models.

Primary Indicators

This section assesses the observed surface climate to update and expand the previous indicators report for Ireland "Climate Change: Indicators for Ireland" published in 2002, with data from 2000 up to early 2005. In the previous report, only a limited number of indicators were examined. A more consistent database now exists, and a greater array of indices. The STARDEX indicators are utilised in this report to maintain consistency and comparability with other countries in Europe and further afield. The indicators used are listed in Table 2. The temperature indicators measure the magnitude and frequency of events, while the precipitation indicators are measuring intensity, frequency and duration of events.

Table 2 List of indicators used in analysis

Indicator	Number of stations	Unit
Global and Irish air temperature anomaly	4	^{o}C/year
Long-term mean annual air temperature index	4	^{o}C/year
Annual and seasonal mean temperature	11	^{o}C/year
Seasonal maximum and minimum temperature	11	^{o}C/year
Diurnal temperature range (DTR)	11	^{o}C/year
Number of frost days	11	No. of days
Frost seasonal length	11	No. of days
Heat and cold waves	11	No. of days
Long-term total annual precipitation	2	mm/year
Annual and seasonal total precipitation	11	mm/year
Maximum number of consecutive wet and dry days	11	No. of days
Number of days when precipitation greater than, or equal to, 10 mm	11	No. of days
Greatest 3-day, 5-day, 10-day rainfall totals	11	mm
Number of events greater than 90th percentile	11	No. of events

Air Temperature Indicators in Ireland

Global and Irish Air Temperature Anomaly

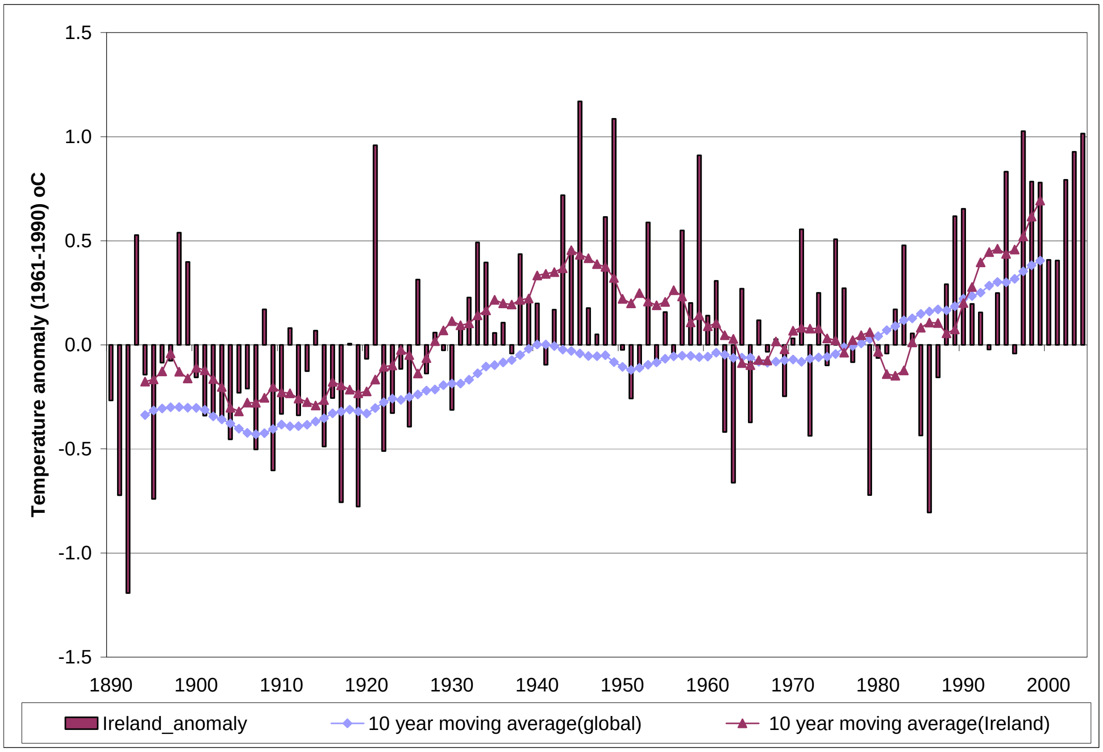

Figure 2 Global and national air temperature anomaly, from the 1961-1990 mean

This analysis is based on data from four stations - Valentia, Malin Head, Armagh and Birr. The monthly temperature records for these sites extend back to 1890. Figure 2 shows an air temperature anomaly for the Irish record, based on the calculation of an annual anomaly[1] for each station from its 1961-1990 baseline period. The average of these data are plotted alongside the 10-year moving average of the combined global land and marine surface temperature record

obtained from the Climate Research Unit (CRU), University of East Anglia.

The global trend shows warming of greater than 0.6^{o} C over the 20th century and up to 2005. This warming is not linear, with greatest warming being observed in the temperature record since the mid 1970s. The global data shows warming from 1910 to 1940, slight cooling

[1] Anomaly, departure from normal; in this case, the difference between the annual value and the 1961-1990 average value.

up to the mid 1970s and thereafter above average warming continuing to the end of the series.

The Irish record shows greater interannual variability but it follows a similar pattern as seen in the global data. Ireland's warmest year occurred in 1945, while 1998 was the warmest year in the global record. According to the CRU (Jones, 2006), 2005 was the second warmest year globally. On the other hand, scientists at the North American Space Agency's (NASA) Goddard Institute for Space Studies (GISS) noted that 2005 was the warmest year on record, with the inclusion of data from a number of stations in the Arctic as the main cause of the difference (Hansen *et al.*, 2006). The Fourth Assessment Report (IPCC, 2007a) reported that eleven of the last twelve years (1995-2006) were the warmest on record globally.

Long-term Mean Annual Air Temperature Index

The mean annual air temperature index has been derived from the average of the mean annual temperatures for the four stations (see Figure 3). This statistic indicates that 6 of the 10 warmest years on record have occurred since 1995. The warmest year within this period was 1997. The warmest year in the global analysis is 1998.

The record for Ireland shows clear periods of warming, 1910-1949 and 1980 to 2004. The temperature increase in the latter period has been larger, and the rate of increase more rapid than in the 1910-1949 period. Temperature increases by 0.7^{o}C during the period 1890-2004, at a rate of 0.06^{o}C per decade. From 1910 to 1949 the rate of warming was 0.23^{o}C per decade, while the warming for the latter period, 1980-2004 was 0.42^{o}C per decade. The warming signal is significant at the 99% level. The cooling in the years 1950-1979 is the only period in which there is a non-significant change, with a cooling of 0.06^{o}C per decade and a cooling of 0.19^{o}C for the whole period.

Mean Maximum, Mean Minimum and Mean Temperatures

The most commonly used definition of mean temperature is the mean of the daily maximum and daily minimum temperatures. Annual mean temperature increased significantly at all stations, the rate of increase ranging from 0.05^{o}C per decade at Valentia to 0.3^{o}C per decade at Casement. Figure 4 shows the seasonal and annual mean temperature change for the period 1961 to 2005 at each station. As can be seen, the greatest increase on a seasonal basis at most stations is winter, with the exceptions of Phoenix Park and Clones. Autumn displays the lowest rate of increase in temperature at all stations, with the exception of Valentia. Mean annual temperature increases are significant at the 99% level for all stations.

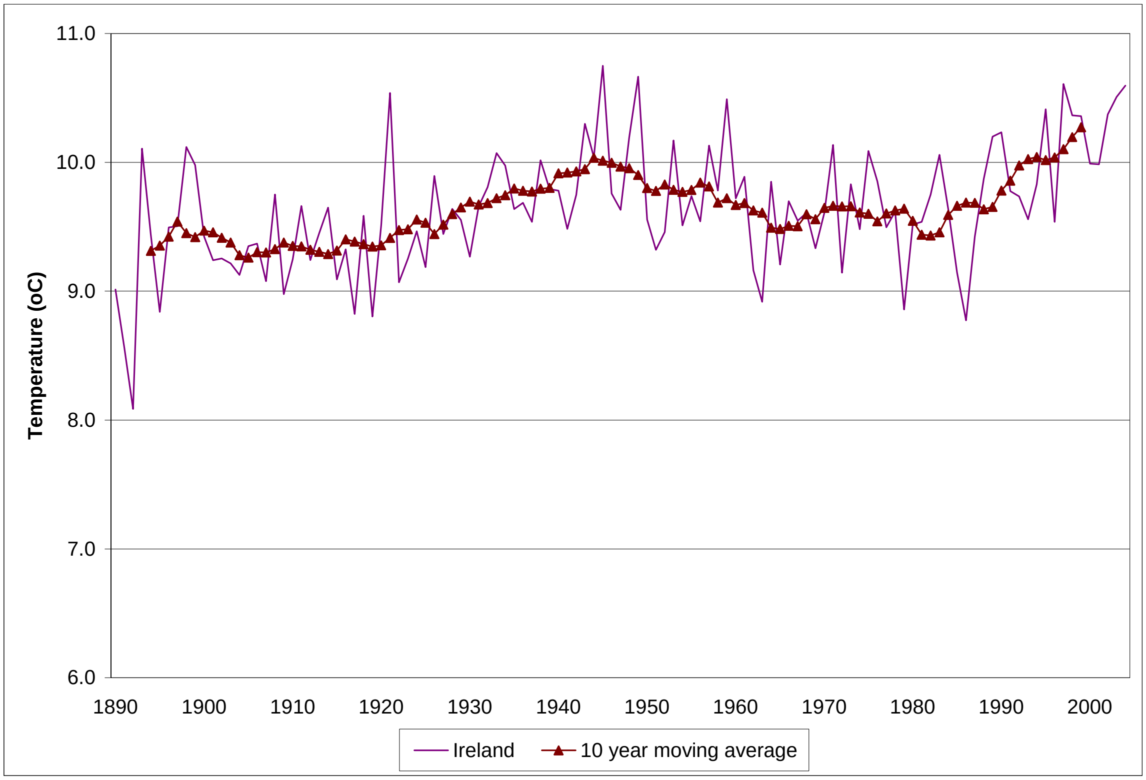

Figure 3 **Mean annual air temperature index, 1890-2004**

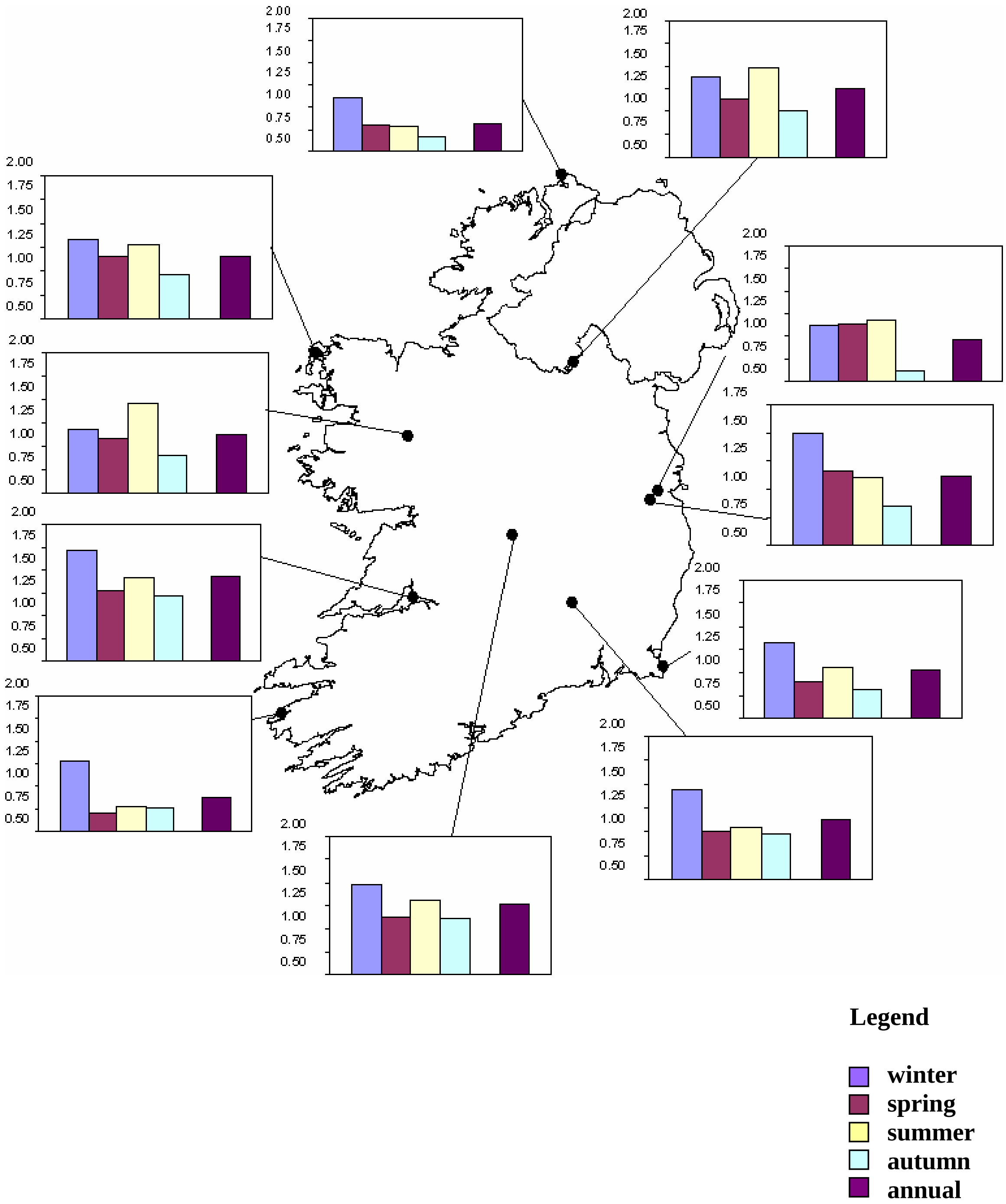

Figure 4 **Change in annual and seasonal mean temperature for the 1961-2005 period. Vertical scale is change in temperature over that period.**

Mean Maximum Temperature

All stations display an increase in the annual mean maximum temperature, significant at the 95% level or greater except for Valentia. The largest increases occurred at Kilkenny, Casement and Phoenix Park. The smallest increases are at the west coast stations of Malin Head and Valentia. Increases are greatest in winter for all stations except Clones. Spring in Valentia is the only season and station to show a decrease in mean maximum temperature, of 0.03^{o}C per decade (0.2^{o}C since 1940). For the 11 stations, there are complete records from 1961 to 2005 (44 to 45 years). The all-station analysis over this period reveals greatest increases in winter (1.37^{o}C), followed by spring (1.16^{o}C), summer (1.07^{o}C) and autumn (0.83^{o}C). The increase in annual mean maximum temperatures, averaged for all 11 stations, is an increase of 1.10^{o}C since 1961.

Mean Minimum Temperature

The general pattern of the annual mean minimum temperature trend is similar to the maximum temperature trend with a warming during all seasons. Mean minimum temperature increases significantly for all stations. Seasonal mean minimum temperatures for the period 1961-2005 reveal greatest increases in summer (1.34^{o}C) followed by 1.27^{o}C in winter, 1.19^{o}C in spring, 0.93^{o}C in autumn. The increase in annual mean minimum temperatures, averaged for all stations for the period 1961-2005, is 1.15^{o}C.

Figure 5 shows the variation in summer and winter mean maximum and mean minimum temperatures for 4 stations. The temporal variations in maximum and minimum temperature trends are generally the same at all stations.

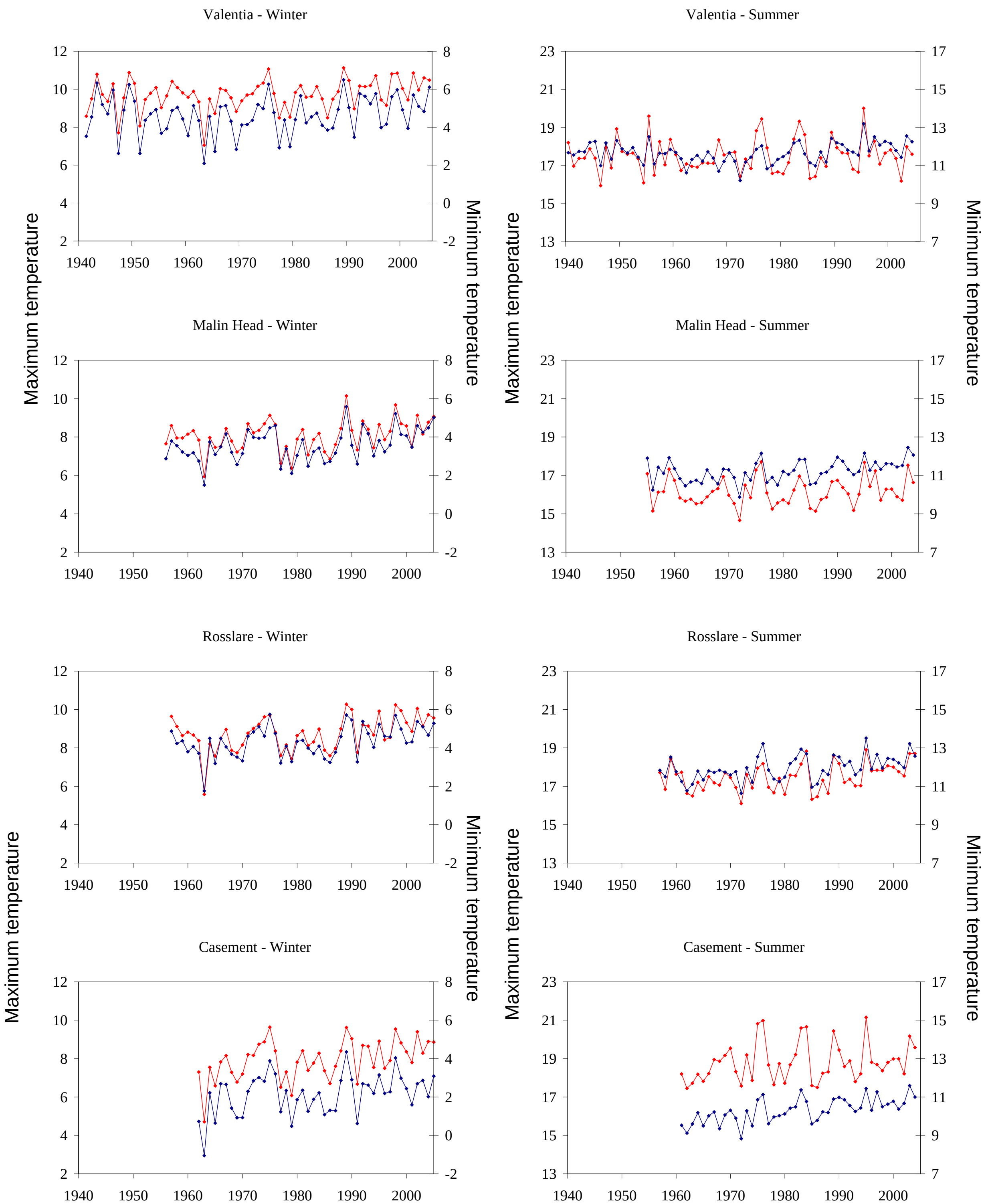

Figure 5 Winter and summer mean maximum and mean minimum temperatures for length of station record. (red line = maximum temperature; blue line = minimum temperature)

Table 3 Increases in maximum and minimum temperature over the period 1961- 2005 for 11 stations.

1961-2005	Spring Max	Spring Min	Summer Max	Summer Min	Autumn Max	Autumn Min	Winter Max	Winter Min
Valentia	0.68*	1.05*	0.43	1.20**	0.54	0.87*	1.17**	1.34*
Shannon	1.27**	1.58**	1.18*	1.70**	1.01*	1.28**	1.50**	1.83**
Malin	0.75*	1.18**	0.63	1.13**	0.47	0.84**	1.04*	1.20**
Belmullet	1.40**	1.21**	1.30**	1.39**	1.16**	0.80*	1.44**	1.23*
Phoenix Park	1.41**	0.88*	1.43**	0.92**	0.84*	0.41	2.52**	0.85
Clones	1.27**	1.33**	1.36**	1.63**	0.92**	1.04*	1.33**	1.41*
Rosslare	1.06**	1.28**	1.12**	1.19**	0.97**	1.02**	1.62**	1.32**
Claremorris	1.32**	1.19**	1.25**	1.49**	0.92*	0.84*	1.22**	1.32*
Kilkenny	1.40**	1.18**	1.22*	1.46**	0.95*	1.21**	1.52**	1.40**
Casement	1.05**	1.27**	0.83*	1.40**	0.55	1.15**	1.61**	1.36*
Birr	1.18**	0.95*	0.98*	1.21**	0.77*	0.77	1.44**	1.14*

* indicates significance at the 95% level. ** indicates significance at the 99% level.

For the 1961-2005 period, some significant trends emerge when comparing the changes in seasonal mean maximum and mean minimum temperature (See Table 3). Nearly all stations and seasons reveal an increasing significant trend, at either the 95 or 99% level. A greater number of stations have mean minimum temperatures increasing more than mean maximum temperature in spring, summer and autumn. All stations, except Phoenix Park, have mean minimum temperature increases greater than mean maxima in summer, and all mean minima changes are significant at the 99% level. In winter, 6 of the 11 stations have mean maximum temperatures increasing at a greater rate than mean minimum, (Birr, Casement, Phoenix Park, Kilkenny and Rosslare), with Belmullet on the west coast making up the 6th station.

Diurnal Temperature Range

Diurnal temperature range, DTR, is defined as the difference between the daytime maximum temperature and night time minimum temperature. There has been a general, but not global, tendency for a reduced DTR, at least since the middle of the 20th century. This is confirmed with data representing more than 50% of the global land mass

(Easterling *et al.*, 1997). The effect is more pronounced in the Northern Hemisphere than in the Southern Hemisphere, probably related to an increase in cloud cover that could be linked to an increase in anthropogenic aerosols (Brunetti *et al.*, 2000). In some areas DTR has decreased because of a smaller increase in daily maxima, compared to minima (Brunetti *et al.*, 2000).

In Ireland, there are contradictory trends, with variation from season to season and from station to station. Phoenix Park shows an increasing DTR in all seasons, while Shannon, Malin Head, Birr and Clones have a decreasing DTR in all seasons. The greatest decreases are found at Shannon, and these decreases are statistically significant at the 99% level. All stations, except Phoenix Park and Belmullet have a decreasing annual DTR, primarily due to minimum temperatures increasing at a faster rate than maximum temperatures. Table 4 shows the change in DTR for each station for the length of station record.

Table 4 Change in Diurnal Temperature Range over the period of record for each station

Station (length of record)	Winter	Spring	Summer	Autumn	Annual
Valentia (65)	1.17	-0.57*	-0.24	-0.03	-0.15
Shannon (60)	-0.94**	-1.38**	-0.92**	-0.63**	-0.98**
Malin Head (50)	-0.29	-0.44**	-0.50**	-0.27	-0.36**
Belmullet (49)	0.10	0.15	-0.15	0.38	0.14
Phoenix Park (44)	0.98**	0.54*	0.52	0.41	0.61**
Clones (55)	-0.48*	-0.45	-0.28	-0.27	-0.35*
Rosslare (48)	0.09	-0.06	-0.18	-0.10	-0.04
Claremorris (55)	-0.26	-0.09	-0.07	0.12	-0.08
Kilkenny (48)	-0.19	0.23	-0.27	-0.35	-0.10
Casement (44)	0.26	-0.22	-0.58	-0.59**	-0.29**
Birr (50)	-0.14	-0.12	-0.42	-0.07	-0.19

* indicates significance at the 95% level. ** indicates significance at the 99% level.

A decrease in DTR would be consistent with an increase in cloudiness which has been highlighted by Palle and Butler (2001) – they have remarked on gradually increasing cloud levels over Ireland since the late 19th century that is also evidenced from declining number of sunshine hours as well as other data. The decrease in the DTR is in general agreement with results found for the northern hemisphere (Karl *et al.*, 1993). They found that the decrease in the DTR is approximately equal to the increase in mean temperature. In our case the observed warming was somewhat larger than the decrease in DTR. Other authors have found a good correlation between increased cloudiness and decreased DTR. However, it still unknown what causes the increase in cloud cover. Atmospheric circulation also plays a role as it governs the day-to-day temperature change (Przybylak, 2000).

Number of Frost Days

There is also a change in extreme temperature indices. The increase in minimum temperatures, especially in winter and spring is associated with a decrease in the number of frost days. Frost day indices are defined as the annual and seasonal count of days when the minimum temperature is less than 0^{o}C. The number of frost days has decreased significantly at all stations, with greatest decreases for the stations at Shannon and Clones. The greatest seasonal decreases are revealed in winter and spring. The decreases in days over the length of station record, on an annual basis, range from 5.0 days at Phoenix Park (45 years) to 32.5 days at Shannon (59 years). Table 5 displays the seasonal and annual decrease in frost days for each of the stations over the length of station record. The time series of frost days for Birr and Shannon are shown in Figure 6.

Table 5 **Seasonal and annual decrease in number of frost days over length of station record**

Station (length of record in years)	Spring	Summer	Autumn	Winter	Annual	Annual (percentage)
Valentia (65)	-1.3		-1.3	-4.6	-7.2	-30%
Shannon (60)	-10.2		-4.2	-16.8	-32.5	-88%
Malin Head (50)	-1.5			-7.5	-8.3	-46%
Belmullet (49)	-2.1		-0.1	-4.4	-6.2	-31%
Phoenix Park (44)	-2.7		-1.8	-3.1	-5.0	-14%
Clones (55)	-5.0		-2.7	-17.3	-24.3	-38%
Rosslare (48)	-2.0		-0.5	-6.4	-8.6	-66%
Claremorris (55)	-3.3		-1.7	-13.8	-17.6	-35%
Kilkenny (48)	-2.9		-3.8	-10.6	-16.0	-38%
Casement (44)	-4.1		-4.4	-9.2	-17.2	-41%
Birr (50)	-4.1		-3.0	-11.2	-18.5	-23%

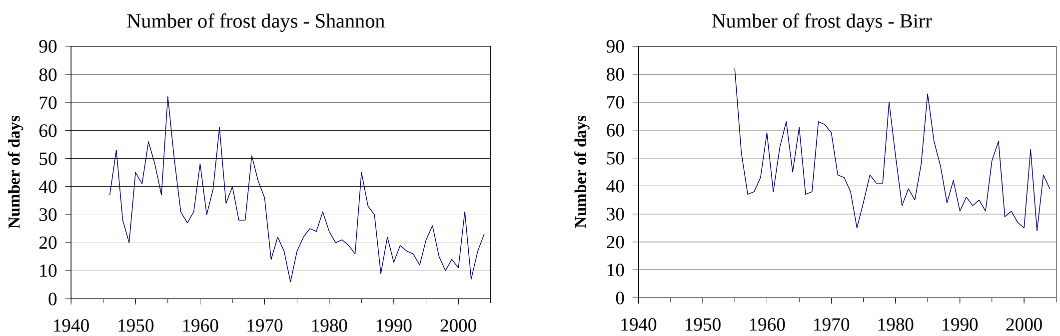

Figure 6 **Number of frost days at Shannon and Birr**

Frost Season Length

Frost season length is defined as the number of days between the date of first and last frost. An early frost can lead to crop failure, while late frost can shorten the growing season. The frost season length has decreased at all stations except Valentia. At a number of these the decreases are significant, at the 99% level for Shannon and Rosslare, and at the 95% level for Clones and Belmullet. The decrease in frost season length ranges from 5 days at Phoenix Park to 73 days at Shannon. Figure 7 displays the length of frost season at a number of stations Shannon, Clones, Belmullet and Kilkenny. Variability between stations is quite large, with stations on the coast having very short seasons, while those inland can have up to 250 days between first and last frost.

.

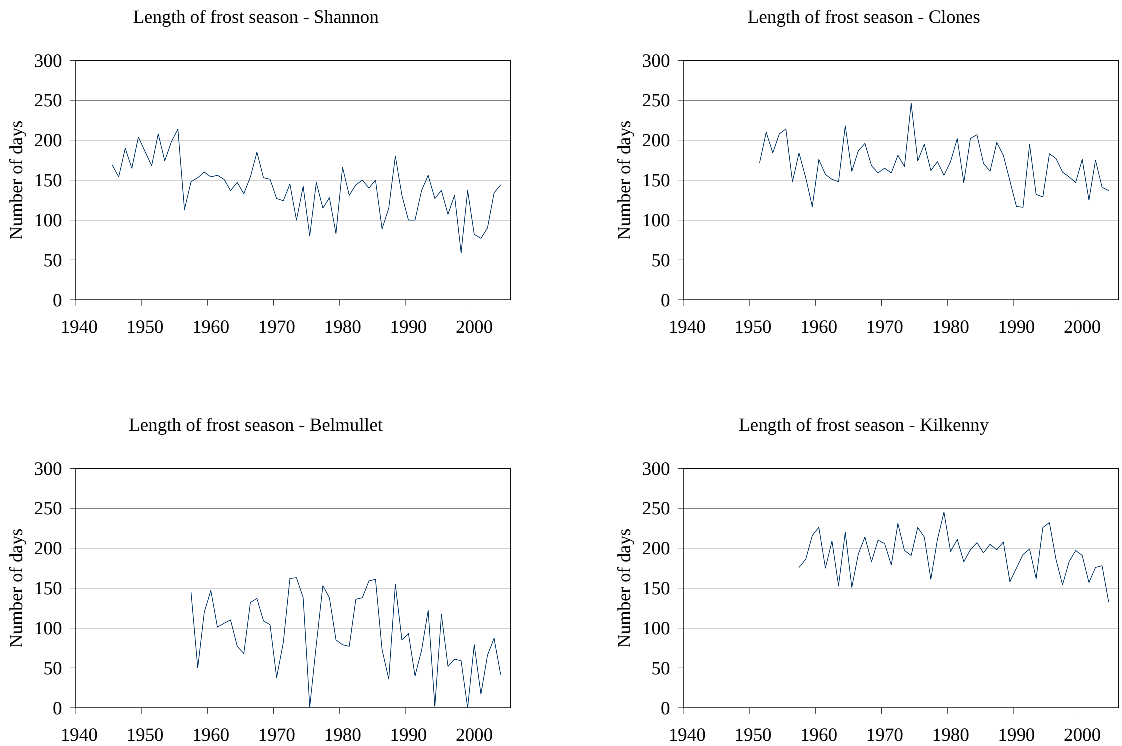

Figure 7 Frost season length at Shannon, Clones, Belmullet and Kilkenny

Heat Wave Duration and Cold Wave Duration

Heat waves are a major cause of weather related deaths. With global warming it is predicted that heat waves will increase in severity, frequency, duration or a real extent in the future (Robinson, 2001). The heat wave in Western Europe during the summer of 2003 claimed more than 35,000 lives (Schar *et al.*, 2004; Souch and Grimmond, 2004). The heat wave duration (HWD) index is defined as the total number of days when, for at least 6 consecutive days, the maximum temperature is at least 5^{o}C greater than the 1961-1990 climatological mean value.

The HWD index has increased at a number of stations – Valentia, Claremorris, Clones, Birr and Phoenix Park. Greatest increases are during spring, summer and winter at Clones and Phoenix Park. However, the only significant seasonal result is for spring at Casement, with an increase of 0.8 heat wave days, significant at the 95% level. The heat wave duration threshold was never breached at Rosslare in any season or annually.

The cold wave duration index is defined as the total number of days when the minimum temperature is at least 5°C lower than the 1961-1990 climatological mean value for at least 6 days. Cold waves usually only occur in the winter and autumn seasons. There are a number of trends in CWD which are significant:

- In winter, cold waves have decreased significantly at Shannon and Clones;
- In spring cold waves have decreased at Birr and Shannon;
- In autumn cold waves have decreased at Valentia and Birr;
- The annual CWD index at Shannon has decreased, significant at the 95% level;
- There has been no change in cold wave duration at all at Malin Head or at Rosslare;
- With the exception of Birr and Shannon, there have been none in the spring or summer seasons. For stations where there was a change in cold wave duration in autumn, there was generally a positive increase in cold wave duration for the midland and eastern stations of Phoenix Park, Casement, Clones and Kilkenny.

In winter all stations which record a change, display a decrease in cold wave duration, probably related to the general increase in winter temperatures.

Table 6 and Table 7 show the change in heat and cold waves respectively, measured as change in number of days over the period of record for each season.

Table 6 Change in heat wave duration, measured as change in number of days over period of record

Station (Length of record)	Spring	Summer	Autumn	Winter	Annual
Valentia (65)	0.4	-0.2			0.7
Shannon (60)	0.4	-0.6	-0.4		-1.1
Malin Head (50)			-0.6		-0.7
Belmullet (49)	-0.2	-0.6			-0.8
Phoenix Park (44)	0.6	0.4		0.9	1.8
Clones (55)	0.3	0.8		0.6	1.6
Rosslare (48)					
Claremorris (55)	0.4	0.3			0.7
Kilkenny (48)	-1.1	0.9	-0.7		-0.5
Casement (44)	0.8*	-0.1			-0.1
Birr (50)		0.2	0.3	0.5	0.7

* indicates significance at the 95% level.

Table 7 **Change in cold wave duration, measured as change in number of days over period of record**

Station (Length of record)	Spring	Summer	Autumn	Winter	Annual
Valentia (65)			-0.5*	-0.6	-0.8
Shannon (60)	-1.0		-1.4	-2.6*	-5.7*
Malin Head (50)					
Belmullet (49)				-0.4	-0.4
Phoenix Park (44)			1.4	-0.7	0.7
Clones (55)			0.2	-1.3*	-0.6
Rosslare (48)					
Claremorris (55)				-1.0	0.2
Kilkenny (48)			0.4	-0.3	0.7
Casement (44)			0.4	-0.7	-0.2
Birr (50)	-0.7*		-0.4	-0.9	-1.9

* indicates significance at the 95% level.

Precipitation Indicators in Ireland

Analyses at the global level reveals that average annual precipitation over global land areas has increased by 11 to 21 mm (nearly 1% per decade) over the period 1901-2004. However, there are regional differences. It is also considered likely that there has been an increase in the numbers of heavy precipitation events, even in places where there has been a reduction in total precipitation. Recent analysis indicates that in Europe, a majority of stations have displayed an increase in the number of moderate and very wet days during the second half of the 20th century (Klein Tank and Konnen, 2003; Haylock and Goodess, 2004). There is also evidence for Europe and the United States that there is a disproportionate increase in heavy and extreme events relative to the total precipitation amount (Klein Tank and Konnen, 2003; Groisman *et al.*, 2004).

In the following sections a number of different methods for assessing changes to precipitation amount and intensity will be examined, including total precipitation indices, maximum number of consecutive wet and dry days, simple daily intensity indices and number of days greater than or equal to 10 mm of precipitation.

Long-term Precipitation Series

There are three long-term stations for which there are monthly data extending back to 1890 – Malin Head, Birr and Roche's Point. However, the Roche's Point data end in 1990 so they are not used in this analysis. At Malin Head (Figure 8) there is a significant increase in total annual rainfall amounts (at the 99% level). The 10-year moving average shows that rainfall amounts increased from 800 mm in the 1890s to 1100 in the 1990s, *i.e.* an increase of 300 mm over 100 years. Four of the five wettest years at Malin Head occurred in the 1990s. The 1961-1990 mean rainfall total is 1,060 mm. This value has been exceeded in most years since the mid-1970s. 2003 and 2001 however, are the years with the lowest total annual precipitation, a turnaround from the wet years of 1999, 1990, 1998 and 1992.

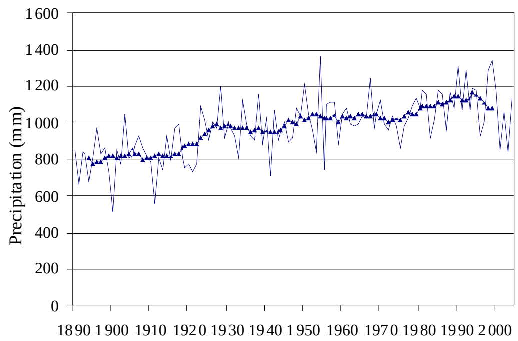

Figure 8 Total annual precipitation at Malin Head

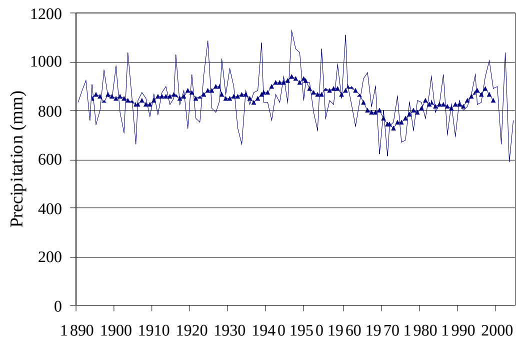

Figure 9 Total annual precipitation at Birr

No significant trends are found in annual precipitation levels for Birr (Figure 9). There was a decrease of 150 mm in the 1960s followed by a steady increase up to 2000. In recent years, this seems to be decreasing again with 2 of the 5 lowest annual totals recorded in 2001 and 2003. Conversely, 2002 was also the 2nd wettest year in the Birr record since 1960.

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

Generalised Change in Precipitation since 1960

Total seasonal and annual precipitation increases in all seasons at Valentia, Belmullet and Casement since 1960. Summer precipitation decreases at Rosslare, Claremorris and Birr while winter precipitation decreases at Phoenix Park and Kilkenny. In autumn, there are decreases in precipitation at Birr, Claremorris, Clones, Phoenix Park, Malin Head and Shannon. Only the changes in spring precipitation at Clones and Valentia are significant at the 95% level. The average annual precipitation increased by between 0.05% at Birr to 19.2% at Belmullet and 18.7% at Valentia. In general, the annual percentage change in precipitation increases from east to west. Phoenix Park deviates slightly from this trend with small decreases in annual precipitation (-2.3%). Figure 10 shows the spatial pattern of percentage change in annual precipitation. In most cases, highest annual precipitation totals were measured in the late 1990s (1998, 1999, 1994), 2000 and 2002. The lowest precipitation totals were measured in the early 1970s (1971 and 1975) as well as in 2001 and 2003.

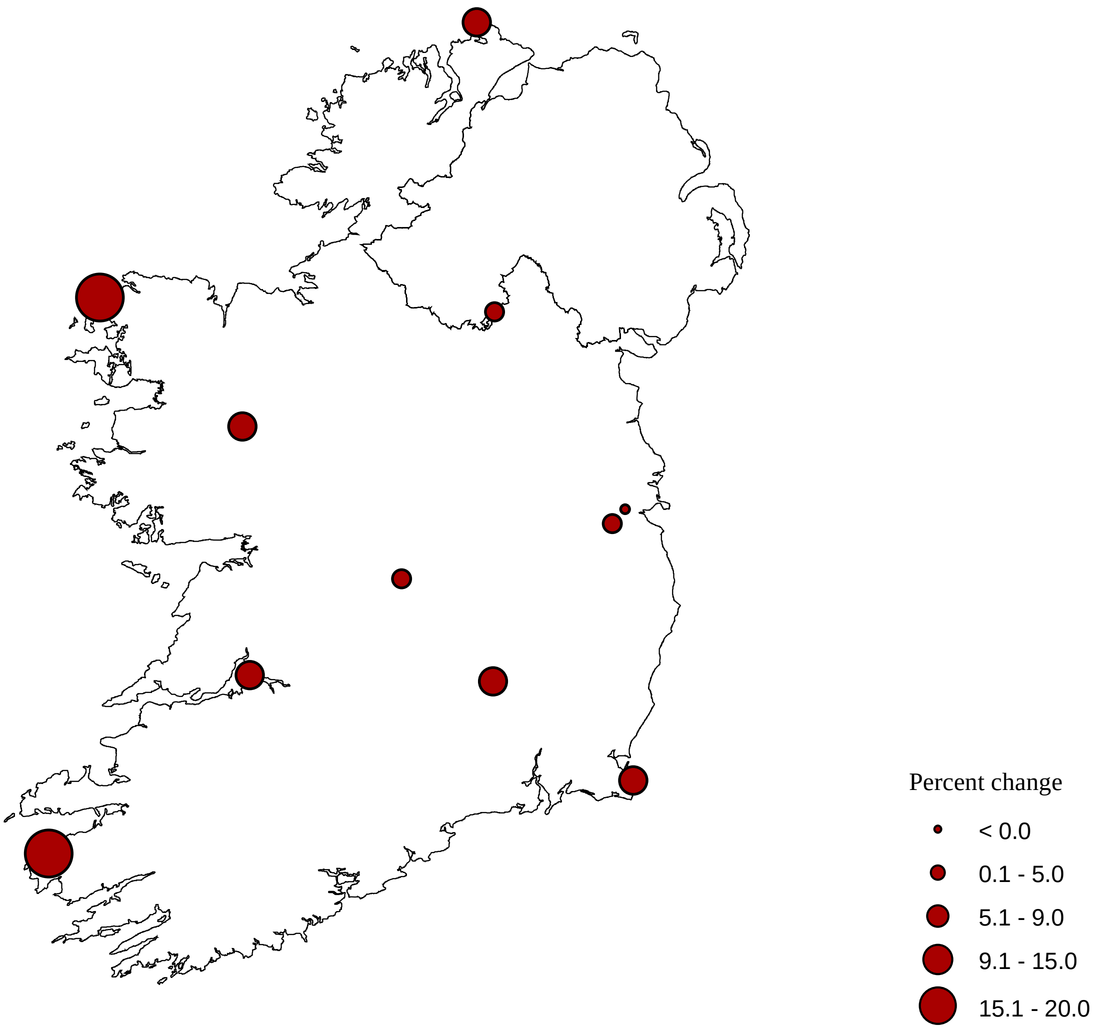

Figure 10 Percentage change in annual precipitation, 1960-2005

Maximum Number of Consecutive Wet and Dry Days

A wet day is defined by STARDEX as a day with greater than 1.0 mm rainfall. The duration of rain spells can be investigated by summing the number of consecutive wet days. The maximum number of consecutive wet days in the year has increased at all stations except for

Phoenix Park. An increase of 4 days was found at Belmullet. However, there are no significant increases in an annual index. A significant winter increase in the index was found at Phoenix Park; a significant spring increase at Valentia, Claremorris and Belmullet was observed and a significant increase at Valentia in autumn. There are broad seasonal trends. Generally, the maximum duration of rainy spells has increased in winter, spring and autumn while in summer it has decreased. The greatest increases are at the west coast stations of Belmullet, Claremorris, Malin Head and Valentia (See Table 8).

Dry spells can be investigated using a similar index. STARDEX define a dry day as a day with less than or equal to 1.0 mm of rainfall. For the maximum number of consecutive dry days (Table 9), there are no significant increases or decreases at any of the stations. There are overall annual increases at Malin Head, Kilkenny and very slightly at Rosslare, while at all other stations there is an annual decrease. There are no significant trends in any season. In winter there are generally increases in the north of the country and decreases in the south, in summer decreases in the north and increases in the south, and in autumn decreases at the east coast stations of Phoenix Park, Casement, Rosslare and Birr.

Table 8 Change (increase/decrease) in maximum number of consecutive wet days number of days over period of record for each station)

Station (Length of record)	Spring	Summer	Autumn	Winter	Annual
Valentia (64)	2.6*	-0.5	4.4*	1.1	0.8
Shannon (64)	1.2	-1.3	2.3	-1.0	0.4
Malin Head (48)	0.5	-0.8	2.1	2.2	2.2
Belmullet (49)	3.7*	-0.7	2.6	2.6	3.8
Phoenix Park (64)	1.2	-0.5	0.3	1.7*	-1.0
Clones (55)	1.1	1.1	2.0	0.1	0.8
Rosslare (48)	0.3	-1.2	1.3	0.9	0.9
Claremorris (61)	3.5*	-1.3	1.3	-0.7	0.7
Kilkenny (48)	-0.1	-0.2	0.6	1.8	1.6
Casement (51)	0.0	0.3	-0.8	1.2	0.8
Birr (50)	0.7	-0.4	-0.6	1.0	0.1

***** indicates significance at the 95% level.

Table 9 Change (increase/decrease) in maximum number of consecutive dry days (number of days over period of record for each station)

Station (Length of	Spring	Summer	Autumn	Winter	Annual
Valentia (64)	-0.4	0.9	0.2	-0.2	-0.6
Shannon (64)	-1.3	-0.4	1.6	-0.4	-2.6
Malin Head (48)	1.9	-3.4	1.9	-0.3	1.1
Belmullet (49)	1.2	-3.2	0.8	0.2	0.0
Phoenix Park (64)	-1.0	0.7	-0.9	-0.8	-2.2
Clones (55)	-1.1	-1.1	1.1	2.8	-1.9
Rosslare (48)	1.8	3.2	-0.5	-1.7	0.3
Claremorris (61)	-2.8	0.6	0.3	2.7	-0.9
Kilkenny (48)	3.1	1.6	1.0	-1.5	1.7
Casement (51)	1.5	-2.0	-0.4	3.8	-0.5
Birr (50)	1.8	-1.8	-1.1	0.6	-2.9

Number of Days when Precipitation is Greater Than, or Equal to, 10 mm.

Variation in precipitation can be caused by changes in the frequency of precipitation events, or changes in the intensity of these events. It has been shown that with an increase or decrease in total precipitation, disproportionate changes occur in the upper ends of the precipitation frequency distribution (Karl and Knight, 1998; Groisman *et al.*, 1999, 2001; Easterling *et al.*, 2000; IPCC, 2007a; in Groisman *et al.*, 2004). Heavy or extreme precipitation events can be defined in a number of different ways: as days with precipitation greater than a given threshold (*e.g.* 10 mm or 50 mm); as precipitation above specific percentiles of the distribution (*e.g.* 90th or 95th); or as precipitation events that occur once every number of years (*e.g.* 50 or 100). Extreme precipitation events are of great importance, as they affect many people through loss of life and cause much economic damage and disruption.

In the first instance, number of days when daily precipitation is greater than or equal to 10 mm is analysed. This is one indicator of whether there is an increase or decrease in rainfall intensity. Over the period of record at each station, there are significant annual increases at the west coast stations of Malin Head, Belmullet, Claremorris and Valentia. Shannon and Kilkenny also have non-significant increases while Clones, Phoenix Park, Casement, Birr and Rosslare have non-significant decreases. Comparing the stations during the period 1960-2005 when there are records for all stations (Figures 11 to 14), we see that Claremorris, Valentia and Belmullet are the only stations to have an increase in number of days with precipitation greater than 10 mm in all seasons. Conversely, at Phoenix Park, there are decreases in all seasons. Generally, there is an increase in number of days on the west coast while there are decreases on the east coast.

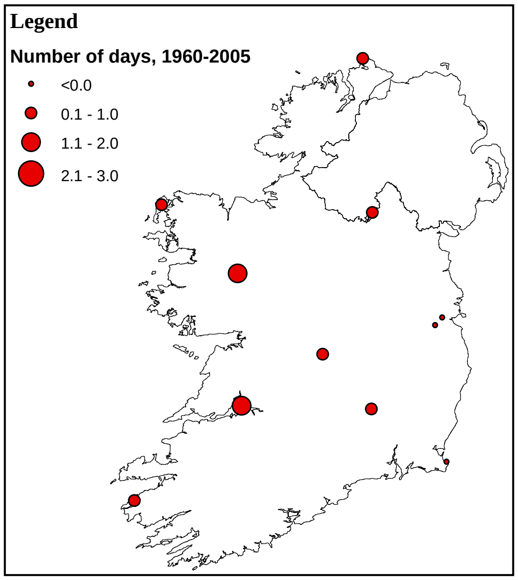

Figure 11 Change in number of days in Spring when precipitation is greater than, or equal to 10 mm.

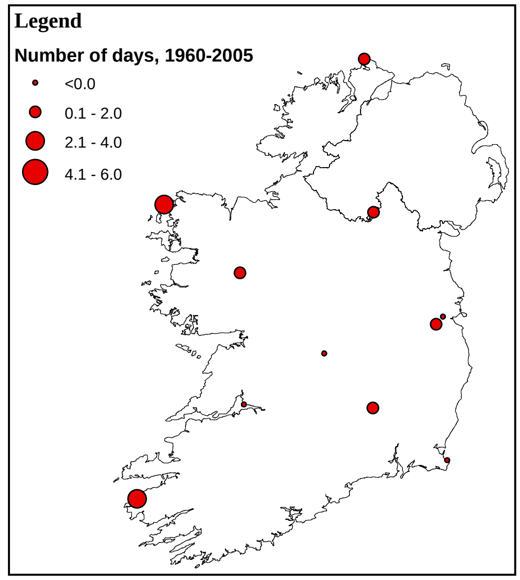

Figure 12 Change in number of days in Summer when precipitation is greater than, or equal to 10 mm.

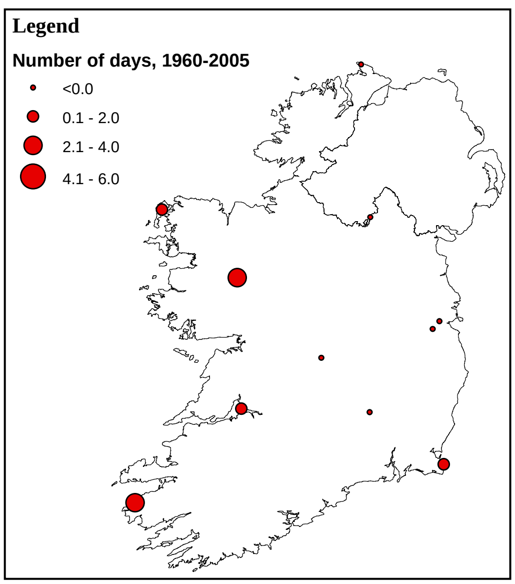

Figure 13 Change in number of days in Autumn when precipitation is greater than, or equal to 10 mm.

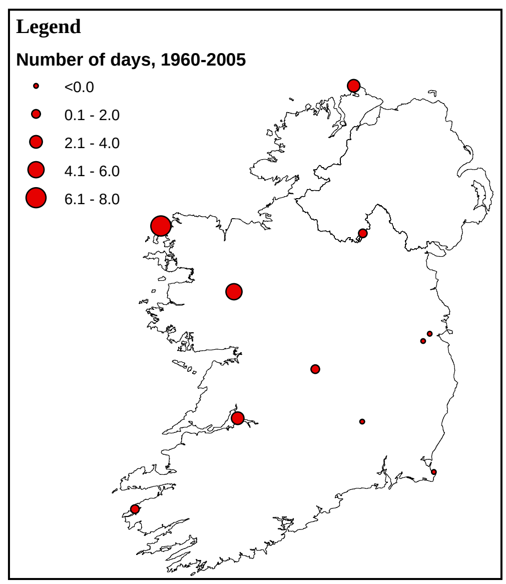

Figure 14 Change in number of days in Winter when precipitation is greater than, or equal to 10 mm.

Greatest 3-Day, 5-Day and 10-Day Rainfall Totals

Greatest 3-day, 5-day and 10-day rainfall totals are important from the perspective of flooding and vulnerability of local populations and environment. In Ireland, annual increases in rainfall totals are revealed for the majority of stations. Table 10 shows the percentage change in greatest 3-day rainfall totals for all stations. There is a decrease for all stations on the south-west and east in winter while there are increases in the north-west and midlands.

The opposite appears to occur for summer, with decreases in the north and north-west stations of Belmullet, Claremorris, Malin Head, Clones and also at Birr, while there are increases for Valentia, Shannon, Kilkenny, Casement and Phoenix. Rosslare is unusual in this regard, with decreases in greatest 3-day rainfall totals in summer. For the greatest 5-day and 10-day rainfall totals (not shown), all four seasons at Belmullet and Valentia reveal increases, significant for summer and autumn at Valentia and on an annual level at Belmullet for the greatest 10-day rainfall increase. The majority of the greatest 5-day and 10-day totals occur in the 1980s and 1990s so these decades appear to be having a greater intensity of rainfall.

Table 10 Percentage change (increase/decrease) in greatest 3-day rainfall totals (mm)

Station (Length of record)	Spring	Summer	Autumn	Winter	Annual
Valentia (64)	13.4	40.5*	2.9*	-1.7	26.8
Shannon (64)	-9.6	1.4	-1.0	-1.7	0.6
Malin Head (48)	9.7	-13.0	-9.0	16.6	-7.6
Belmullet (49)	32.1	-5.3	6.3	30.8	11.0
Phoenix Park (64)	-12.2	20.8	33.8	-21.0	9.1
Clones (55)	38.9**	-12.8	0.5	10.5	-1.0
Rosslare (48)	0.6	-6.1	0.8	-4.3	11.2
Claremorris (61)	12.0	-2.8	7.7	32.5*	16.6
Kilkenny (48)	16.8	17.1	-4.9	-24.4	2.5
Casement (51)	-9.0	2.0	39.3	-20.7	23.7
Birr (50)	8.1	-7.5	-8.8	2.2	1.7

* indicates significance at the 95% level. ** indicates significance at the 99% level.

Number of Events Greater Than the Long-term 90th Percentile

A further method for analysing extreme precipitation events is to consider events which pass specific thresholds. In this case, the number of events greater than the 90th percentile is examined. Percentiles are useful as they are location specific and represent anomalies relevant to the local climate which is particularly important for a climate variable such as precipitation. By comparing the same part of the precipitation distribution for each station, spatial comparison is more straightforward and improved. There have been increases in the number of events greater than the 90th percentile during all seasons at the north and west and north coast stations of Valentia, Shannon, Malin Head and Belmullet. At Kilkenny, Phoenix Park, Casement and Birr there are decreases in winter while at Clones, Rosslare, Claremorris and Birr there are decreases in summer. Table 11 shows the change in number of precipitation events greater than the long-term 90th percentile for the length of each station record.

Table 11 Change (increase / decrease) in number of precipitation events greater than the long-term 90th percentile.

Station (Length of record)	Spring	Summer	Autumn	Winter	Annual
Valentia (64)	1.4	2.2*	1.9	0.3	5.0*
Shannon (64)	1.1	0.6	0.6	1.1	1.2
Malin Head (48)	1.4	0.8	0.0	2.2*	3.6
Belmullet (49)	0.1	0.3	2.0	3.8	6.4
Phoenix Park (64)	-0.3	0.0	0.2	-0.1	-1.3
Clones (55)	1.2	-2.1	0.5	0.2	-0.6
Rosslare (48)	-0.1	-0.7	0.1	0.2	1.2
Claremorris (61)	1.4	-1.7	0.3	0.9	1.6
Kilkenny (48)	0.5	1.0	-0.4	-1.3	-0.7
Casement (51)	-0.7	0.0	0.5	-1.4	-3.1
Birr (50)	0.2	-1.5	-0.3	-0.4	-1.4

***** indicates significance at the 95% level.

Conclusion

This report provides an updated analysis of signals of climate change in the meteorological records. Temperature and precipitation remain the two key climatic parameters showing indication of climate change. In this report, greater emphasis has been placed on daily data, and longer time series of data. The findings are generally in line with the previous analysis and show a continuation of the previously observed trends. Signals of climate change consistent with global warming are apparent in the meteorological records. The main findings are:

- Ireland's mean annual temperature has increased by 0.7^{o}C between 1890 and 2004.
- The average rate of increase is 0.06^{o}C per decade. However, as Ireland experiences considerable climate variability, the trend is not linear. The highest decadal rate of increase has occurred since 1980, with a warming rate of 0.42^{o}C per decade.
- The warmest year on record was 1945, although 6 of the 10 warmest years have occurred since 1990.
- An alteration of the temperature distribution has occurred, with a differential warming rate between maximum and minimum temperatures. Minimum temperatures are increasing more than maximum temperatures in spring, summer and autumn, while maximum temperatures are increasing more than minimum temperatures in winter.
- There has been a reduction in the number of frost days and a shortening of the frost season length.
- The annual precipitation has increased on the north and west coasts, with decreases or small increases in the south and east.
- The wetter conditions on the west and north coastal regions appear due to increases in rainfall intensity and persistence.
- There is an increase in precipitation events over 10 mm on the west coast with decreases on the east coast, there is an increase in the amount of rain per rain day on the west coast, and a greater increase in number of events greater than the 90th percentile also on the west coast.

The increases in intensity and frequency of extreme precipitation events provide a cause for concern as they may have a greater impact upon the environment, society and the economy. The precipitation series however require further analysis as there is large spatial and temporal variability associated with daily precipitation series. Emphasis should be placed on gathering reliable data and on the updating of this data network.

The analysis in this report should be updated regularly, *i.e.* on an annual or biannual basis. Other indicators should also be examined so that changes in these may be included in future analysis. Continued monitoring and updating of these indicators will support policy decisions on climate change in Ireland.

Appendix 1

Future projections of climate suggest that:

- Globally-averaged surface temperature is likely to increase by between 1.8°C (low emissions scenario) and 4°C (high emissions scenario) over the course of this century.

- Precipitation increases are likely in the mid- to high-latitudes in winter by the middle of the present century. However, there will be large spatial and seasonal variations.

- There is likely to be an increase in maximum temperatures and in the frequency of hot days.

- More intense precipitation events are also very likely over mid- to high-latitude areas of the Northern Hemisphere.

- The present day retreat of mountain glaciers is likely to continue during the course of the 21st century. While Antarctica is likely to gain mass due to enhanced precipitation, Greenland is likely to lose mass due to a greater increase in runoff over precipitation increases.

- The best estimates for global mean sea-level rise over the present century are in the range 18 to 38 cm for the low emissions scenario and 26 to 59 cm for the high emissions scenario.

Source: IPCC (2007a).

References

Brunetti, M., Buffoni, L., Maugeri, M. & Nanni, T. (2000) Trends in Minimum and Maximum daily temperatures in Italy from 1865-1996. *Theoretical and Applied Climatology*, **66**, 49-60

Easterling, D. R., Evans, J. L., Groisman, P. Ya., Karl, T. R., Kunkel, K. E., Ambenje, P. (2000) Observed Variability and Trends in Extreme Climate Events: A Brief Review. *Bulletin of the American Meteorological Society*, **81**, 2000, 417 – 425

Easterling, D. R., B. Horton, D. Philip, T. C. Jones, T. R. Karl, D. E. Parker, M. J. Salinger, V. Razuvayev, N. Plummer, P. Jamason, C. K. Folland. (1997) Maximum and minimum temperature trends for the globe. *Science*, 277.

Groisman, P. Y., Knight, R. W., Karl, T. R., Easterling, D. R., Sun, B. & Lawrimore, J. H. (2004) Contemporary changes of the hydrological cycle over the contiguous United States: trends derived from in situ observations. *Journal of hydrometeorology*, 5, 64-85.

Groisman, P. Y., Knight, R. W. and Karl, T. R. (2001) Heavy precipitation and high streamflow in the contiguous United States: Trends in the 20th century. *Bulletin of the American Meteorological Society*, 82, 219-246.

Groisman, P. Y., Karl, T. R., Easterling, D. R., Knight, R. W., Jamason, P. F., Hennessy, K.. J., Suppiah, R., Page, C. M., Wibig, J., Fortuniak, K., Razuvaev, V. N., Douglas, A., Forland, E. & Zhai, P.M. (1999) Changes in the probability of heavy precipitation: important indicators of climatic change. *Climatic Change*, **42**, 243-283.

Hansen, J., Ruedy, R., Sato, M. and Lo, K. (2006) Global temperature trends: 2005 summation. data.giss.nasa.gov/gistemp/2005/

Haylock, M. R. & Goodess, C. M. (2004) Interannual variability of European extreme winter rainfall and links with mean large-scale circulation. *International Journal of Climatology*, **24,** 759-776.

Intergovernmental Panel on Climate Change (IPCC) (2007a) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK. (In Press).

Intergovernmental Panel on Climate Change (IPCC) (2007b) *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK. (In Press).

Jones, P. (2006) Global temperature record. Climate Research Unit. www.cru.uea.ac.uk/cru/info/warming/

Karl, T. R. & Knight, R. W. (1998) Secular trends of precipitation amount, frequency and intensity in the United States. *Bulletin of the American Meteorological Society*, **79 (2),** 231-241.

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

Klein Tank, A. M. G. & Konnen, G. P. (2003) Trends in indices of daily temperature and precipitation extremes in Europe, 1946-99. *Journal of Climate*, **16**, 3665-3680.

Palle, E. and Butler, C. J.. (2001) Sunshine records from Ireland, cloud factors and possible links to solar activity and cosmic rays. *International Journal of Climatology*, **21**, 709-729.

Parry, M. L. (2000) Assessment of Potential effects and adaptations for climate change in Europe: the Europe ACACIA report. Jackson environment institute, University of East Anglia, UK

Przybylak, R. (2000) Diurnal temperature range in the Arctic and its relation to Hemispheric and arctic circulation patterns. *International Journal of Climatology*, **20,** 231-253.

Robinson, P. J. (2001) On the definition of a heat wave. *Journal of Applied Meteorology*, **40 (4)** 762-755

Schar, C., Vidale, P. L., Luthi, D., Frei, C., Haberi, C., Liniger, M. A. and Appenzeller, C. (2004) The role of increasing temperature variability in European summer heatwaves. *Nature*, **427**, 332-336.

Sillmann, J. (2005) Extreme Events in climate model data: What is happening over Europe in present and in future centuries?. IPCC Workshop 2005.
www.mpimet.mpg.de/fileadmin/Climate_Scenarios/IPCC_Sillmann.pdf

Souch, C. & Grimmond, C. S. B. (2004) Applied climatology: 'heat waves'. *Progress in Physical Geography*, **28 (4),** 599-606.

Sweeney, J., Donnelly, A., McElwain, L. & Jones, M. (2002) *Climate change: Indicators for Ireland*. Environment Protection Agency, Wexford.

Tomozeiu, R., Pavan, V. & Cacciamani, C. (2003) Observed changes in extreme minimum and maximum temperature in Emilia-Romagna (1958-2000). *Geophysical Research Abstracts*, vol 5.

Acronyms and Notation

CRU	**Climate Research Unit , University of East Anglia.**
CWD	**Cold Wave Duration**
DTR	**Diurnal Temperature Range**
GISS	**Goddard Institute for Space Studies**
HWD	**Heat Wave Duration**
ICARUS	**Irish Climate Analysis and Research Units**
IPCC	**Intergovernmental Panel on Climate Change**
NASA	**North American Space Agency**
STARDEX	**Statistical and Regional Dynamic Downscaling of Extremes for European Regions**
TAR	**Third Assessment Report**