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Refining the Impacts for Ireland

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STRIVE Report

Prepared for the Environmental Protection Agency

by

National University of Ireland, Maynooth

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Executive Summary

1 International Context

As a mid-latitude country Ireland can expect its future temperature changes to mirror quite closely those of the globe as a whole.

Best estimates of global temperature change by the end of the present century are currently in the region 1.8–4.0°C[1].

2 Regional Context: Weighted Ensemble Downscaling from Global Climate Models

Global climate models (GCMs) have greatly improved in reliability and resolution as computing power has increased and better inputs from earth observation have become available. Despite this, they remain too coarse in terms of their grid size to enable climate scenarios at the scale necessary for impact analysis to be achieved. This study employs a statistical downscaling approach to overcome these difficulties and also to provide new information on model uncertainty with a view to reducing uncertainty in key sectors such as water resource management, agriculture and biodiversity.

- Mean annual temperatures in Ireland have risen by 0.7°C over the past century. Using a multi-model ensemble involving three different GCMs for downscaling to the Irish Synoptic Station Network, this study concludes that mean temperatures in Ireland relative to the 1961–1990 averages are likely to rise by 1.4–1.8°C by the 2050s and by in excess of 2°C by the end of the century. Summer and autumn are projected to warm much faster than winter and spring, with a pronounced continental effect becoming apparent whereby the midlands and east warm more than coastal areas. With temperature projections of this kind, a high degree of confidence exists.

- Future precipitation changes in Ireland are subject to greater uncertainty with all modelling approaches. Nonetheless, these are suggested to be the most important aspect of future climate change for Ireland. Using an approach based on General Linear Modelling, winter rainfall in Ireland by the 2050s is projected to increase by approximately 10% while reductions in summer of 12–17% are projected by the same time. By the 2080s, winter rainfall will have increased by 11–17% and summer rainfall will have reduced by 14–25%. Spatially, the largest percentage winter increases are expected to occur in the midlands. By the 2050s, summer reductions of 20–28% are projected for the southern and eastern coasts, increasing to 30–40% by the 2080s.

- Changes in the frequency of extreme events will accompany these climate changes. Lengthier heatwaves, a substantial reduction in the number of frost days, lengthier rainfall events in winter and more intense downpours in summer are projected. At the same time an increased summer drought propensity is indicated, especially for eastern and southern parts of Ireland.

Hydrological modelling based on nine key catchments was undertaken using the future scenarios developed above. Significant reductions in soil moisture storage were projected. Individual catchment characteristics play a major role in determining the severity of response to climate change soil permeability considerations. Catchments more dependent on groundwater, such as the Suir, Blackwater and Barrow, appear most vulnerable to a range of impacts:

- Soil moisture deficits commence earlier, and extend later, in the year as the century proceeds

- Groundwater recharge to be lower for longer, sustained periods, increasing the risk of drought

1. IPCC, 2007. *Climate Change 2007: The Physical Science Basis of Climate Change*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Qin, D. and Solomon, S. (Eds) Cambridge University Press, Cambridge UK and New York, USA. 996 pp.

when a dry summer follows a drier than average winter.

Significant changes in streamflow are projected with winter increases particularly likely to occur. For the 2050s, increases in February of 12–20% are typical. Significant reductions in streamflow are also projected for late autumn in some catchments, particularly in the east where major reductions are anticipated by the end of the century.

These hydrological changes manifest themselves more clearly in changes in high and low flow frequencies. In terms of high flow events the 10-year flood reduces to a 3- to 7-year event on most catchments by the 2050s. The 50-year flood becomes a 6- to 35-year event on all but one catchment studied. Despite drier summer conditions, most Irish rivers show a reduction in extreme low flows through the summer months for the early decades of this century as a result of groundwater contributions. However, rivers less dominated by groundwater contributions show increasing frequency of low flow days.

The main challenges for Irish agriculture will come from wetter winter and drier summer soils. Spatial contrasts will develop as follows.

- In east Ulster and east Leinster, water stress in grass, barley and potato and, to a lesser extent, maize will occur on a much-increased frequency. Summer soil moisture deficits will be problematical for dairying, losses from which may be partially compensated by reductions in fertiliser inputs. Late summer feed deficits may require supplementation or the introduction of a mid-season housing period.

- In much of Connaught and central Ulster, less stresses are apparent in summer and good yields of grass, barley, maize, potato and, later in the century, soybean can be expected. Scope for reduced fertiliser inputs will be greater in areas of poorly drained soils.

- In the extreme north-west, cool temperatures and relatively wet conditions will produce lower grass, maize and soybean yields, but good barley and potato yields. Dairying will not be heavily impacted.

- In south and south-west Munster, the combination of warmer and relatively moist conditions will suit most crops and enable dairying to continue much as at present. Potato yields will be limited and summer droughts will be more common, though not as severe as further east.

- Adaptation to climate change for Irish agriculture will centre either on maximising outputs or minimising inputs. Generally the potential for considerable reduction in nitrogen application rates will occur.

- For the key dairying sector, a range of response options exists for adapting to climate change that should mean the continuing viability and profitability of this sector.

Changes in biodiversity across Ireland will occur in conjunction with the projected climate changes. Changes in the timing of life cycle events such as leafing, bud burst and leaf fall will be instrumental in this. Particularly vulnerable ecosystems can also be identified where successful adjustment to new conditions is unlikely.

- Temperature and photoperiod exert strong controls on bud burst, though different species are likely to respond to changes in these parameters in varied ways. Winter chilling requirements mean that simple responses to warming of Irish climate are complicated and require species-specific modelling to predict.

- Long-term shifts of habitats in Ireland will be dependent on human controls such as the availability of suitable migration corridors.

- The most vulnerable habitats include sand dunes, lowland calcareous and calaminarian grasslands, montane heath, raised bogs, calcareous fens, turloughs and upland lakes.

- Increased decomposition of Irish peatlands will be facilitated mainly by cracking during drier summers. Compositional changes within the peatlands will be associated with further deterioration.

- As determined by climate envelope modelling, the suitable climate area for fens may have declined by 40% by mid-century with corresponding losses for raised and blanket bogs of over 30% and for turloughs 45% over the same period.

3 Conclusions

Over the next half-century significant changes are projected to occur in Irish climate. This study uses a novel ensemble downscaling method to provide an integrated impact analysis. Considerable uncertainty remains in several areas and further research into these is highly desirable to increase confidence for policy makers. This is not, however, a justification for not accelerating measures to promote adaptation and mitigation both at a national and a global scale. Both require urgent implementation in Ireland if the worst impacts of climate change are to be avoided.

1 Global and Irish Trends in Climate

John Sweeney and Rowan Fealy
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1.1 Introduction

The need to address potential impacts of climate change in Ireland has become increasingly recognised in recent years as the environmental consequences of rapid economic growth become more acute. Irretrievable commitments of finite natural resources such as soil, water, energy and land accelerate and require careful management if the quality of life of future generations is not to be adversely affected. For many projects, plans and programmes, a medium- to long-term view of climate change impacts is an essential ingredient in this process in order that adaptation or mitigation can be undertaken.

As a member of the international community, Ireland, with one of the highest *per capita* greenhouse gas emission rates in the world, also has obligations. These are specified under its ratification of the United Nations Framework Convention on Climate Change, the Kyoto Treaty and its commitments to avoid 'dangerous climate change' as defined by the EU Council of Ministers. A revised Irish Climate Change Strategy has now been formulated to address these issues. This will, however, even if successful, not obviate short- and medium-term impacts in key sectors of the Irish economy, which are inevitable due to the nature of anthropogenic climate change.

Impact analysis in Ireland has been tackled in particular sectors over many years, though the first comprehensive approach was that of McWilliams (1991). This set prescribed climate scenarios for impact modellers to use. The second main assessment occurred in 2003 using downscaled global climate data as inputs to models in several key sectors (Sweeney *et al.*, 2003). While this provided strong signals regarding spatial variations in impacts throughout Ireland, it was based on one global climate model. Progress since then has been significant in developing global climate model outputs in an increasingly sophisticated manner, enabling multiple runs of multiple models to be used as a vehicle for reducing the cascade of uncertainty which exists between future socio-economic projections and climate responses. This work seeks to employ such an approach to provide policymakers with more specific tools for managing the Irish environment in the three key sectors of water resources, agriculture and biodiversity.

1.2 Current Trends in Global Climate

The average global surface temperature has increased by 0.76°C over the period 1850–1899 to 2001–2005, with an acceleration in the rate of warming to 0.13°C/decade over the past 50 years (IPCC, 2007). While slightly different combinations of stations are used to calculate the global average by various scientific groups, most identify 1998 and 2005 as the warmest 2 years in the instrumental temperature records since 1850. Some, however, place 2005 as equal first or clear first in the series, somewhat unusual since 2005 was not a marked El Niño year (Kennedy *et al.*, 2006). Eleven of the 12 warmest years in the instrumental record have occurred since 1995, indicating that a period of further accelerated warming is under way (Fig. 1.1).

Warming has been most pronounced over the land masses and, for the northern hemisphere, the 1990s constituted the warmest decade of the warmest century of the last millennium. The warming has been greatest during the winter season (Jones *et al.*, 2001). Minimum temperatures have been increasing at approximately twice the rate of maximum temperatures, a phenomenon already confirmed by many national-scale studies (Zhai and Ren, 1999; Vincent and Gullet, 1999; McElwain and Sweeney, 2007). Concerns that these temperature changes might have been unduly biased by an urban heat island influence have been shown to be unfounded, with urban effects only of the order of 0.06°C on global averages over the course of the 20th century

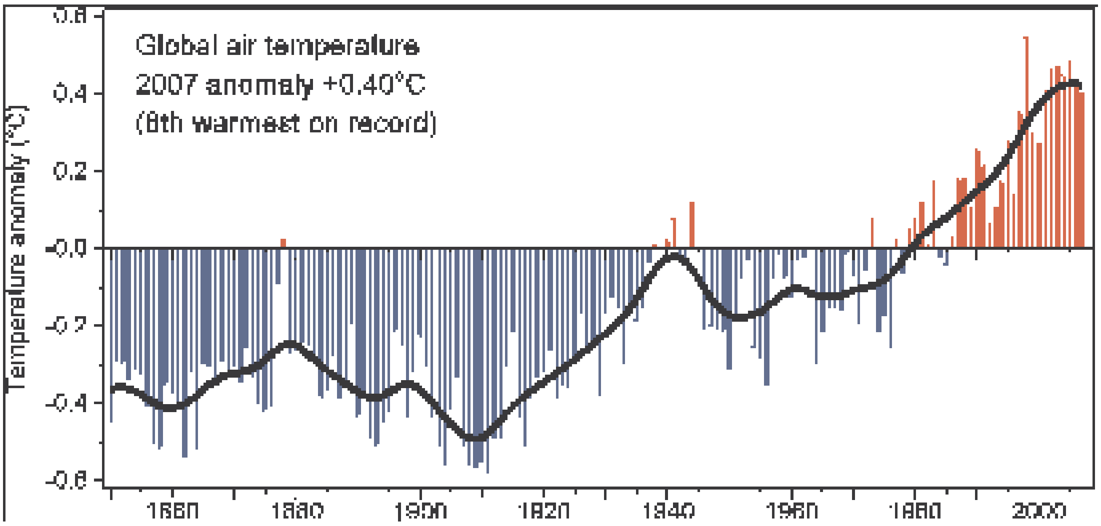

Figure 1.1. Global temperature anomaly 1890–2007 relative to 1961–1990.

(Easterling *et al.*, 1997; Peterson *et al.*, 1999). Neither are changes in solar irradiance now believed to be capable of explaining the changes in global temperature over the past century (Tett *et al.*, 1999).

Decreases in the daily temperature range suggest that cloud cover changes may be involved and indeed cloudiness has increased in most regions in recent decades. Associated with this, global land precipitation has increased by 2% per over the past century (Jones and Hulme, 1996). This increase was most pronounced polewards of 30^{o} in both hemispheres, with many areas experiencing increases of 6–8% from 1900 to 2005 (IPCC, 2007). In the subtropical Northern Hemisphere land areas, precipitation has decreased by 0.3% per decade (IPCC, 2001) though trends are less pronounced. Associated with these precipitation changes has been a tendency towards an increase in the frequency of more intense precipitation events, even in areas where precipitation reductions have occurred (IPCC, 2007). Such events, more so than changes in the mean conditions, are likely to provide the most serious challenges for environmental management in the years ahead.

The climate system naturally fluctuates on a range of temporal and spatial scales. The record of this has been revealed by various palaeoclimatic reconstruction techniques such as documentary sources, tree ring analysis, palynology and ice and ocean core analysis. These have enabled the longer-term temporal context into which present and future changes fit to be assessed. Polar ice cores in particular have clarified the climatic fluctuations of the past 2 million years and have confirmed that astronomical forcing of climate is not in itself enough to explain these. It is now clear that climate also has a capability of changing in a radical fashion within a few decades. ‘Abrupt’ regime shifts, often triggered by oceanic circulation changes, are now known to have taken place several times during the last glacial–interglacial cycle (Dansgaard *et al.*, 1993) and there is a growing realisation that human actions may prematurely activate some of these natural ocean–atmosphere mechanisms. On a shorter time scale, decadal modes of variability including the Arctic Oscillation, the North Atlantic Oscillation and the El Niño Southern Oscillation are also associated with significant changes in oceanic and atmospheric circulation, and these need to be incorporated in any impact assessment at regional scale.

The current scientific consensus attributes most of the observed increase in global temperatures over the past 50 years as being ‘very likely’ due to anthropogenic activities associated with increasing atmospheric concentrations of greenhouse gases (IPCC, 2007). The principal contribution has been made by CO_2 which has increased from pre-Industrial Revolution levels of 280 ppmv (parts per million volume) to current levels of over 385 ppmv. This is a concentration that has not been exceeded during the past 650,000 years and most likely not since the Mid-Pliocene (3.3–3.0 Ma) when warmer conditions than today existed and sea levels were 15–25 m higher than today (IPCC, 2007). A significant contribution to the atmosphere's greenhouse gas loading also comes from methane concentrations which have already doubled from their pre-industrial levels. Anthropogenic sources are currently over double the natural contribution and over half the anthropogenic contribution comes from activities associated with bioresource exploitation. Because of its relatively short residence time in the atmosphere removing a tonne of methane from the atmosphere today would contribute 60 times as much benefit to reducing global warming over the next 20 years as removing the same amount of CO_2 (IPCC, 2001).

1.3 Current Trends in Irish Climate

Ireland lies on the westernmost edge of the European continent on the fringe of the North Atlantic Ocean. As a consequence of its proximity to this large body of water and being situated within the prevailing westerlies of the mid-latitudes, its climate is predominantly maritime in character.

Mean annual temperatures in Ireland have risen by 0.74°C over the past 100 years (McElwain and Sweeney, 2007). This increase largely occurred in two periods, from 1910 to the 1940s and from the 1980s onwards, with a rate of warming since 1980 of 0.42°C per decade. In Ireland, 6 of the 10 warmest years have occurred since 1995 with the warmest year within this period being 1997. Increases in minimum temperatures were greater than maximum during summer while in winter the opposite is the case (Sweeney *et al.*, 2002). As with global trends, a reduction in the average daily temperature range has occurred, though this has now ceased in recent decades at the global level (IPCC, 2007).

Significant temporal and spatial changes are also apparent in precipitation receipts in Ireland. Annual precipitation is increasing in the north of the country, while decreases in receipts are evident in the south. Increases in the frequency of rain and wet days were also found to be occurring during the months of March and October, with decreases in the May to September period and in December (McElwain and Sweeney, 2007). While the North Atlantic Oscillation was found to account for some of the variation in precipitation, other factors are necessary in order to account for the changes apparent in precipitation.

The Irish climate is experiencing changes which have been found to be consistent with those occurring at a global scale and there now is growing confidence that these changes are largely attributable to global warming.

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2 Climate Scenarios for Ireland

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2.1 Introduction

According to the latest report, the Fourth Assessment Report, from the Intergovernmental Panel on Climate Change (IPCC) warming of the climate system is 'unequivocal' (IPCC, 2007). Most of the warming observed over the 20th century is 'very likely' (greater than 90% likelihood) due to the observed increases in anthropogenic greenhouse gas emissions (IPCC, 2007). Pre-industrial atmospheric concentrations of CO_2, which had been relatively stable at 280 ppmv (parts per million volume), have increased by more than 35% to their present levels of over 385 ppmv. If we include the global warming potential, or CO_2 equivalent, of the full range of greenhouse gases, then present-day concentration levels are closer to 425 ppmv CO_2 equivalent. For example, when compared over a 100-year time frame, the global warming potential of 1 t of methane (CH_4) is approximately 21 times that of an equivalent amount of CO_2.

If emissions of greenhouse gases continue to increase at current rates, a doubling of atmospheric concentrations of CO_2 is likely to occur by the end of the present century, or sooner if we include all the greenhouse gases. However, future emissions cannot be 'predicted' with confidence for decades ahead, and yet this must be attempted if we are seeking to model future changes in the climate system. To address this major uncertainty the IPCC commissioned a study to provide a range of plausible future socio-economic development 'pathways' which could then be 'translated' into emissions scenarios (Fig. 2.1; Appendix 2.1) and subsequently, atmospheric loadings of greenhouse gases and aerosols (Fig. 2.2). These different socio-economic scenarios represent different future global development pathways, based on assumptions about economic growth, future global population levels and future levels of reliance on fossil fuels. Based on these assumptions, a range of 'storylines' was produced of which four marker emissions scenarios were used to drive global climate models (GCMs).

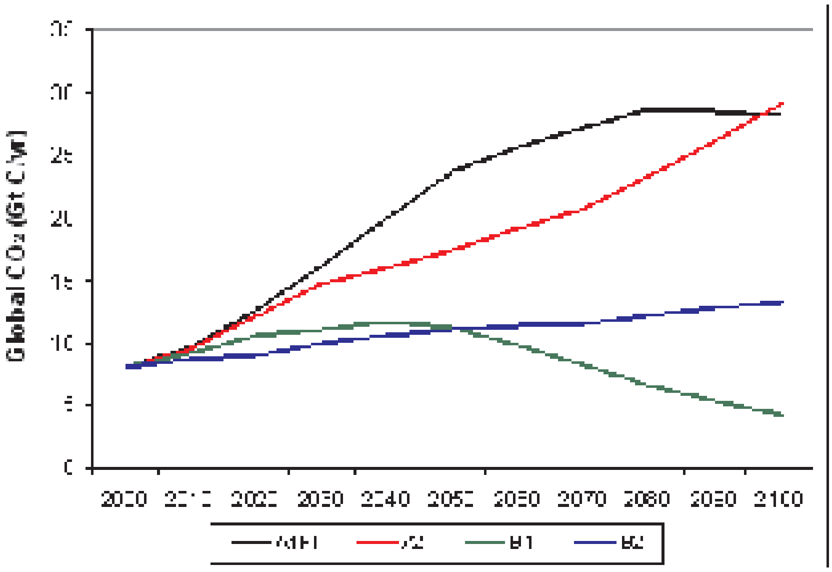

Figure 2.1. Carbon dioxide (CO_2) emissions, 1990–2100, for the four marker emissions scenarios (IPCC, 2001).

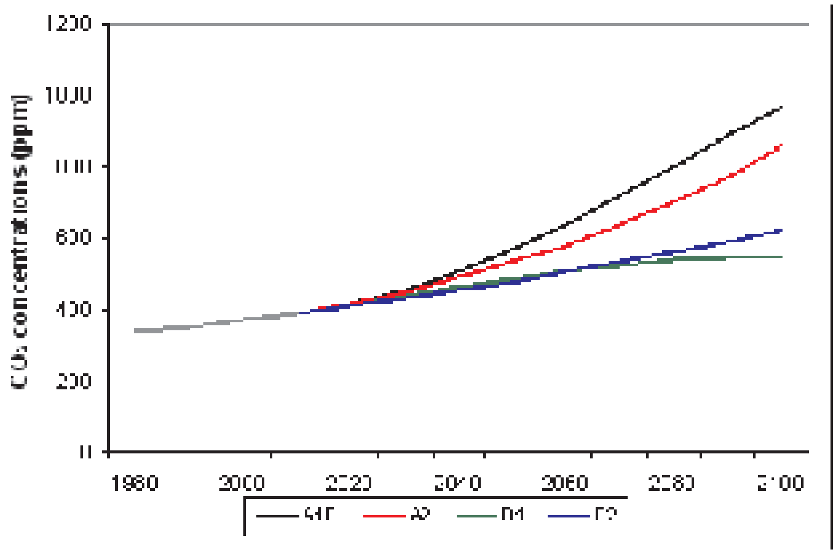

Figure 2.2. Projected CO_2 concentrations for the present century (IPCC, 2001).

2.2 Future Projections of Climate Change

Based on the prescribed set of IPCC Special Report on Emissions Scenarios (SRES) markers, globally averaged surface temperatures are likely to increase by approximately 1.8°C (likely range is 1.1–2.9°C) for the B1 scenario, to 4.0°C (likely range is 2.4–6.4°C) for the A1FI scenario, over the present century, relative to the 1980–1999 period (Fig. 2.3). Inter-model differences reflect different responses of the model climate to a doubling of CO_2 or 'equilibrium climate sensitivity', which is likely to lie in the range 2–4.5°C, with a most likely value of about 3°C (IPCC, 2007). Such temperature increases are unlikely to be uniformly distributed and there is likely to be a large degree of regional variation in the spatial distribution of these increases.

Future projections of climate suggest that:

- Globally averaged surface temperature is likely to increase by approximately 1.8°C (likely range is 1.1–2.9°C) to 4.0°C (likely range is 2.4–6.4°C) over the present century relative to the 1980–1999 period

- Precipitation increases are likely by the middle of the present century in the mid to high latitudes in winter, with large year-to-year variations (Giorgi and Bi, 2005)

- An increase in maximum temperatures and in the frequency of hot days is likely to have been occurring during the latter half of the last century due to human influence on climate (Stott *et al*., 2004) and confidence is high that this trend will continue

- Storm tracks are projected to migrate polewards resulting in changes in precipitation. While the interannual variability of precipitation is likely to increase, increased atmospheric humidity is likely to result in more intense precipitation events

- 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 run-off over precipitation increases (IPCC, 2001). Under the A2 scenario, 90% of the upper layer of the world's permafrost is expected to melt by 2100 (Lawrence and Slater, 2005) and the disappearance of Arctic summer sea ice by the same time is projected by some models (ACIA, 2005)

- Global mean sea level is projected to rise by between 0.28 and 0.4 m

- Although models suggest that a weakening of the meridional overturning circulation (MOC) will occur

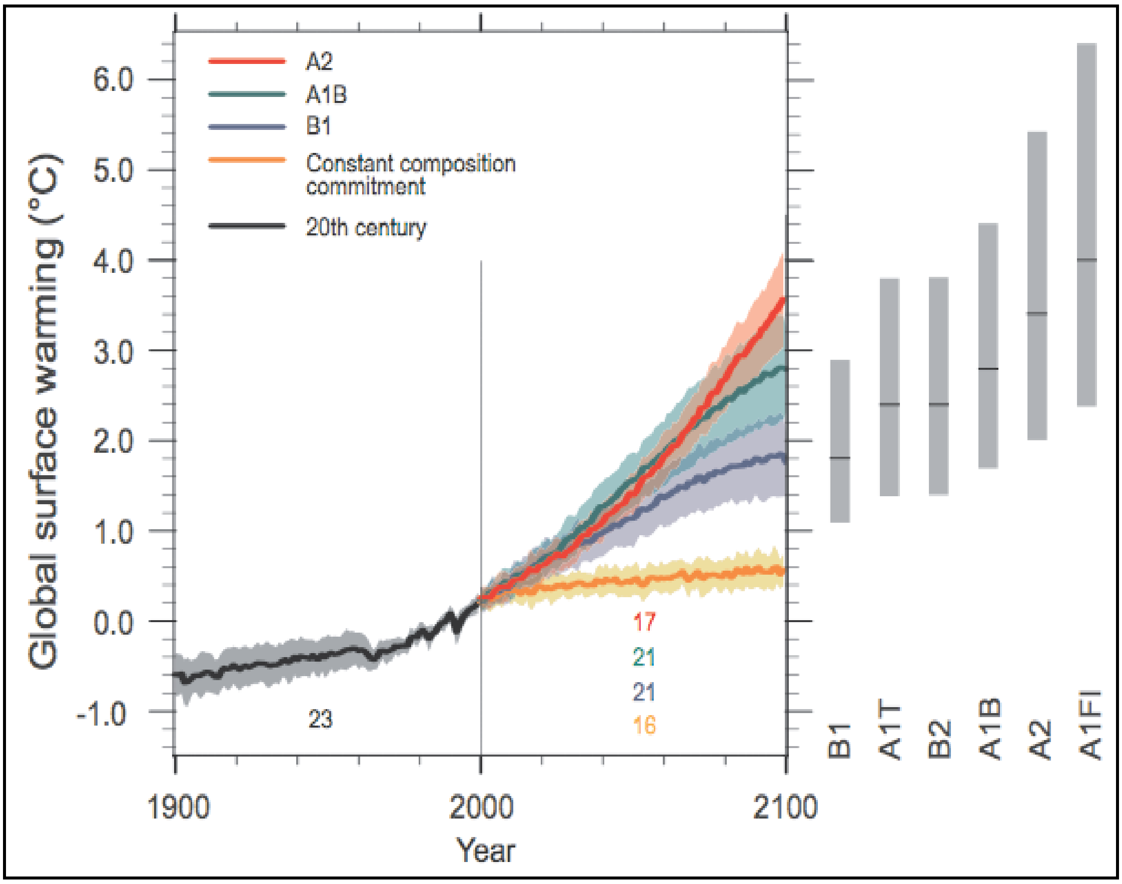

Figure 2.3. Globally averaged surface temperature change by 2100 depending on emissions scenario (IPCC, 2007).

during the present century, no models project a collapse

- Temperatures in the North Atlantic region are expected to continue to warm due to the dominant role of human influences (Dai *et al.*, 2005).

An increase in global temperatures of the magnitude projected by GCMs is likely to have a significant impact on climate processes operating at various scales, from global- and hemispherical-scale processes to the regional- and local-scale surface environmental variables. Confidence in the simulations of these models is largely based on the assumptions and parameterisations used to develop them but also on the ability of these models to reproduce the observed climate (Fig. 2.4) (Karl *et al.*, 1990). In recent years, increasing sophistication of these models has resulted from an improved understanding of the underlying climate process and ability to incorporate these advances into these numerical models. Complexity of the climate system is also accounted for with the incorporation of horizontal and vertical exchanges of heat, moisture and momentum extending into the atmosphere and ocean.

2.3 Downscaling Global Climate Models

Despite the high degree of sophistication of GCMs, their output is generally too coarse to be useful for regional- or local-scale impact analysis, as important processes which occur at the sub-grid scale are not at present resolved by these models (Wilby *et al.*, 1999). Changes in both temporal and spatial variability, which may be just as important as the magnitude of change, are also masked at the sub-grid scale (Wigley *et al.*, 1990), as it is unlikely that all locations will warm by the same amount and at the same rate. Global variations in the amount and rate of warming will also affect the distribution and rates of change of other meteorological variables, such as precipitation.

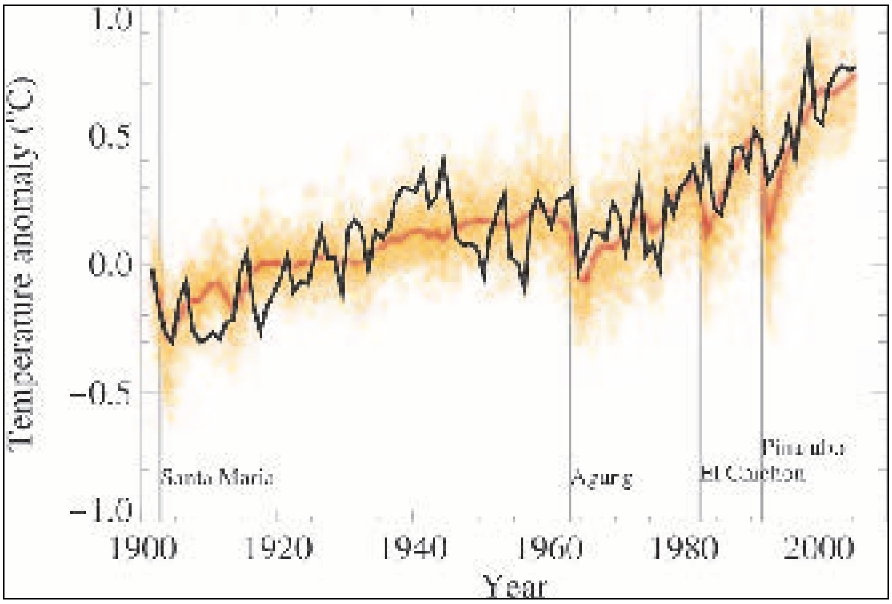

Figure 2.4. Comparison between global mean surface temperature anomalies from observations (black) and Atmosphere–Ocean Global Climate Model (AOGCM) simulations (yellow), based on 58 simulations from 14 models, forced with both anthropogenic and natural forcings and multi-model ensemble mean (red) (IPCC, 2007).

Therefore, a disparity of scales exists between the global scenarios, as output by GCMs, and changes that could occur at the regional or local level due to these large-scale changes. In order to overcome some of these scale differences, a number of techniques have been developed in which large-scale GCM output can be translated or 'downscaled' into information about changes in the climate which can then be used for local-scale impact analysis.

2.3.1 Regional climate models

The application of regional climate models (RCMs), which are dynamical in nature, to the downscaling problem has become more widespread in recent years due to the increase in available computational resources. Regional climate models are fundamentally similar to GCMs in that they utilise physical parameterisations that are either consistent with their respective resolutions or each other (Yarnal *et al.*, 2001). Their added value is derived from the fact that they operate on a much smaller domain and as such offer a much higher resolution than that of the parent GCM within which they are nested. The optimum resolution at which nested RCMs operate is in the tens of kilometres, which may still be too coarse for some impact analysis needs.

2.3.2 Empirical statistical downscaling

Empirical statistical downscaling has become a viable alternative to that of RCMs, where high spatial and temporal resolution climate scenarios are required. It requires substantially less computational resources and produces results that are comparable to those output from RCMs. The methodologies employed in statistical downscaling are largely in common with those of synoptic climatology; however, the goal of downscaling is to adequately describe the relationship between atmospheric circulation and the surface environment, with attention being focused more on model parsimony and accuracy, rather than on understanding the relationship between them (Yarnal *et al.,* 2001). As a consequence of their relative ease of implementation and comparability of output to RCMs, the use of statistical downscaling methodologies to produce climate scenarios from GCMs is now the preferred technique for many researchers.

2.3.2.1 Methodology

Empirical statistical downscaling is based on the development of mathematical transfer functions or relationships between observed large-scale atmospheric variables and the surface environmental variable of interest. The transfer functions are generally regression based and are derived between a set of atmospheric variables, or predictors, output from both reanalysis projects and GCMs, and a surface environmental variable of interest or predictand, such as temperature or precipitation. However, a large number of techniques fall into the category of empirical statistical downscaling.

The use of statistical downscaling requires that a number of assumptions are made, the most fundamental of which assumes that the derived relationships between the observed predictor and predictand will remain constant under conditions of climate change and that the relationships are time-invariant (Yarnal *et al*., 2001). It also assumes that the employed large-scale predictor variables are adequately modelled by the GCM for the resultant scenarios to be valid. Busuioc *et al.* (1998), in their verification of the validity of empirical downscaling techniques, found that in the case considered, GCMs were reliable at the regional scale with respect to precipitation in their study area and that the assumptions of validity of the predictor–predictand relationship held up under changed climate conditions.

Von Storch *et al.* (1993) suggested that, if statistical downscaling is to be useful, the relationship between predictor and predictand should explain a large part of the observed variability, as is the case with temperature, and that the expected changes in the mean climate should lie within the range of its natural variability. However, due to the influence of ‘local’ factors on precipitation occurrence and amounts, the relationship between the large-scale predictors used when calibrating the statistical model and site-specific variability is often obscured and, hence, only reflects a small part of the actual observed variability. This situation is further complicated in areas such as Ireland due to relief effects on precipitation.

2.3.2.2 Data and analysis

Observed daily data for precipitation, temperature and sun hours were obtained from 14 synoptic stations from the Irish Meteorological Service, Met Éireann, for the period 1961–2000. Potential evapotranspiration, based on the Penman–Monteith formula, was obtained for the 1971–2000 period, while radiation for the 1961–2000 period was only available from a selection of synoptic stations. The synoptic stations, which are geographically dispersed around the island, represent low-lying conditions for a mixture of coastal and interior locations (Fig. 2.5). No prior homogeneity analysis of the daily data was performed. However, the data obtained are from the synoptic network, manned by experienced meteorological officers, and are considered to be of good quality. The data are, however, provided with quality-control flags, indicating whether the measurement is the value as read, accumulated, trace or otherwise, therefore enabling the researcher to decide on a suitable threshold for accepting the data as valid. In the present research, all values not directly measured by the observer were removed from the analysis, with the exception of potential evapotranspiration which is a calculated variable.

Large-scale surface and atmospheric data were obtained from the UK Statistical DownScaling Model (SDSM) data archive (Wilby and Dawson, 2004), derived from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Project. The NCEP/NCAR data, originally at a resolution of 2.5° $\times$ 2.5°, were re-gridded to conform with the output resolution of the Hadley Centre (HadCM3) GCM (Wilby and Dawson, 2004). Prior re-gridding of the reanalysis data is important in order to overcome any mismatch in scales that may exist between predictor data sets. Standardised reanalysis variables, as advocated by Karl *et al.* (1990), were then used as candidate predictor variables to calibrate the transfer functions, linking the large-scale surface and atmospheric variables to the daily precipitation series for each of the 14 synoptic stations. Even though the reanalysis data are essentially modelled data, they are constrained by observational data from the global monitoring network and are a modelled, gridded replicate of the observed

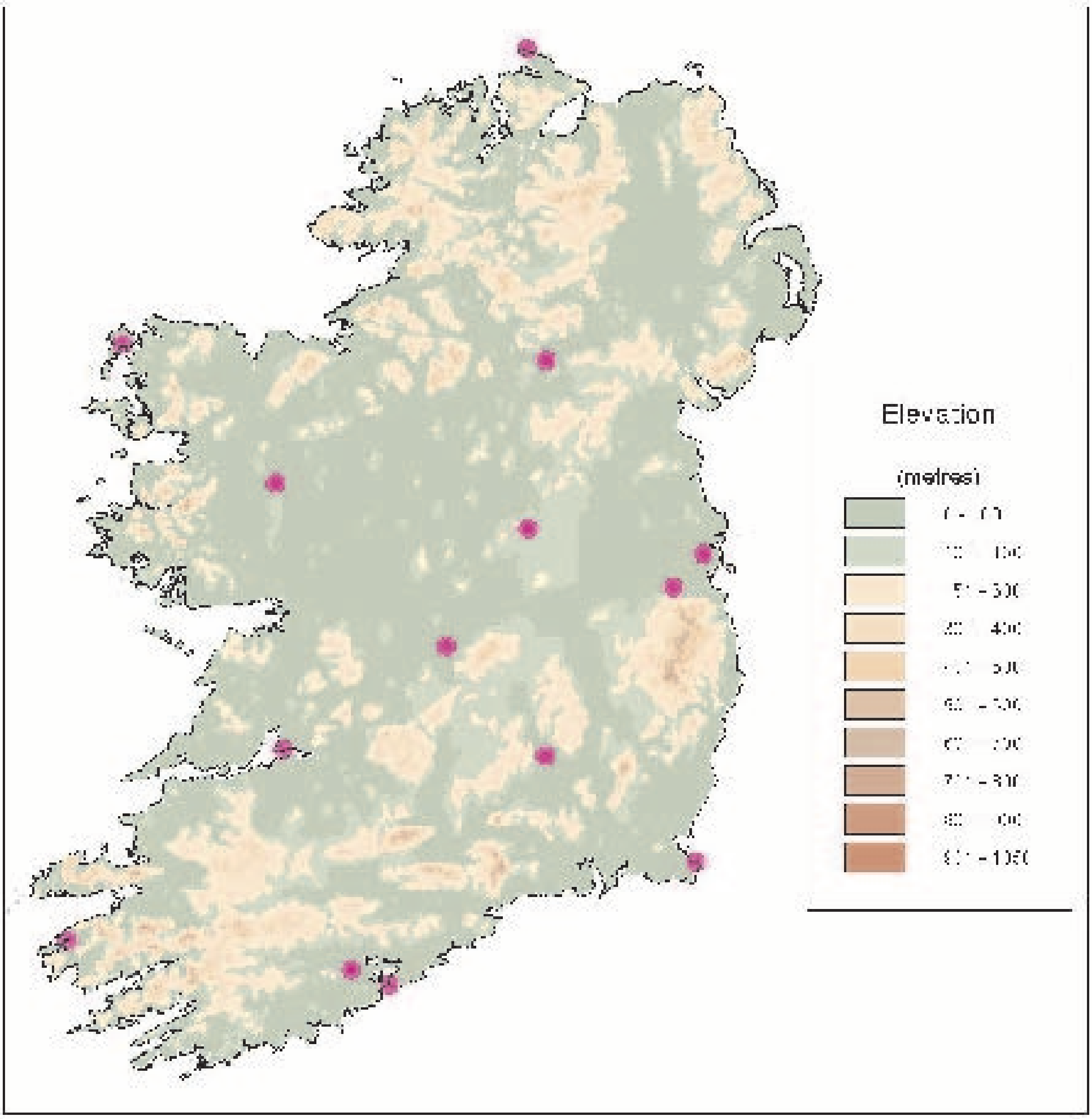

Figure 2.5. Location of synoptic stations.

data. Relationships between grid box values, representing Ireland, for a selection of variables from the reanalysis data were found to be significantly correlated with that of the actual observed upper air variable measured at the two upper air stations in Ireland, Valentia in the south-west and Aldergrove in the north.

In order to derive the future climate scenarios based on the transfer functions, GCM data were obtained, again from the UK SDSM archive, for three models, namely the HadCM3, the Canadian Centre for Climate Modelling and Analysis (CCCma) (CGCM2) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO Mark 2), for both the A2 and B2 emissions scenarios (Wilby and Dawson, 2004). Details of the socio-economic assumptions for these emissions pathways are available in Appendix 2.1. The use of just one GCM and one emissions scenario in impacts analysis was common practice until recently, in spite of the fact that GCMs produce significantly different regional climate responses even when forced with the same emissions scenario (Table 2.1). To cater for these uncertainties, the use of three GCMs and two emissions scenarios were employed in this study.

Table 2.1. Projected global (ΔT_{global}) and regional (ΔT_{JJA}, ΔT_{DJF}, ΔT_{ANN})* temperature changes for Ireland from three global climate models (GCMs) and four marker emissions scenarios (data from Mitchell *et al.*, 2002).

Model	Scenario	ΔT_{global}	ΔT_{JJA}	ΔT_{DJF}	ΔT_{ANN}
CGCM2	A1F1	4.38	3.3	2.7	2.8
CGCM2	A2	3.55	2.7	2.1	2.2
CGCM2	B2	2.46	2.0	1.6	1.7
CGCM2	B1	2.02	1.6	1.3	1.4
CSIRO2	A1F1	4.86	2.8	2.9	2.7
CSIRO2	A2	3.94	2.7	3.1	2.7
CSIRO2	B2	3.14	2.2	2.6	2.2
CSIRO2	B1	2.59	2.1	2.2	2.0
HadCM3	A1F1	4.86	3.1	2.7	3.0
HadCM3	A2	3.93	2.3	2.3	2.4
HadCM3	B2	3.07	1.5	1.4	1.5
HadCM3	B1	2.52	1.5	1.6	1.5

*JJA, June–August; DJF, December–February; ANN, Annual.

All the modelled gridded data sets exist on a common grid resolution, that of 2.5° × 3.75°, and were obtained for the grid box representing Ireland in the GCM domain. The lead and lag of each predictor were also calculated to allow for NCEP daily averaging (00:00–24:00 h) and reporting of daily precipitation (09:00–09:00 h). Employing lagged variables as predictors also allows for a temporal lag which may occur between the predictor and predictand.

2.3.2.3 Predictor selection

Wilby and Wigley (2000), in an analysis of suitable GCM predictors for use in downscaling precipitation, found that spatial offsets can occur in the relationship between predictors and predictands and that the use of atmospheric variables from the grid cell directly over the point of interest can fail to capture the strongest relationships. This spatial offset in the relationship between predictor and predictand was found to vary both seasonally and geographically, indicating the importance of domain size when selecting predictors. Selection of domain size is also important from the point of view of GCM output as the predictive capability or skill of the model is expected to increase with increasing domain size (Goodess and Palutikof, 1998). In order to overcome some of the issues associated with the skill level of various domain sizes, the use of mean sea-level pressure or variables derived from mean sea-level pressure has formed the centrepiece of many downscaling studies due to its relatively conservative variability and hence predictability (Wilby, 1997, 1998; Goodess and Palutikof, 1998; Kilsby *et al.*, 1998; Chen, 2000; Trigo and DaCamara, 2000). Much of the circulation-based downscaling work has focused attention on the use of Lamb Weather Types (LWTs) or the derived objective classification technique of Jenkinson and Collison (1977) and Jones *et al.* (1993) in an extension of the methods used in synoptic climatology. Modelled mesoscale predictor variables, such as mean sea-level pressure and geopotential heights, are also considered to have a much improved skill level in comparison to grid precipitation which depends on sub-grid-scale processes such as clouds being adequately modelled (Wilby and Wigley, 2000). In addition to the primary predictor variables, secondary airflow indices, calculated from a larger domain of nine grid boxes (3 × 3) centred over Ireland (after Jones *et al.*, 1993), were obtained from the UK SDSM data archive.

The selection of an optimum predictor set of atmospheric variables has been the focus of much research. However, no one technique or predictor set has come to the fore and there has been little research in evaluating the skill of various atmospheric predictor sets between studies and regions. Cross-comparisons between predictors and evaluation of skill have been complicated by the fact that different studies have utilised different techniques and atmospheric predictor combinations for different regions. A number of studies have shown that choice of technique (Wilby *et al.*, 1998; Huth, 2003) and predictors can have an impact on the resulting downscaled scenarios (Winkler *et al.*, 1997; Huth, 2003).

In one of the few studies in which a comparison between techniques was conducted, Wilby *et al.* (1998) employed a range of different statistical downscaling models to downscale daily precipitation in order to compare methods. They used a standard set of observed and GCM-derived predictors for a number of methods, two of which were based on weather generators, two which employed grid point vorticity and two which were based on artificial neural networks, to facilitate an evaluation of skill of the different methods. This study indicated that significant differences in the level of skill were evident between the observed and modelled data, depending on which technique was employed (Wilby *et al.*, 1998).

Ultimately the number and choice of candidate predictors available for use are constrained by the overlap between the NCEP data and those output from the various modelling centres (Wilby and Dawson, 2004). The calibration periods for both temperature and the occurrence and amounts models were selected as 1961–1978 and 1994–2000, with the period 1979–1993 being withheld for verification purposes. These time periods were selected subjectively as they coincided with the calibration time periods being employed by STARDEX (Statistical and Regional Dynamical Downscaling of Extremes for European regions).

2.3.3 Downscaled variables: temperature

Temperature is largely a homogenous variable over space with a significant degree of its variation being accounted for by the large-scale atmospheric forcing mechanisms. Temperature also tends towards a normal distribution and can therefore be adequately modelled using a standard multiple linear regression technique, as follows:

$$Y = a_0 + a_1x_1 + a_2x_2 .... a_nx_n + \varepsilon$$

where Y is the predictand, a_n is the coefficient, x_n is the predictor and ε is the error term.

ε, the error term, is used to inflate the variance of the downscaled weather variables, which often tends to be underestimated in statistical downscaling, by adding 'white noise' to the predicted series.

Daily maximum and minimum temperature data for the 1961–2000 period were split into two periods, one for calibration, with the remainder withheld for verification, as described previously. Results from the statistical downscaling are shown in Tables 2.2 and 2.3 for both maximum and minimum temperatures for both the calibration and verification periods. A significant portion of the variance is accounted for in the seasonal regression models of the daily temperature data, suggesting satisfactory modelling of both the maximum and minimum temperature series in all seasons. Figures 2.6 and 2.7 show the mean monthly observed and modelled data for maximum temperatures for Valentia, a coastal site, and Kilkenny, an inland site, for the verification period of 1979–1993.

2.3.4 Downscaled variables: precipitation

In an analysis of the synoptic origins of Irish precipitation, Sweeney (1985) found that the largest mean daily precipitation receipts for 34 stations were associated with southerly, cyclonic and westerly Lamb circulation types. As the main storm tracks pass to the north-west of the island, greater and more frequent falls of precipitation in the north-western counties are experienced than in the south-east (Keane and Sheridan, 2004). Frontal systems, associated with these Atlantic depressions, and airflow interaction with local topography, result in precipitation being one of the most variable meteorological parameters measured in Ireland, with large variations in receipts both spatially and temporally (Rohan, 1975; Keane and Sheridan, 2004). Additionally, daily precipitation tends to be characterised by long-duration low-intensity events. As a consequence of the large monthly and seasonal variations in precipitation, no clearly defined 'wet' and 'dry' seasons exist. However,

Table 2.2. Pearson's R values for the seasonal calibration (Cal.) and verification (Ver.) periods for maximum temperatures.

Stations	DJF		MAM		JJA		SON	
	Cal.	Ver.	Cal.	Ver.	Cal.	Ver.	Cal.	Ver.
Valentia Observatory	0.88	0.87	0.89	0.90	0.83	0.84	0.88	0.86
Shannon Airport	0.89	0.88	0.89	0.91	0.82	0.84	0.88	0.87
Dublin Airport	0.82	0.81	0.87	0.89	0.80	0.82	0.87	0.87
Malin Head	0.83	0.86	0.83	0.86	0.78	0.78	0.85	0.84
Roche's Point	0.89	0.88	0.85	0.87	0.76	0.80	0.86	0.87
Belmullet	0.85	0.86	0.85	0.87	0.79	0.79	0.86	0.85
Clones	0.86	0.85	0.87	0.90	0.81	0.82	0.87	0.86
Rosslare	0.90	0.90	0.86	0.86	0.74	0.79	0.87	0.87
Claremorris	0.87	0.86	0.87	0.90	0.79	0.82	0.86	0.86
Mullingar	0.88	0.88	0.87	0.91	0.80	0.85	0.87	0.87
Kilkenny	0.90	0.89	0.89	0.91	0.83	0.85	0.87	0.87
Casement Aerodrome	0.90	0.89	0.88	0.90	0.81	0.84	0.87	0.87
Cork Airport	0.90	0.89	0.87	0.89	0.80	0.84	0.87	0.87
Birr	0.89	0.88	0.89	0.92	0.83	0.85	0.87	0.87

DJF, December–February; MAM, March–May, JJA, June–August; SON, September–November.

Table 2.3. Pearson's R values for the seasonal calibration (Cal.) and verification (Ver.) periods for minimum temperatures.

Stations	DJF		MAM		JJA		SON	
	Cal.	Ver.	Cal.	Ver.	Cal.	Ver.	Cal.	Ver.
Valentia Observatory	0.83	0.81	0.82	0.81	0.73	0.74	0.84	0.85
Shannon Airport	0.84	0.83	0.84	0.86	0.77	0.80	0.88	0.89
Dublin Airport	0.79	0.81	0.83	0.85	0.75	0.81	0.88	0.89
Malin Head	0.77	0.80	0.80	0.82	0.72	0.74	0.84	0.83
Roche's Point	0.85	0.84	0.88	0.89	0.82	0.85	0.90	0.90
Belmullet	0.81	0.80	0.81	0.82	0.70	0.72	0.81	0.81
Clones	0.78	0.79	0.82	0.83	0.74	0.77	0.86	0.86
Rosslare	0.81	0.82	0.86	0.88	0.81	0.84	0.89	0.89
Claremorris	0.81	0.80	0.82	0.83	0.73	0.75	0.85	0.86
Mullingar	0.79	0.78	0.83	0.82	0.75	0.76	0.87	0.87
Kilkenny	0.78	0.77	0.79	0.79	0.71	0.73	0.83	0.85
Casement Aerodrome	0.80	0.80	0.82	0.82	0.75	0.77	0.87	0.88
Cork Airport	0.85	0.85	0.87	0.88	0.83	0.84	0.91	0.91
Birr	0.82	0.82	0.84	0.82	0.74	0.77	0.87	0.88

DJF, December–February; MAM, March–May, JJA, June–August; SON, September–November.

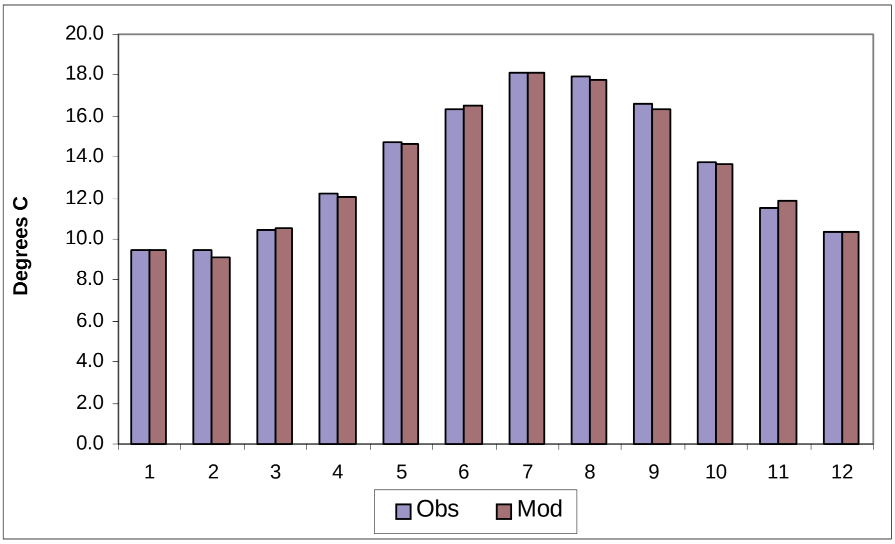

Figure 2.6. Comparison of observed and modelled maximum temperatures from Valentia for the independent verification period 1979–1993.

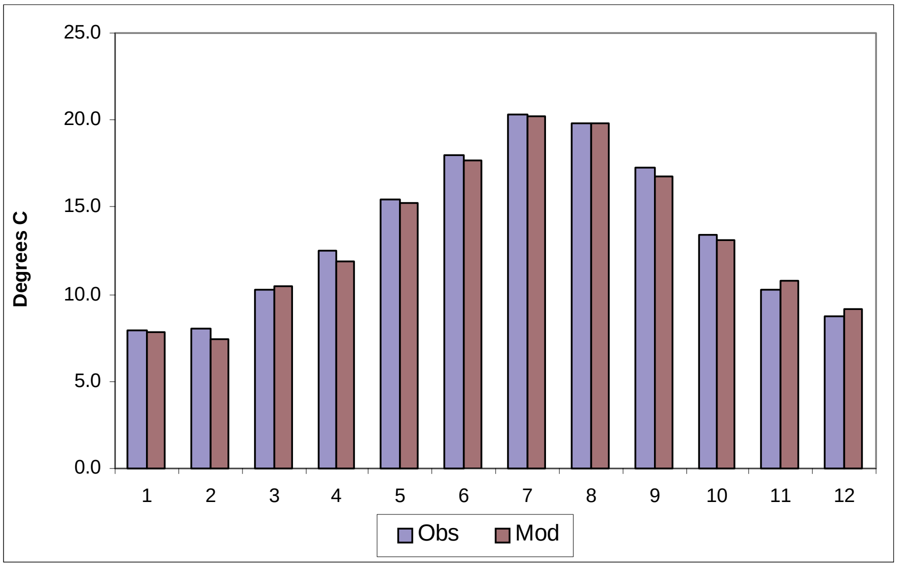

Figure 2.7. Comparison of observed and modelled maximum temperatures from Kilkenny for the independent verification period 1979–1993.

the period February to July tends to be drier than August to January (Sweeney, 1985). Year-to-year variability also tends to be quite large.

Producing plausible output from statistically downscaled models of daily precipitation remains a significant challenge when producing climate scenarios for impact assessments. This challenge arises primarily as a consequence of a number of difficulties that arise when working with the higher-resolution daily precipitation data. Precipitation receipts at a site tend to be largely heterogeneous over space and time as local factors play an important role in determining whether it rains or not. More crucially from the point of view of statistical analysis, daily precipitation data are rarely, if ever, normally distributed, resulting from a high-frequency occurrence of low fall events and a low frequency of high fall events. Additionally, modelling precipitation requires a two-step procedure. First, precipitation occurrence must be modelled, then a model is fitted to precipitation amounts which describes the rainfall distribution for days on which precipitation occurs. The technique employed, described below, is one that overcomes some of the difficulties encountered and produces plausible precipitation amounts for the selected synoptic station in Ireland. However, difficulties still exist with predicting extreme precipitation events, which tend to be underestimated.

2.3.4.1 Precipitation occurrence model

Sequences of daily occurrences of precipitation are commonly modelled using a two-state Markov chain of first or higher order, expressed as:

$$\Pr(X_{t+1}|X_t, X_{t-1}, X_{t-2},\ldots,X_1) = \Pr(X_{t+1}|X_t)$$

(Wilks, 1995).

For a first-order Markov chain, the probability of rain occurring tomorrow is dependent on whether or not it rains today. Transitions between states are based on conditional probabilities. However, there is evidence to suggest that these conditional probabilities may be non-stationary.

For the purposes of the present study, logistic regression, which is a particular type of generalised linear model (GLM), was employed to model wet- and dry-day sequences of precipitation. The logistic regression model, or logit, can be written as

$$\ln\left(\frac{P}{1-P}\right) = B_0 + B_1x_1 + \ldots B_{n+1}x_{n+1}$$

which can be rewritten in terms of odds rather than log odds

$$\frac{P}{1-P} = e^{B_0 + B_1x_1 + \ldots B_{n+1}x_{n+1}}$$

where P is the probability of an event, e is the base of the natural logarithms, x is the independent variable, and B_0 and B_1 are the coefficients estimated from the data.

The maximum likelihood method is used to select parameters within the logistic regression. Use of the logistic regression approach offers a significant improvement over multiple linear regression as the distribution of errors is normal and, additionally, the predicted values can be interpreted as probabilities which ensures that P lies in the interval between 0 and 1.

In order to assess the relative skill of the fitted models, the Heidke Skill Score (HSS) was employed, a method commonly used to summarise square contingency tables (Wilks, 1995). The HSS is calculated as follows:

$$\text{HSS} = \frac{2(ad - bc)}{(a + c)(c + d) + (a + b)(b + d)}$$

where:

	Yes	No
Yes	a	b
No	c	d

(Wilks, 1995).

A score of 1 indicates a perfect forecast, while forecasts equivalent to the reference forecast produce a score of zero. Scores less than zero indicate that forecasts were worse than the reference forecast (Wilks, 1995). Results for the seasonal occurrence models are shown in Table 2.4. Results indicate that all models are substantially better than the reference forecast. Values of the HSS for the independent verification period are comparable at all stations and for all seasons with the scores for the calibration periods, indicating that the predictors at least adequately capture some of the more important mechanisms responsible for precipitation occurrence at the stations employed in the analysis.

2.3.4.2 Precipitation amounts model

A GLM was employed to model precipitation amounts conditional on a range of atmospheric variables. The technique, developed by McCullagh and Nelder (1989), has been previously applied to model climatological series in a number of studies, mainly by Chandler and Wheater (1998, 2002), Chandler (2003) and Yan *et al.* (2002). Generalised linear models are particularly useful for modelling climatological series, as they do not require the dependent variable to be normally distributed and can be applied to any variable that falls into the exponential family of distributions. Therefore, when modelling climatological series such as precipitation or wind speeds, no prior normalisation of the dependent variable is required, minimising any data loss.

Table 2.4. Heidke skill scores for the seasonal precipitation occurrence models for both calibration (1961–1978; 1994–2000) and verification (1979–1993) periods.

Stations	DJF		MAM		JJA		SON	
	Cal.	Ver.	Cal.	Ver.	Cal.	Ver.	Cal.	Ver.
Valentia Observatory	0.68	0.66	0.64	0.63	0.61	0.61	0.60	0.69
Shannon Airport	0.63	0.67	0.64	0.65	0.60	0.63	0.64	0.65
Dublin Airport	0.51	0.52	0.60	0.57	0.56	0.56	0.54	0.49
Malin Head	0.58	0.62	0.58	0.58	0.60	0.52	0.57	0.63
Roche's Point	0.64	0.58	0.60	0.60	0.59	0.58	0.57	0.59
Belmullet	0.58	0.58	0.59	0.62	0.56	0.51	0.57	0.59
Clones	0.62	0.64	0.65	0.64	0.66	0.62	0.60	0.62
Rosslare	0.56	0.54	0.64	0.57	0.56	0.55	0.58	0.57
Claremorris	0.65	0.66	0.62	0.61	0.65	0.56	0.62	0.63
Mullingar	0.58	0.58	0.68	0.65	0.64	0.60	0.54	0.62
Kilkenny	0.59	0.59	0.65	0.65	0.58	0.58	0.57	0.59
Casement Aerodrome	0.53	0.58	0.64	0.59	0.55	0.57	0.54	0.54
Cork Airport	0.62	0.58	0.61	0.59	0.58	0.60	0.58	0.62
Birr	0.59	0.63	0.65	0.65	0.58	0.55	0.60	0.62

DJF, December–February; MAM, March–May, JJA, June–August; SON, September–November.

Generalised linear models have the added advantage in that they fit probability distributions to the variable being modelled, which should offer an improvement over normal linear regression techniques, which only model the mean of the distribution. This is likely to be of significant benefit in climate change research as changes in the shape of the distribution are likely to occur as a consequence of climate change (Yan *et al.*, 2002). Fitting probability distributions in this manner should also improve how extreme values in the tails of the distributions are handled within the modelling framework. A constant coefficient of variation, where the standard deviation is proportional to the mean, also ensures that variance of wet-day amounts increase with the expected value, a far more realistic assumption than that of constant variance for precipitation (Beckmann and Buishand, 2002).

The GLM relates the response variable (Y), whose distribution has a vector mean $\mu = (\mu_1,\ldots, \mu_n)$ to one or more covariates (x) via the relationship:

$$\mu = E(Y)$$

where $E(Y)$ is the expected value of Y

$$g(\mu) = \nu$$

$$\nu = a_0 + a_1x_1+\ldots+a_nx_n$$

A log link function, $g(\mu)$, and gamma distribution were employed for the purposes of modelling precipitation amounts. While the mixed exponential distribution has been found to provide a better fit to precipitation amounts (Wilks and Wilby, 1999), the relationship between the mean and variance for this distribution makes it difficult to incorporate into a GLM. Nonetheless, the gamma distribution GLM has been found to be an extremely good fit to precipitation amounts in a number of regions (Richard Chandler, personal communication, 2003).

Table 2.5 shows the explained variance for all stations for both calibration and verification periods. The months of March, April and May appear to have the best results for the calibration period, with a Pearson's R value of 0.66 being attained for the model for Roche's Point, in the south of Ireland. However, results are reasonably comparable between seasons and stations and between both calibration and verification periods.

Despite the apparently low explained variance for the precipitation amounts models, Figs 2.8 and 2.9 show

Table 2.5. Pearson's R values for the seasonal precipitation amounts models for both calibration (1961–1978; 1994–2000) and verification (1979–1993) periods.

Station	DJF		MAM		JJA		SON	
	Cal.	Ver.	Cal.	Ver.	Cal.	Ver.	Cal.	Ver.
Valentia Observatory	0.51	0.57	0.55	0.53	0.59	0.60	0.55	0.51
Shannon Airport	0.52	0.51	0.47	0.46	0.47	0.49	0.49	0.38
Dublin Airport	0.45	0.45	0.45	0.41	0.46	0.42	0.43	0.33
Malin Head	0.45	0.52	0.47	0.40	0.44	0.42	0.47	0.40
Roche's Point	0.48	0.49	0.66	0.49	0.58	0.55	0.45	0.35
Belmullet	0.54	0.52	0.50	0.52	0.47	0.50	0.52	0.53
Clones	0.49	0.55	0.49	0.47	0.48	0.48	0.44	0.41
Rosslare	0.49	0.47	0.50	0.43	0.37	0.44	0.46	0.39
Claremorris	0.50	0.54	0.54	0.53	0.49	0.52	0.50	0.46
Mullingar	0.50	0.52	0.54	0.41	0.42	0.51	0.47	0.43
Kilkenny	0.56	0.49	0.53	0.50	0.47	0.40	0.48	0.49
Casement Aerodrome	0.46	0.42	0.38	0.36	0.40	0.46	0.48	0.33
Cork Airport	0.55	0.55	0.60	0.56	0.53	0.61	0.51	0.49
Birr	0.48	0.48	0.46	0.41	0.46	0.41	0.46	0.43

DJF, December–February; MAM, March–May, JJA, June–August; SON, September–November.

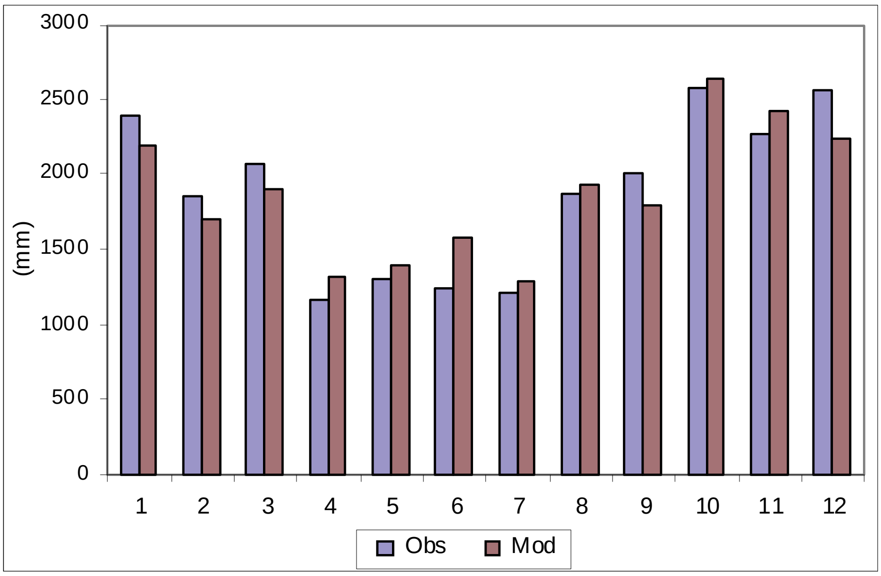

Figure 2.8. Comparison of observed and modelled precipitation from Valentia, a west coast station with high annual receipts, for the independent verification period 1979–1993.

the comparison between monthly precipitation amounts for both the observed and modelled series for the independent verification period of 1979–1993 which demonstrate a good correspondence. Figure 2.10 shows the interannual variability for two stations, one west coast and one east coast, between the observed and modelled series again for the 1979–1993 period. While the correlation between day-to-day variability may be low, monthly and yearly accumulations would appear to have been adequately

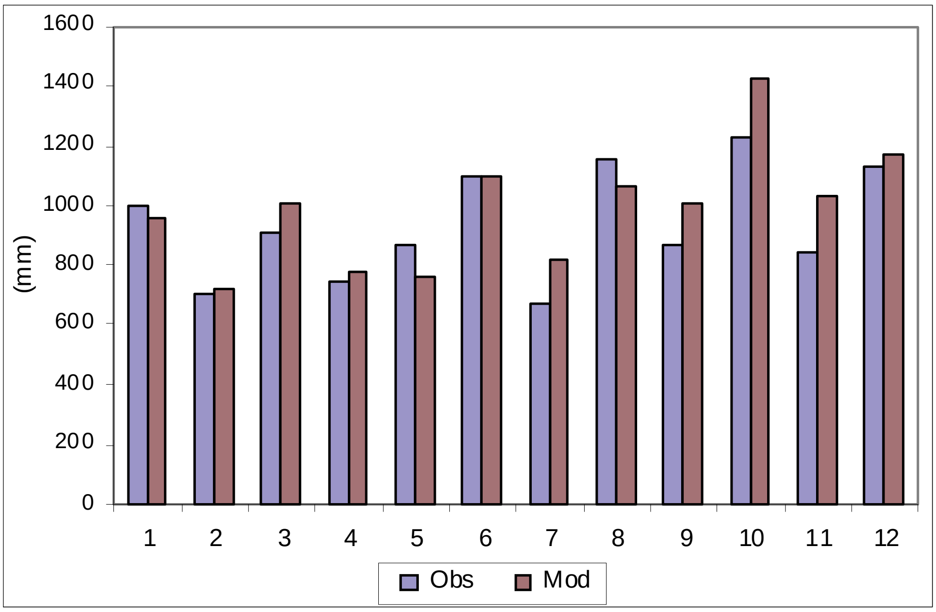

Figure 2.9. Comparison of observed and modelled precipitation from Dublin Airport, an east coast station with low annual receipts, for the independent verification period 1979–1993.

Figure 2.10. Interannual variability for observed and model precipitation from Shannon Airport, west coast, (top) and Casement Aerodrome, east coast, (bottom) for the independent verification period 1979–1993.

captured by the model, an important requirement when assessing climate impacts on such systems as the hydrological system.

2.3.5 Downscaled variables: radiation and potential evapotranspiration

An alternative modelling technique to that of temperature and precipitation, but within the remit of statistical downscaling techniques, was employed to generate daily values of radiation and potential evapotranspiration (PE). As global solar radiation is only measured at a limited number of synoptic stations, sun hours, measured at all synoptic stations, was used in conjunction with the Ångstrom formula in order to convert sun hours to radiation (Ångstrom, 1924; Brock, 1981). Values for the constants *a* and *b*, employed in the Ångstrom formula, have been previously established for Ireland by McEntee (1980) and were found to provide a reasonably good approximation for global solar radiation in Ireland (Sweeney and Fealy, 2003) when applied to the Ångstrom formula.

The technique employed is one that was adapted from conventional weather generator techniques, where the local variables are employed as predictors in conjunction with the large-scale predictors in some form of a regression model as opposed to just employing the large-scale forcing provided from the reanalysis data. As radiation is dependent on local conditions such as cloud cover, a process occurring at the sub-grid scale and not well resolved by GCMs, the use of local climate variables, such as temperature range and precipitation, reflecting thermal heating and local cloud cover, as predictors should provide additional and useful local-scale information. Similarly, as radiation receipt is an important factor in determining the PE at a location, local-scale predictors were again employed in a regression model to predict PE.

Large-scale temperature from the reanalysis data and precipitation and temperature range (maximum–minimum temperature) from the relevant synoptic station were used as inputs to a regression model to predict radiation, derived from the Ångstrom formula. Figures 2.11 and 2.12 show the results of the modelled radiation derived from sun hours, for the verification period. Results indicate that mean daily values are adequately captured by the technique employed, which uses a combination of large-scale and local predictors. Figure 2.13 shows the comparison between actual measured radiation at Valentia and modelled radiation, again for an independent verification period of 1961–1970. Slight underestimations in the modelled radiation values are apparent from the January to September period, due to the underestimation of radiation derived from the Ångstrom formula used to calibrate the downscaling model. However, results are encouraging despite the fact that observed global solar radiation was not available for use as input into the regression model.

Radiation, precipitation occurrence and precipitation amounts were then used as inputs into the regression model for calibrating PE. While wind plays an important role in PE, it has a seasonal dependence, being more influential during the winter months and diminishing during the spring, summer and autumn months. As PE values are at a minimum during the

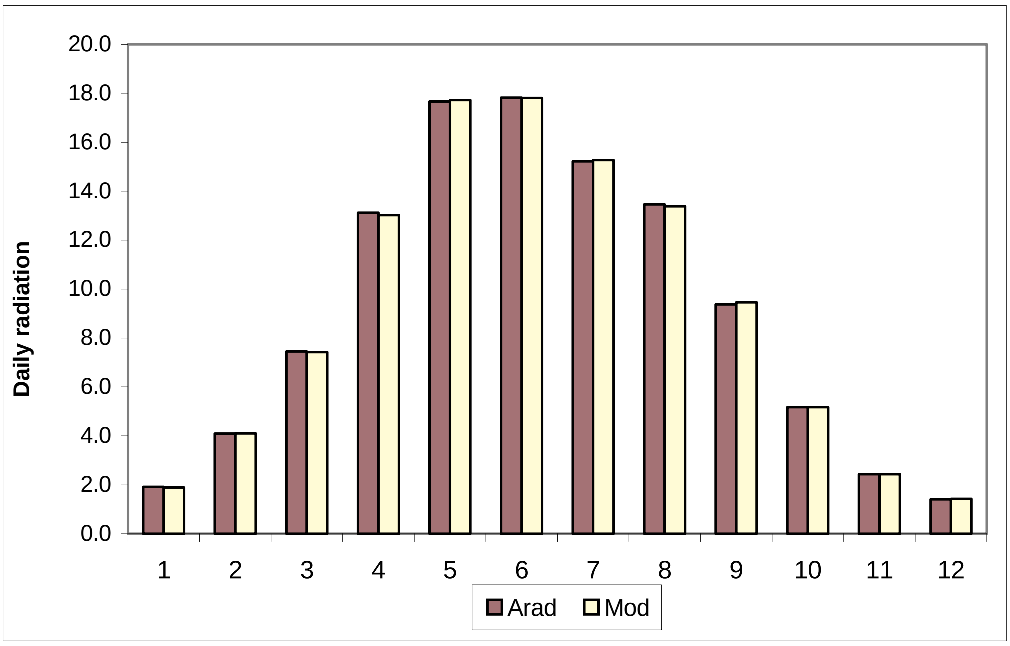

Figure 2.11. Comparison of mean daily radiation derived from sun hours from Malin Head and modelled radiation for an independent verification period of 1961–1970.

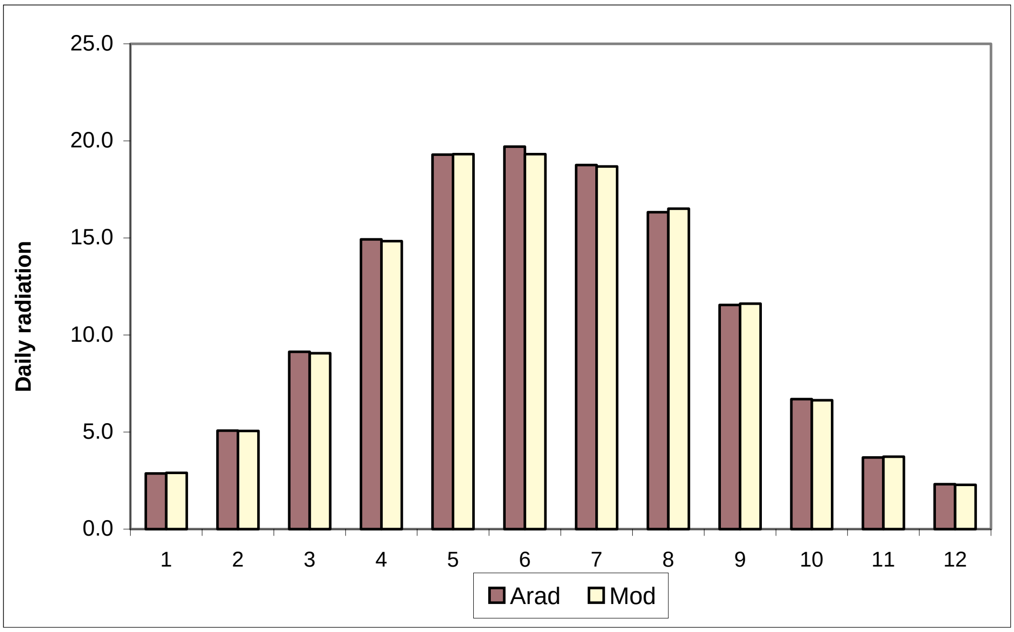

Figure 2.12. Comparison of mean daily radiation derived from sun hours from Rosslare and modelled radiation for an independent verification period of 1961–1970.

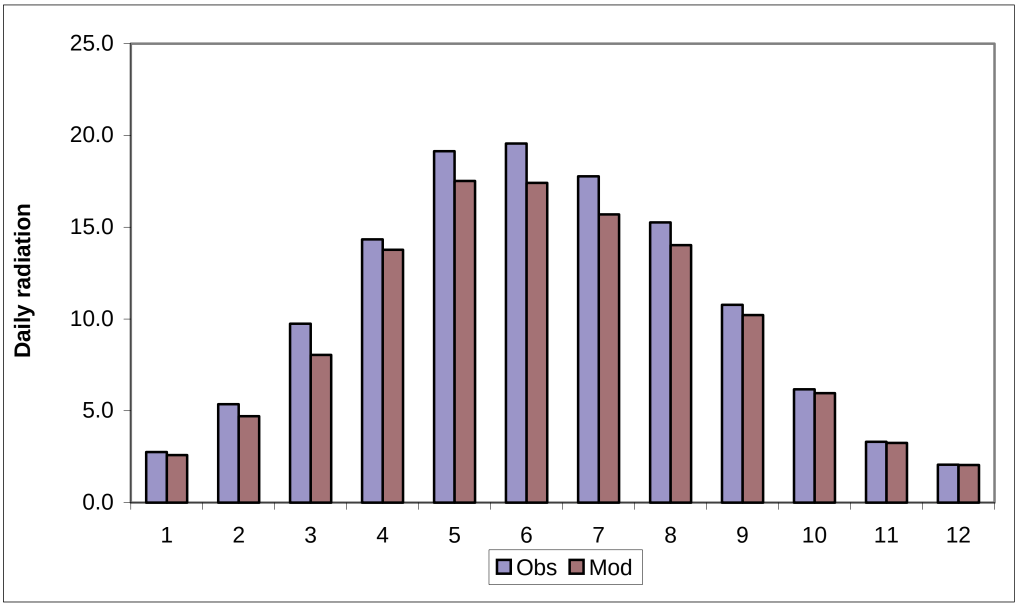

Figure 2.13. Comparison of observed mean daily radiation from Valentia and modelled radiation for an independent verification period of 1961–1970.

winter months, the exclusion of this variable is unlikely to impact too much on the predicted values of PE.

Figures 2.14 and 2.15 show the comparison between derived PE at Valentia and Kilkenny and the modelled values of PE from the statistical downscaling models. Again, the correspondence between both data sets suggests that a significant proportion of the variance has been captured by the modelling technique employed. While the model has a slight tendency to overestimate PE during June, July and August, the month-by-month results are again encouraging.

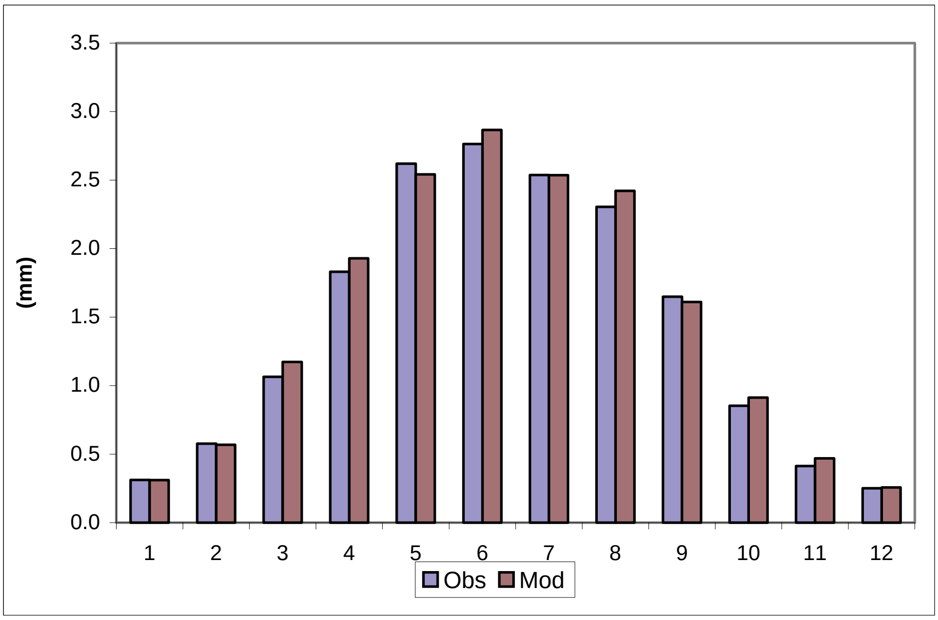

Figure 2.14. Comparison of observed mean daily potential evapotranspiration from Valentia and modelled potential evapotranspiration for an independent verification period of 1991–2000.

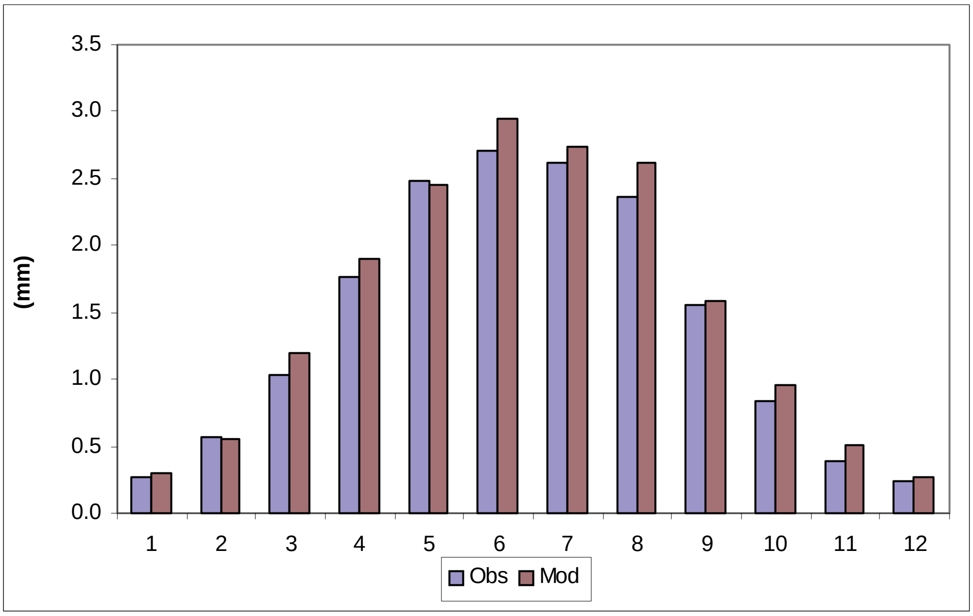

Figure 2.15. Comparison of observed mean daily potential evapotranspiration from Kilkenny and modelled potential evapotranspiration for an independent verification period of 1991–2000.

2.4 Results

2.4.1 Temperature

The stations showing the largest and the smallest change in downscaled temperature for the different GCMs are illustrated in Figures 2.16–2.18 for each of the three time periods and seasons for the A2 emissions scenario. In general, the CCCma GCM is associated with the largest amount of seasonal warming across the three time periods. The HadCM3 suggests slight cooling during the winter period for the 2020s, largely inconsistent with the other two GCMs,

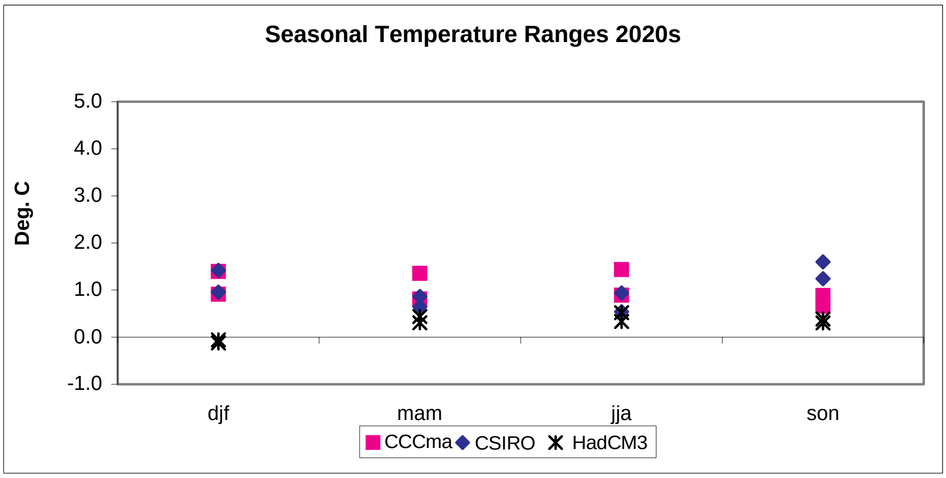

Figure 2.16. Seasonal temperature ranges for the 2020s for stations showing the smallest and greatest changes for the A2 emissions scenario. djf, December–February; mam, March–May; jja, June–August; son, September–November. CCCma, Canadian Centre for Climate Modelling and Analysis; CSIRO, Commonwealth Scientific and Industrial Research Organisation; HadCM3, Hadley Centre Coupled Model, version 3.

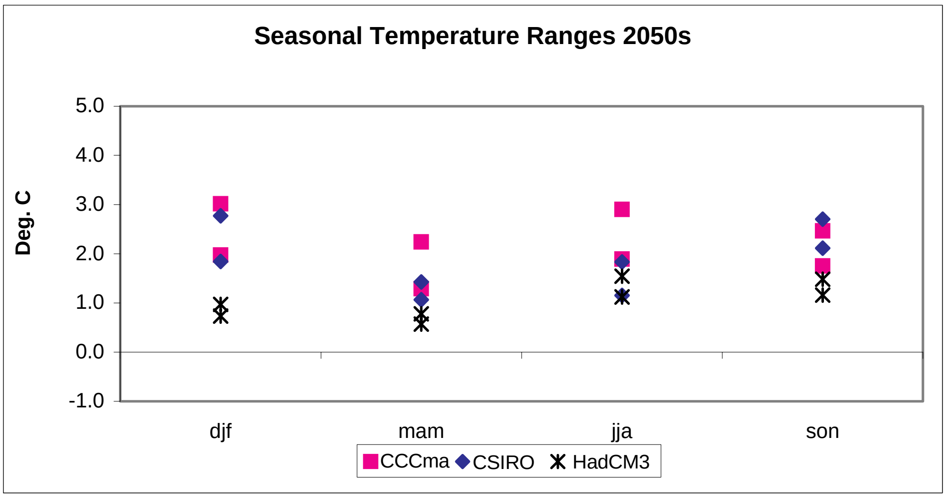

Figure 2.17. Seasonal temperature ranges for the 2050s for stations showing the smallest and greatest changes for the A2 emissions scenario. djf, December–February; mam, March–May; jja, June–August; son, September–November. CCCma, Canadian Centre for Climate Modelling and Analysis; CSIRO, Commonwealth Scientific and Industrial Research Organisation; HadCM3, Hadley Centre Coupled Model, version 3.

both of which indicate warming during this period. The three models also suggest a difference in the seasons likely to experience the greatest warming.

By the 2050s, all models indicate warming for all seasons. The between-stations range is greatest for the CCCma GCM and smallest for the HadCM3 GCM. While the downscaled data from all the models are all consistent in predicting an increase in temperatures for all seasons, the range between the 'warmest' stations from both the HadCM3 and CCCma models suggests a difference of almost 2°C in the winter season. This range is further enhanced by the 2080s, when the 'warmest' stations from the 'warmest' and 'coolest' GCMs suggest a difference of almost 3°C. These differences largely arise due to different GCM model

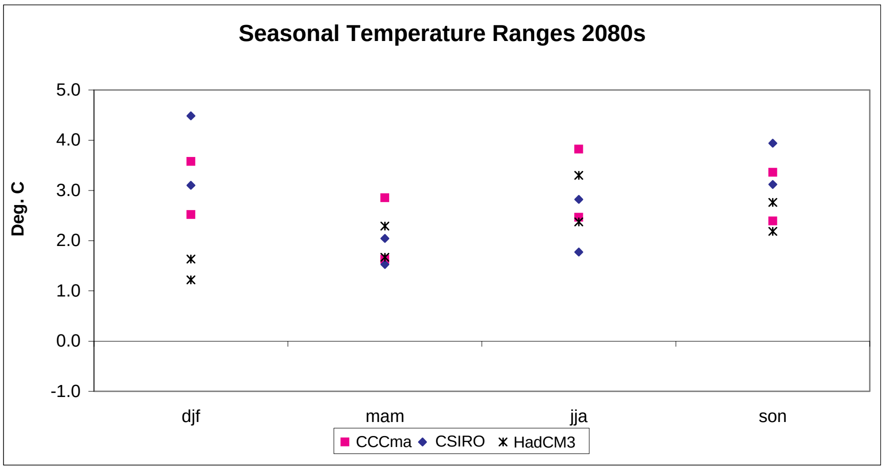

Figure 2.18. Seasonal temperature ranges for the 2080s for stations showing the smallest and greatest changes for the A2 emissions scenario. djf, December–February; mam, March–May; jja, June–August; son, September–November. CCCma, Canadian Centre for Climate Modelling and Analysis; CSIRO, Commonwealth Scientific and Industrial Research Organisation; HadCM3, Hadley Centre Coupled Model, version 3.

climate sensitivities and, therefore, equilibrium temperatures under a doubling of the pre-1990 atmospheric CO_2 concentrations.

2.4.2 Precipitation

The stations showing the largest and the smallest percentage change for the different GCMs are illustrated in Figs 2.19–2.21 for each of the three time periods and each season for the A2 emissions scenario. The range between these stations varies for each of the GCMs, with larger percentage and positive increases being demonstrated by the CCCma GCM, while the downscaled data from the CSIRO GCM suggest that some stations will increase while others will experience a decrease in winter precipitation by the 2020s. The HadCM3-based data indicate that all

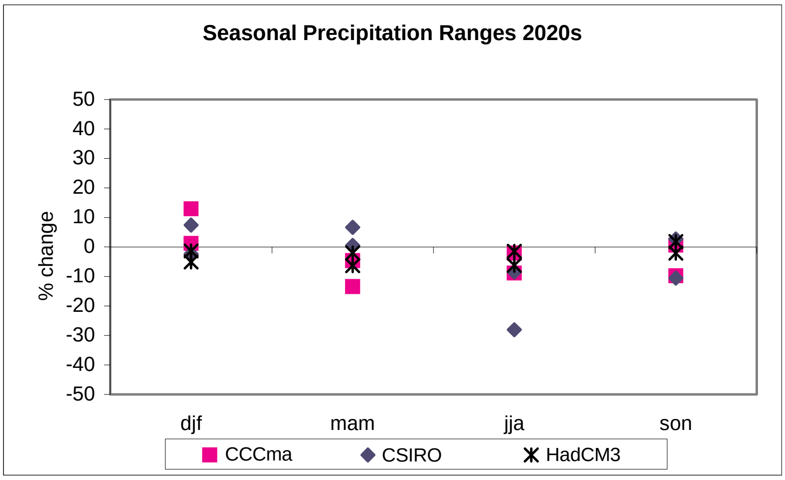

Figure 2.19. Seasonal precipitation ranges for the 2020s for stations showing the smallest and greatest changes for the A2 emissions scenario. djf, December–February; mam, March–May; jja, June–August; son, September–November. CCCma, Canadian Centre for Climate Modelling and Analysis; CSIRO, Commonwealth Scientific and Industrial Research Organisation; HadCM3, Hadley Centre Coupled Model, version 3.

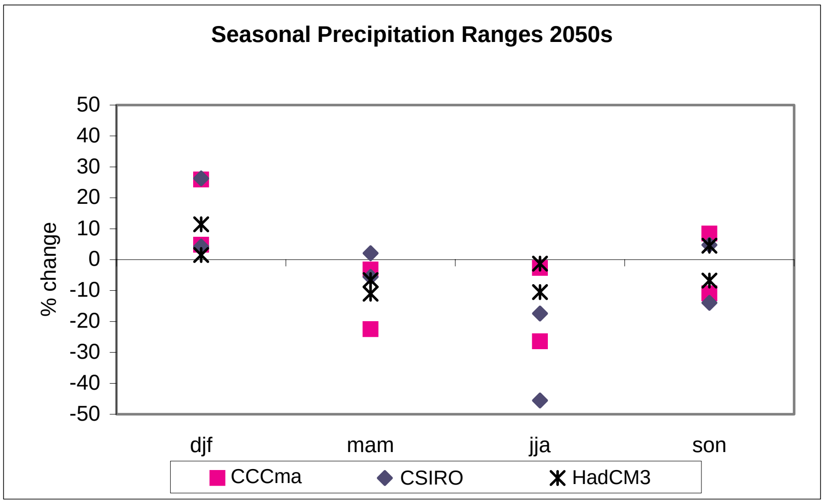

Figure 2.20. Seasonal precipitation ranges for the 2050s for stations showing the smallest and greatest changes for the A2 emissions scenario. djf, December–February; mam, March–May; jja, June–August; son, September–November. CCCma, Canadian Centre for Climate Modelling and Analysis; CSIRO, Commonwealth Scientific and Industrial Research Organisation; HadCM3, Hadley Centre Coupled Model, version 3.

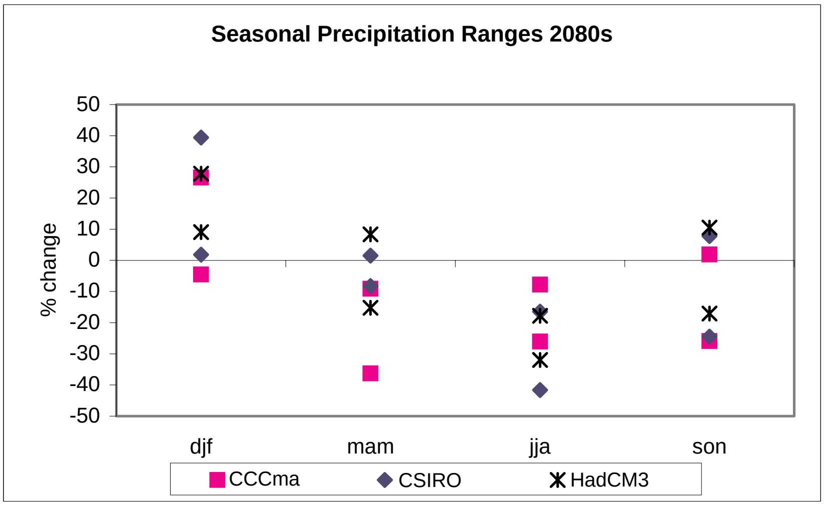

Figure 2.21. Seasonal precipitation ranges for the 2080s for stations showing the smallest and greatest changes for the A2 emissions scenario. djf, December–February; mam, March–May; jja, June–August; son, September–November. CCCma, Canadian Centre for Climate Modelling and Analysis; CSIRO, Commonwealth Scientific and Industrial Research Organisation; HadCM3, Hadley Centre Coupled Model, version 3.

stations will experience a slight decrease in winter precipitation for this period. The summer months are the only period in which all models agree that there will be a decrease in receipts, but again the changes vary between models. A clearer seasonal picture emerges for the winter and summer periods by the 2050s, with all models again suggesting an increase in winter and a decrease in summer, but again the ranges between the 'driest' stations and 'wettest' stations and models are large. Similar results are found for the 2080s. Again, these results illustrate the large seasonal and spatial ranges that can occur, even over an area the size of Ireland. Differences in the GCM model ranges demonstrate the importance of using a number of

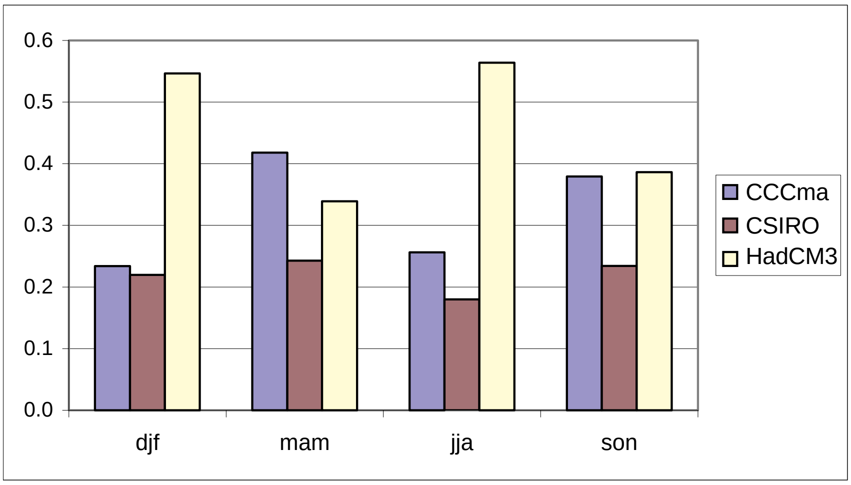

Figure 2.22. Seasonal weights derived from the Climate Prediction Index score for each of the global climate models to produce the weighted ensemble mean. djf, December–February; mam, March–May; jja, June–August; son, September–November. CCCma, Canadian Centre for Climate Modelling and Analysis; CSIRO, Commonwealth Scientific and Industrial Research Organisation; HadCM3, Hadley Centre Climate Model 3.

GCMs when conducting impact analysis due to the various uncertainties that cannot be accounted for when employing just one GCM.

2.5 Ensembles

In spite of the fact that it has long being recognised that different GCMs produce significantly different regional climate responses even when forced with the same emissions scenario (Hulme and Carter, 1999), it was common practice until recently for many impact studies to employ only one climate change scenario, based on one emissions scenario, derived from a single GCM. Hulme and Carter (1999) consider this practice, which ultimately results in the suppression of crucial uncertainties, as 'dangerous' due to any subsequent policy decisions which may only reflect a partial assessment of the risk involved.

In order to try and account for different model and emissions uncertainties, ensembles or averaging of the downscaled results were produced. Results from a weighted ensemble mean, based on the Climate Prediction Index (CPI) (Murphy *et al.*, 2004) and modified by Wilby and Harris (2006) for application to a narrower suite of GCM outputs, will be discussed in the remainder of this section. The modified CPI index or Impacts Relevant Climate Prediction Index (IR-CPI) is weighted based on the individual GCM's ability to reproduce the properties of the observed climate, derived from the NCEP data, and is derived from the root-mean-square difference between modelled and observed climatological means, assessed over the baseline period (Wilby and Harris, 2006). Weights are derived based on the individual contribution of each GCM to overall error. Weights were calculated for each season and model (Fig. 2.22), with the HadCM3 consistently performing well throughout three of the four seasons. The IR-CPI-derived scores are then used to weight the relevant downscaled output from the different GCMs in order to produce an ensemble mean for both the A2 and B2 emissions separately and all emissions, together.

2.5.1 Temperature

The mean ensembles, produced from the weighted averaging described above, suggest that by the 2020s, average seasonal temperatures across Ireland will increase by between 0.75 and 1.0°C (Table 2.6), part

Table 2.6. Mean temperature increases for each season and time period.

Season	2020	2050	2080
December–February	0.7	1.4	2.1
March–May	0.8	1.4	2.0
June–August	0.7	1.5	2.4
September–October	1.0	1.8	2.7

of which has already been experienced over the period since 1990. The largest differences between the A2 and B2 emissions scenarios are evident for both the winter and autumn seasons (Fig. 2.23). By the 2050s, Irish temperatures are suggested to increase by 1.4–1.8°C, with the greatest warming occurring during the autumn (Fig. 2.24). By the 2080s, increases in the range 2.1–2.7°C are suggested by the ensemble

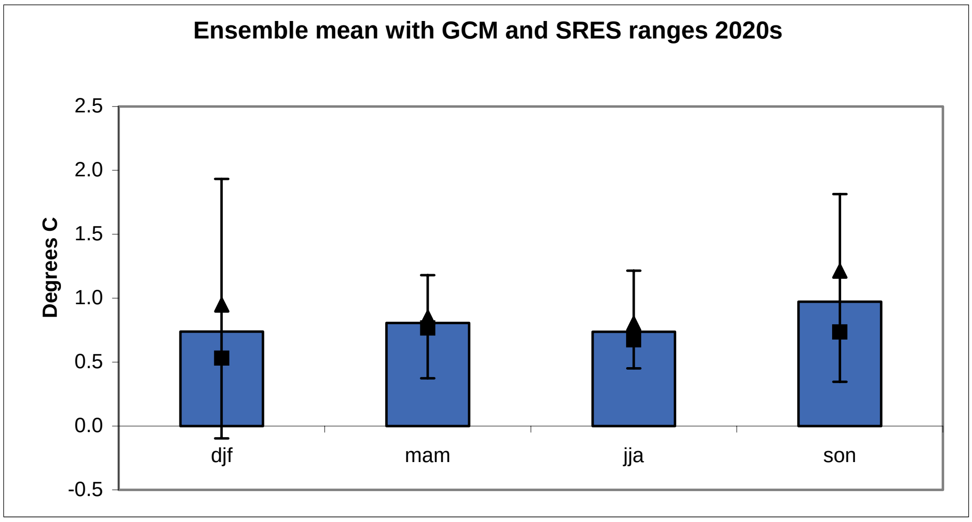

Figure 2.23. Ensemble mean temperature for the 2020s produced from the weighted ensemble of all global climate models (GCMs) and emissions scenarios (bars) (SRES, Special Report on Emissions Scenarios). Upper and lower ranges (lines) are the results from the individual GCMs and emissions scenarios. Ensemble A2 scenario (■) and B2 scenario (▲). djf, December–February; mam, March–May; jja, June–August; son, September–November.

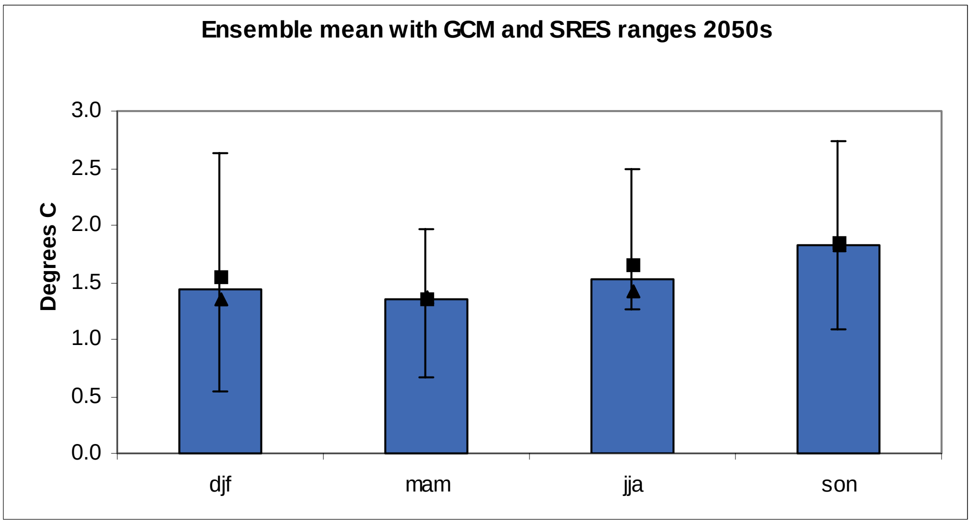

Figure 2.24. Ensemble mean temperature for the 2050s produced from the weighted ensemble of all global climate models (GCMs) and emissions scenarios (bars) (SRES, Special Report on Emissions Scenarios). Upper and lower ranges (lines) are the results from the individual GCMs and emissions scenarios. Ensemble A2 scenario (■) and B2 scenario (▲). djf, December–February; mam, March–May; jja, June–August; son, September–November.

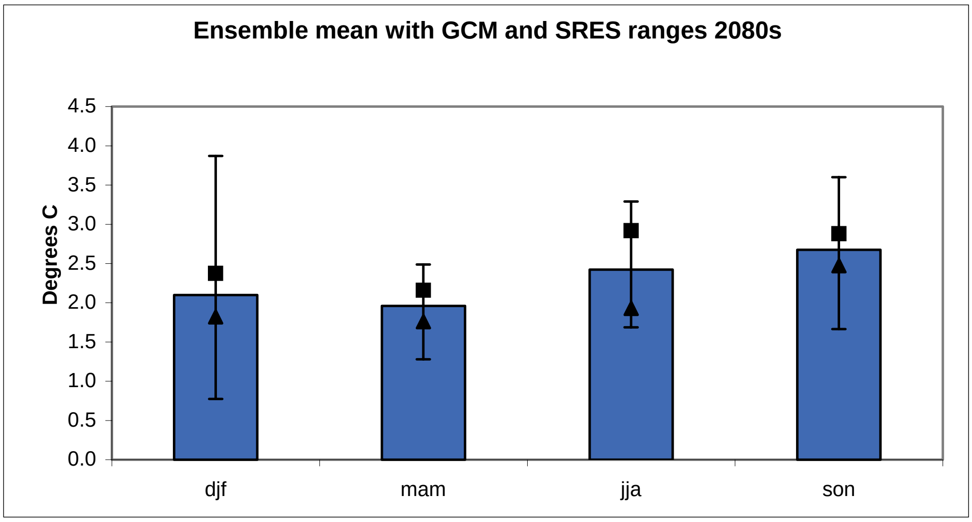

Figure 2.25. Ensemble mean temperature for the 2080s produced from the weighted ensemble of all global climate models (GCMs) and emissions scenarios (bars) (SRES, Special Report on Emissions Scenarios). Upper and lower ranges (lines) are the results from the individual GCMs and emissions scenarios. Ensemble A2 scenario (■) and B2 scenario (▲). djf, December–February; mam, March–May; jja, June–August; son, September–November.

analysis (Fig. 2.25). Spatial differences also become more apparent, with an enhanced 'continental' effect occurring during all seasons (Fig. 2.26).

This 'continental' effect is further enhanced during the 2080s period, particularly during the autumn season, which accounts for the greatest warming during the 2080s, with an increase of 2.7°C (Fig. 2.26). The mean temperature in all seasons is suggested to increase by 2°C or more (Table 2.6). Summer increases in the order of 2.5°C are indicated from the ensemble mean; however, under the A2 emissions scenario, this increase may be as high as 3°C (Fig. 2.25).

2.5.2 Precipitation

Based on the ensemble mean scenarios, winter precipitation is likely to increase marginally by the 2020s, by approximately 3% (Fig. 2.27), with summer reductions of a similar order, approximately 3%; however, reductions of between 10 and 16% are suggested for regions along the southern and eastern coasts (Fig. 2.30). The range of values from the individual GCMs during the summer months for all time periods suggests that the greatest divergence between models occurs during these months as illustrated in the upper and lower ranges on Figs 2.27–2.29.

A greater degree of consistency is evident in the changes for the 2050s, with all GCMs and ensembles suggesting a similar direction of change, but with differences in the magnitude of this change (Fig. 2.28). Again, winter and summer during this time period experience the largest percentage changes in receipt, ranging from 12% increases in winter to reductions of 12% in summer. While increases are experienced along the east coast and midlands during winter, reductions of between 20 and 28% are projected to occur along the southern and eastern coasts during the summer season (Fig. 2.30). If realised, these changes are likely to have a large impact on agriculture and hydrology in Ireland (Holden *et al.*, 2003; Sweeney *et al.*, 2003; Charlton *et al.*, 2006). These seasonal and spatial changes in precipitation are further enhanced by the 2080s, with winter increases of 13–18% and summer reductions of between 14 and 25% (Fig. 2.29). The largest percentage increases in winter precipitation, of up to 20%, are projected to occur in the midlands, while the largest reductions during the summer months are again projected to occur along the southern and eastern coasts, which are likely to experience decreases of between 30 and 40% during these months (Fig. 2.30). Between-model differences are greatest for the spring months during the 2080s,

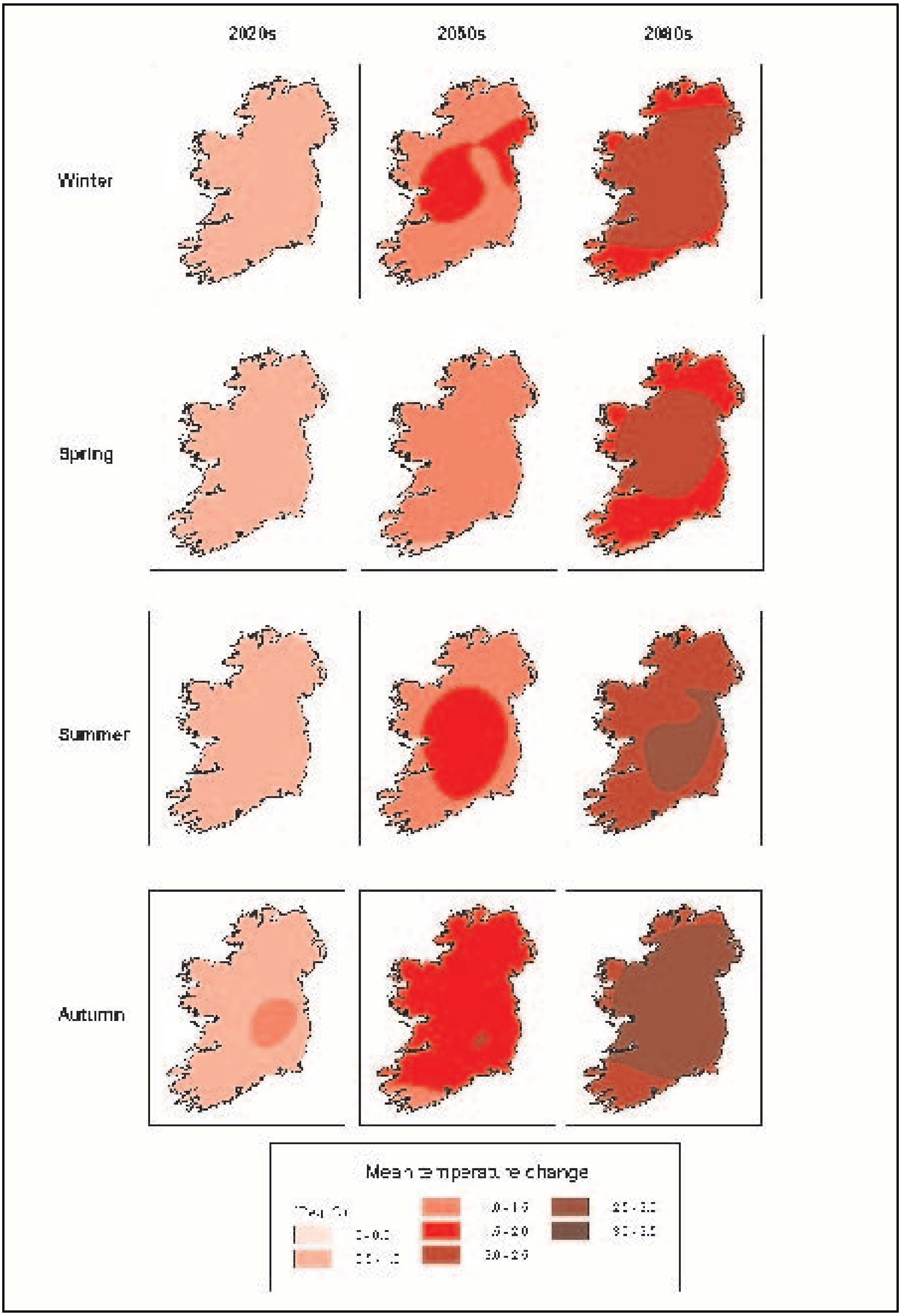

Figure 2.26. Ensemble mean seasonal temperature increases projected for the 2020s–2080s.

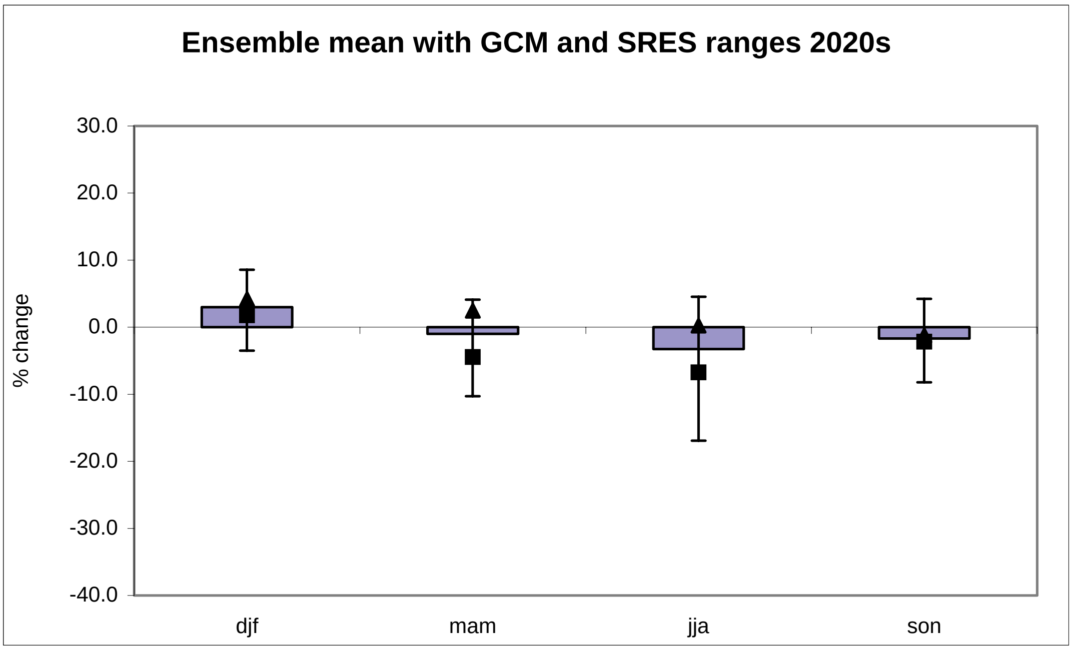

Figure 2.27. Ensemble mean precipitation for the 2020s produced from the weighted ensemble of all global climate models (GCMs) and emissions scenarios (bars) (SRES, Special Report on Emissions Scenarios). Upper and lower ranges (lines) are the results from the individual GCMs and emissions scenarios. Ensemble A2 scenario (■) and B2 scenario (▲). djf, December–February; mam, March–May; jja, June–August; son, September–November.

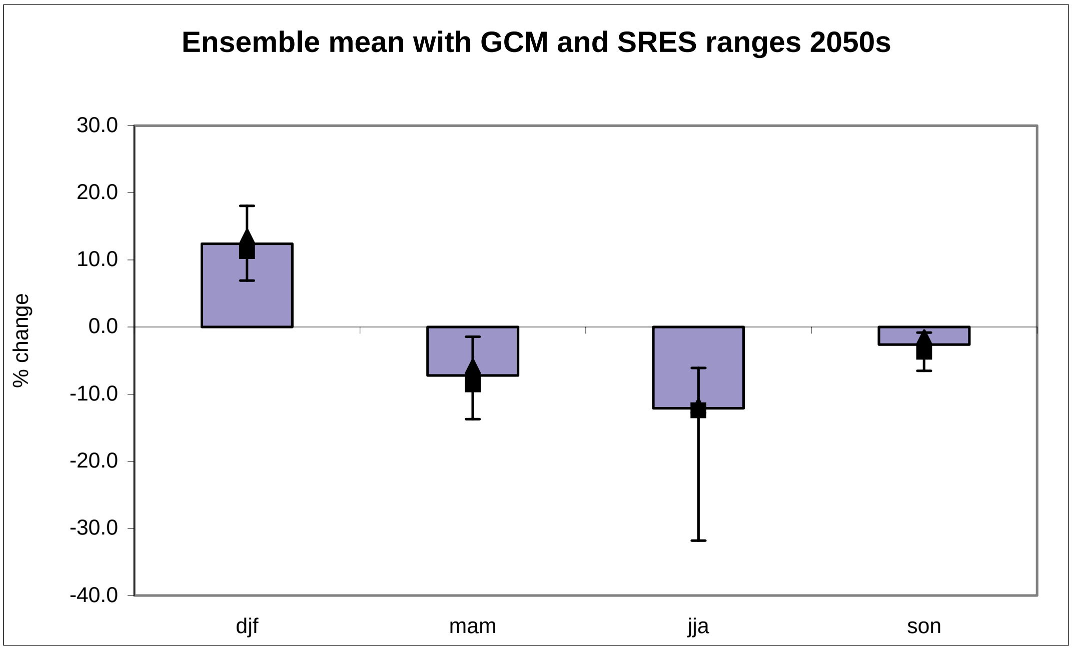

Figure 2.28. Ensemble mean precipitation for the 2050s produced from the weighted ensemble of all global climate models (GCMs) and emissions scenarios (bars) (SRES, Special Report on Emissions Scenarios). Upper and lower ranges (lines) are the results from the individual GCMs and emissions scenarios. Ensemble A2 scenario (■) and B2 scenario (▲). djf, December–February; mam, March–May; jja, June–August; son, September–November.

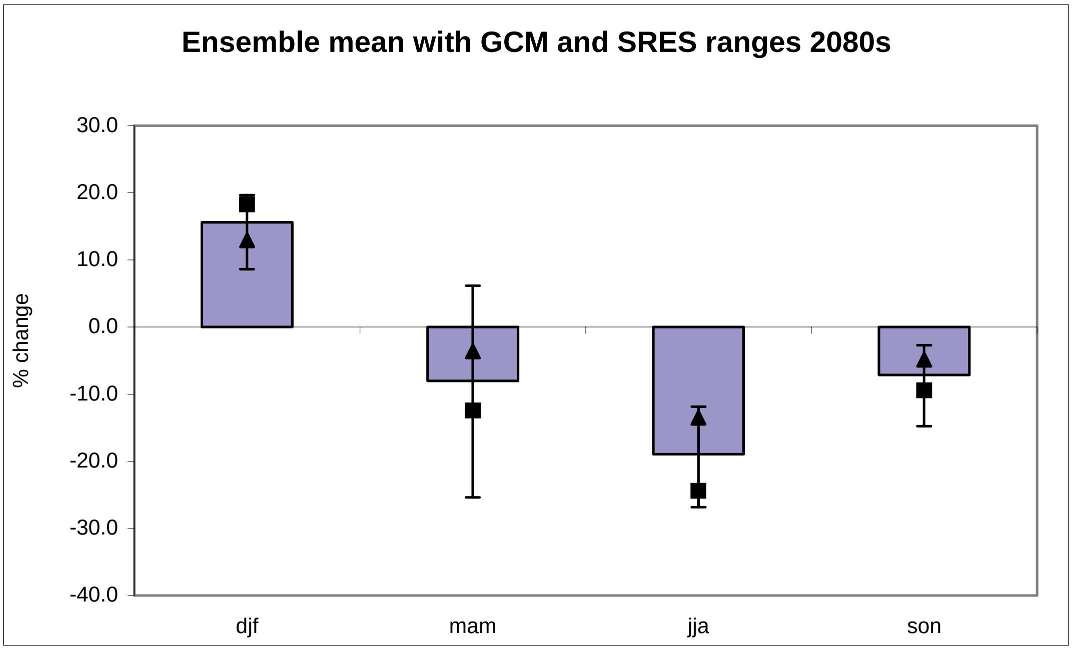

Figure 2.29. Ensemble mean precipitation for the 2080s produced from the weighted ensemble of all global climate models (GCMs) and emissions scenarios (bars) (SRES, Special Report on Emissions Scenarios). Upper and lower ranges (lines) are the results from the individual GCMs and emissions scenarios. Ensemble A2 scenario (■) and B2 scenario (▲). djf, December–February; mam, March–May; jja, June–August; son, September–November.

with two GCMs suggesting a slight increase in spring precipitation. These increases, however, are associated with the lower emissions B2 scenario and show 0.5–6% increases in spring receipts.

2.6 Changes in Extremes of Temperature and Precipitation

Extreme climate events, such as the prolonged heatwave that occurred in Central Europe during the summer of 2003 or the severe flooding in Eastern Europe during the summer of 2002, tend to have a larger impact on human society than changes in the mean climate state. While Ireland has been largely 'buffered' from the extremes that have been witnessed in Central Europe, primarily due to its maritime location, projected changes in the frequency and magnitude of extreme events are increasingly likely to have an effect on human activities in Ireland over the course of the present century.

During the summer of 2006, much of Ireland suffered significant soil moisture deficits due to a combination of above-average mean temperatures, which were over 1°C higher than normal for the 1961–1990 period (nearly 2°C higher than normal for the 1961–1990 period in the midland stations of Clones and Kilkenny), and below average rainfall resulting in it being the warmest, driest and sunniest summer since 1995 (Met Éireann). As temperature and precipitation are two key meteorological parameters, changes in the frequency and magnitude of these variables are provisionally assessed to determine their likely impacts as a consequence of projected climate change. Caution must be exercised with regard to any analysis of projected changes in extremes due to the uncertainties associated with regional projections of these events. In a recent analysis of climate extremes based on various downscaling methodologies, STARDEX found that performance of the models was better for temperature than precipitation, better for means than extremes, and best in winter and worst in summer (STARDEX, 2006). Additionally, the methodology employed in the current research was primarily focused on generating scenarios representing the projected mean climate state for the present century and therefore is likely to underestimate changes in the extremes of temperature

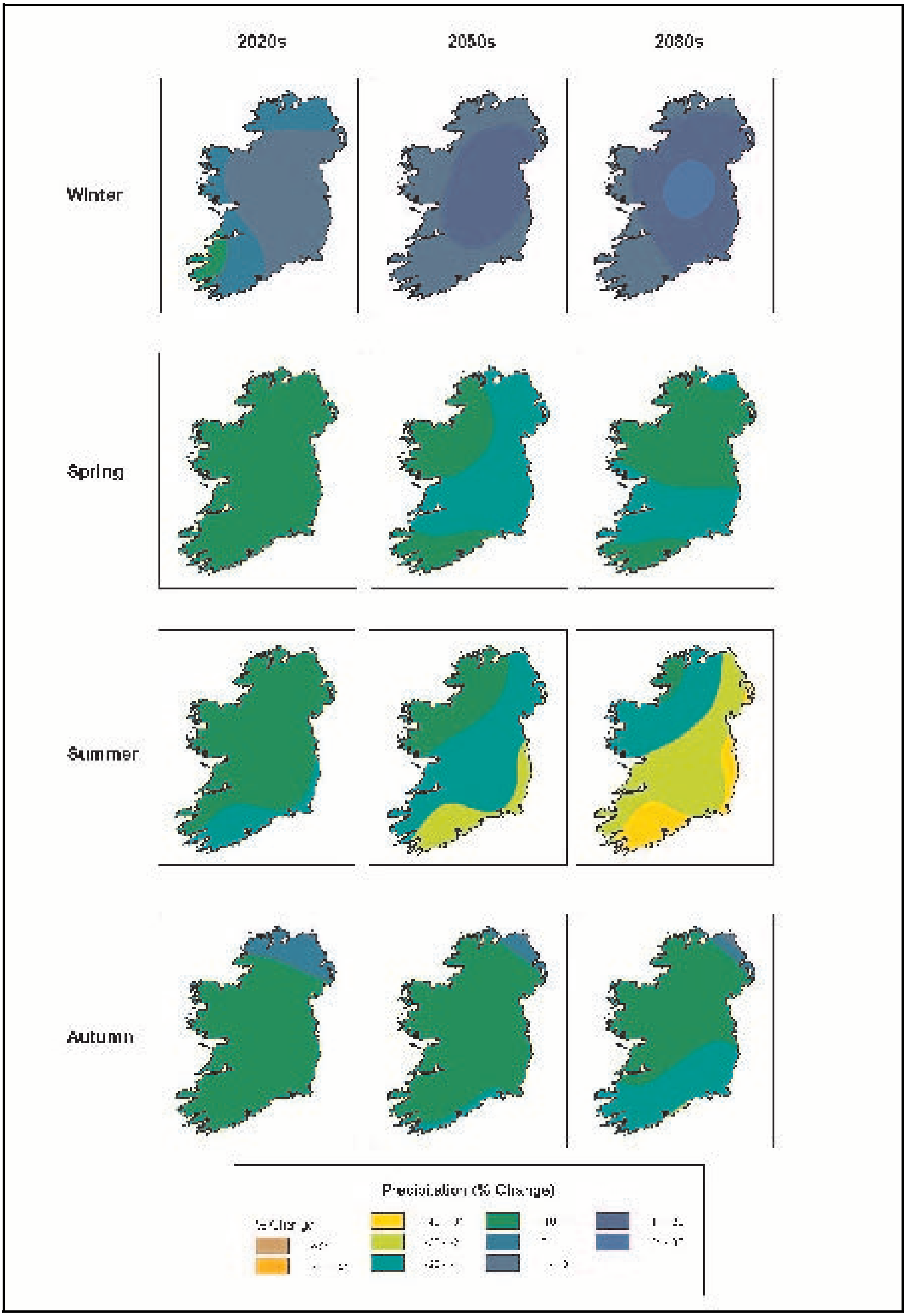

Figure 2.30 Ensemble mean seasonal precipitation changes projected for the 2020s–2080s.

and precipitation. The results should therefore be interpreted as indicative of likely changes based on the projections of climate resulting from climate change.

Ten core indices (Table 2.7), as determined by STARDEX, were selected from a possible 57. The indices are based on thresholds defined by percentiles rather than fixed values (STARDEX, 2006), with the exception of Number of Frost Days, which requires minimum temperatures to be less than 0°C.

Figures 2.31–2.32 show the extreme analysis results, on an annual basis, for both temperature and precipitation for the period 1961–2099, based on the modelled A2 ensemble data. Trends were found to be significant (0.01 significance level) at all stations and for all temperature indices employed in the analysis. The hot-day threshold (10th hottest day per year) indicates warming at all stations and is more pronounced at inland stations, away from the coast. Based on the modelled data, heatwave durations are also suggested to increase by up to 3–4 days per decade. A significant increase in cold night temperatures (10th coldest night per year) and is associated with a significant decrease in the number of frost days per decade.

Analysis of extreme precipitation events, significant at the 0.05 level, suggest an increasing trend in the greatest 5-day rainfall totals at eight of the stations analysed. These stations are located in the midlands and along the east coast. Heavy rainfall days are also suggested to increase significantly at two stations, Mullingar and Dublin Airport, while a decrease in heavy rainfall events is projected for Valentia on the west coast. A positive station trend is also projected in the maximum number of consecutive dry days (longest dry period) with an increasing trend evident from the west to the east coast. Trends in the indices of the heavy rainfall threshold, average wet-day amount and heavy rainfall days were found to be small, but significant, and are therefore not illustrated.

While an assessment of these extreme indices on an annual basis is likely to mute the seasonal changes, all the temperature indices suggest significant trends that are consistent with observations and expectations of changes resulting from climate change. Over the 1961–2005 period, a significant increase in both maximum and minimum observed temperatures, resulting in fewer frost days and a shortening of the frost season, has been identified by McElwain and Sweeney (2007). The duration of heatwaves has also been found to increase, while the number of consecutive cold days has been found to decrease over the same period, at a number of stations in Ireland.

Confidence with regards to the precipitation indices should be considered low despite the trends being significant. However, these trends are consistent with expected changes in precipitation as suggested by GCMs. McElwain and Sweeney (2007) found a

Table 2.7. Indices of extremes employed in analysis.

Temperature indices of extremes	
T_{max} 90th percentile	Hot-day threshold
T_{min} 90th percentile	Cold-night threshold
Number of frost days	Frost days
Heatwave duration	Longest heatwave
Precipitation indices of extremes	
90^{th} percentile of rain-day amounts	Heavy rainfall threshold
Greatest 5-day total	Greatest 5-day accumulation
Daily intensity (rain per rain day)	Average wet-day rainfall
Number of consecutive dry days	Longest dry period
% total rainfall from events >90th percentile	Heavy rainfall proportion
Number of events >90th percentile of rain days	Heavy rainfall days

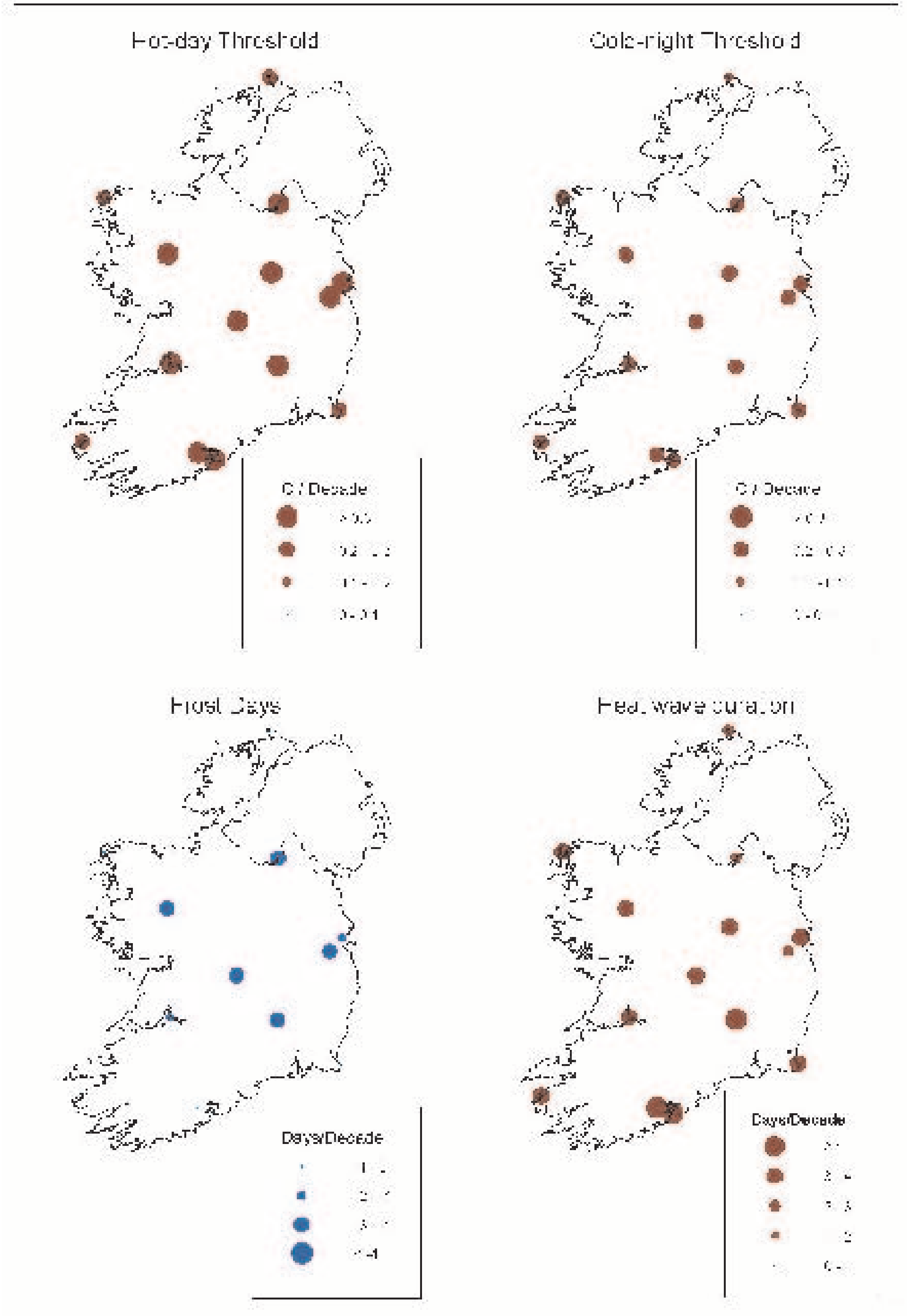

Figure 2.31. Trend/decade in the temperature indices for the A2 ensemble over the 1961–2099 period. All trends are significant at the 0.01 level.

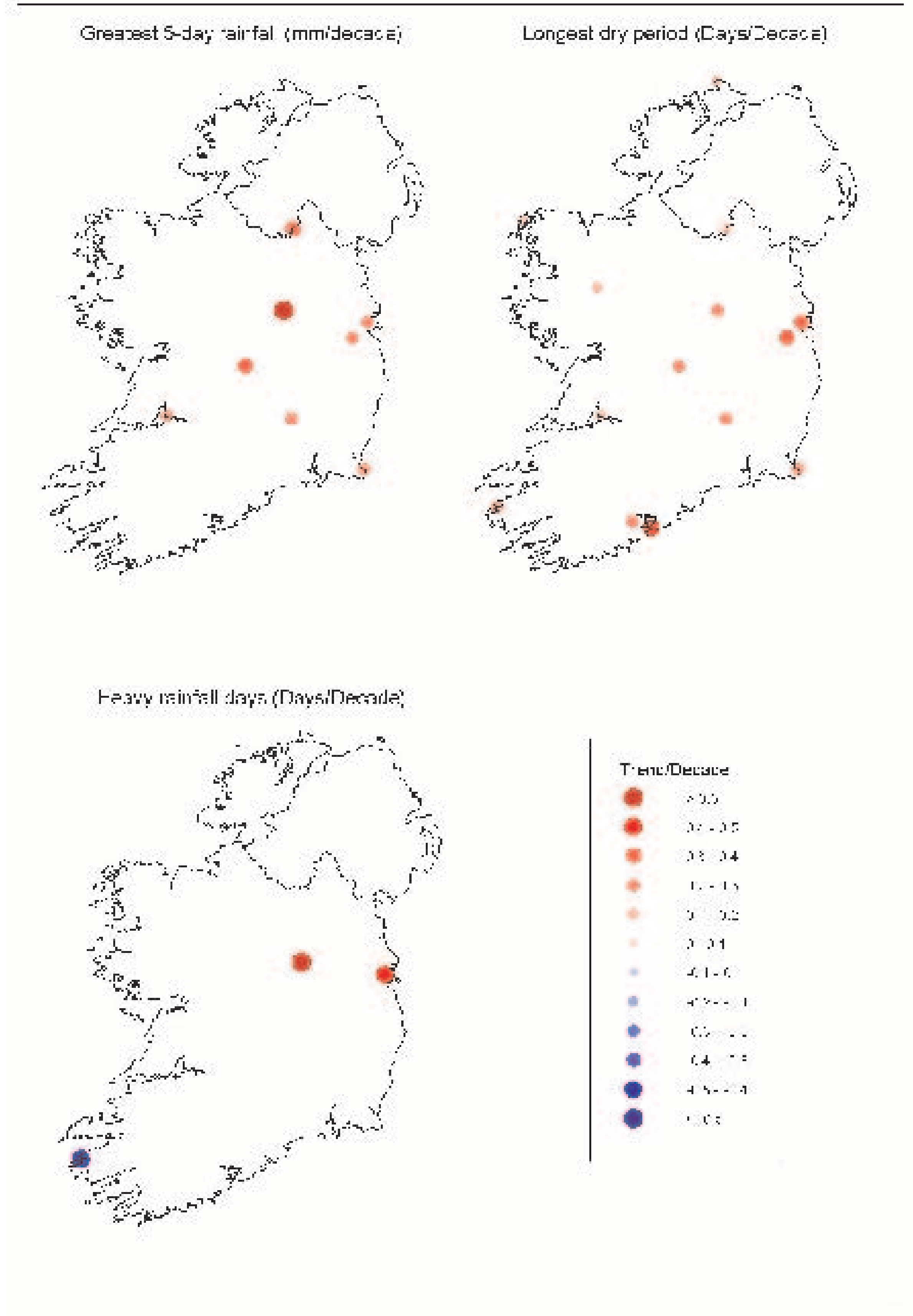

Figure 2.32. Trend/decade in the precipitation indices for the A2 ensemble over the 1961–2099 period. All trends are significant at the 0.05 level or less.

generally increasing tendency in the greatest 3-day rainfall totals on an annual basis; however, these trends were not found to be significant. In contrast to the observed changes in the number of events greater than the long-term 90th percentile (heavy rainfall days), a significant and decreasing trend was found for Valentia based on the downscaled data used in this analysis.

Despite the low confidence associated with the trends in precipitation, much more confidence can be placed in the temperature trends from which changes in precipitation can be inferred. The occurrence of higher temperatures and an increase in heatwave durations are likely in cloud-free skies during the summer months, suggesting an increase in the occurrence and length of dry periods as indicated in Fig. 2.32, as occurred in Ireland during the summer of 2006.

While this section focused on changes in values at the 90th percentile, suggested changes occurring above this cut-off are likely to have a smaller return period and be more extreme than currently experienced. Susceptibility to changes in the mean climate but also to changes in the extremes needs to be adequately assessed in order to minimise potential future risks.

While there will be derived benefits from a changing climate, such as a reduction in mortality rates, less carbon-based fuel required for winter heating or the potential to grow new crop types, such benefits will possibly be negated and severe impacts are likely in the absence of strict controls being placed on global greenhouse gas emissions.

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Appendix 2.1

Description of SRES Marker Scenarios

A1 These scenarios assume rapid economic growth, a global population that peaks in mid-century, and the rapid introduction of new and more efficient technologies. The **A1FI** assumes continuation with a fossil-fuel-intensive energy system, **A1B** assumes a more balanced energy mix, and **A1T** assumes a predominantly non-fossil fuel mix (the 'T' is for technology).

A2 This scenario assumes a continuously increasing global population and economic growth that varies by region and is slower than in other storylines.

B1 This scenario assumes a global population that peaks in mid-century (as with the A1 storyline), but with rapid changes in economic structures toward a service and information economy, reductions in material intensity, and the introduction of clean and resource-efficient technologies. It assumes that nations emphasise global solutions to economic, social, and environmental sustainability, but without additional climate initiatives.

B2 This scenario assumes a continuously increasing global population (as in A2), with intermediate economic growth. It assumes that nations emphasise local solutions to economic, social, and environmental sustainability.

(after Nakicenovic *et al.*, 2000)

Details of the Socio-Economic Assumptions for the A2 and B2 Emissions Scenarios Employed in the Analysis

The A2 and B2 scenarios represent future emissions levels that could be considered 'medium–high' (A2 emissions) and 'medium–low' (B2 emissions). For the A2 emissions scenario, the main emphasis is on a strengthening of regional and local culture. A very heterogeneous world is envisaged with large disparities in wealth and well-being. Population growth is high with global population reaching 15 billion by 2100. Economic growth and technological development is less dramatic. *Per capita* income is slow to increase and less emphasis on environmental protection than the other scenarios is apparent. Its CO_2 emissions are the highest of all four scenario families.

The B2 world sees the population reaching about 10 billion people by 2100. This is in line with both the United Nations and International Institute for Applied Systems Analysis (IIASA) median projections. Global *per capita* income grows at a moderate rate to reach about US$12,000 by 2050. The divergence in incomes between rich and poor nations decreases, although not as rapidly as in scenarios of higher global convergence (A1, B1). Although globally the energy system remains predominantly based on oil and gas to 2100, there is a gradual transition to renewables with a gradual decoupling of energy production and greenhouse gas emissions.

3 Climate Change and Water Resources

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3.1 Introduction

On every scale, changes in global climate are likely to have significant impacts on hydrology and water resources, with increased energy resulting in an intensified hydrological cycle. Given the complex and fragile interaction between the climate system and land-surface hydrology, any changes in the primary processes of precipitation and evaporation will have considerable knock-on effects for the rest of the hydrological cycle. It is not just surface components of the hydrological cycle that show likely changes as a consequence of global warming, subsurface hydrological processes are also likely to be altered. Previous work (Charlton and Moore, 2003) highlighted the likely changes in effective run-off on a national basis. The major findings from this work showed that:

- A widespread reduction in annual run-off is likely, with reductions most marked in the east and south-east of the country
- Winter run-off is likely to increase in the west
- All areas are likely to experience a decrease in summer run-off, with the greatest reductions in the east of the country
- The frequency and duration of low flows are likely to increase in many areas.

Such changes are likely to increase the pressures placed on water resources in many parts of the country. Therefore, this work aims at refining the impacts of climate change on strategically important catchments. In order to take account of uncertainty, downscaled output from three global climate models (GCMs), forced using two emissions scenarios, is used as input to a rainfall run-off model, which is calibrated for each individual catchment. The uncertainty derived from the use of a particular impacts model is also quantified. Changes in catchment storage, average monthly streamflow, streamflow variability, flow percentiles and the magnitude and frequency of extreme events are assessed for each catchment. Key impacts and areas of future vulnerability are highlighted.

3.2 Uncertainty in Future Hydrological Simulations

When modelling the effects of climate change on water resources there is a cascade of uncertainty that begins when future socio-economic storylines are translated into future emission scenarios and ends with impact modelling (Wilby, 2005). As outlined in Chapter 2, large amounts of uncertainty surround the development of future emissions scenarios, while GCM predictions over the current century are necessarily uncertain, both because the sensitivity of the climate system to changing greenhouse gas concentrations as well as the rate of ocean heat uptake is, as yet, poorly quantified (Stott and Kettleborough, 2002). Furthermore, different GCMs show varying sensitivities to similar greenhouse gas forcing, thus producing wide ranges of model output in terms of future changes in temperature and precipitation. As a result, impact modellers and planners are faced with the use of a wide range of predicted changes from different models of unknown relative quantity, owing to large but unquantified uncertainties in the modelling process (Murphy *et al.*, 2006).

As well as uncertainties cascaded into impacts models, impacts models themselves give rise to uncertainty. Conceptual rainfall run-off (CRR) models have been the most widely applied for climate impact assessment (Cunnane and Regan, 1994; Arnell and Reynard, 1996; Sefton and Boorman, 1997; Pilling and Jones, 1999; Arnell, 2003; Charlton and Moore, 2003). However, constraints are placed on such an approach by a lack of knowledge of the workings of the hydrological system, a lack of data and by the volume of complex computations required to simulate every process within the hydrological sphere. Consequently, CRR models incorporate large simplifications in order to represent catchment hydrology. One of the major consequences of such simplifications is the generation of uncertainty within the modelling framework. Such uncertainty is seen in the process of parameter estimation with the inference of values for parameters that cannot be directly measured relying heavily on calibration to an observed time series of river flow. Such calibration is associated with well-known limitations attributable to parameter identifiability, parameter stability, uncertainty and the equifinality of outputs arising from different combinations of model parameters. Wilby (2005) has shown that uncertainty derived from subjective choices in model calibration can be as large as the uncertainty derived from the use of different emissions scenarios. Consequently, there is an 'explosion' or 'cascade' of uncertainty associated with climate impact assessment, with the magnitude of uncertainty being multiplied through each step in the methodology (Jones, 2000). It is therefore desirable to quantify this uncertainty, so that the full range of possible future impacts can be accounted for.

3.3 Research Outline

This research follows a well-established methodology for simulating the impacts of climate change on water resources. The ensembles derived from each GCM run using both emissions scenarios are used to drive a hydrological model representing the catchment system, so that simulations of future changes can be assessed. A CRR model, applied on a daily time step, is calibrated on past hydrological and climatological data for each catchment in the analysis. Central to the use of CRR models in climate impact assessment is their ability to represent the catchment system as a simplified agglomeration of stores representing catchment processes, thus enabling such models to be applied to a wide variety of catchments. Simplification results in the reduction of the amount of data necessary to run the model and, in turn, CRR models tend to contain a small number of parameters, many of which can be measured from physical reality. Consequently, simple model structures and ease of application have led to the widespread use of CRR models in climate impact assessment. Once validated, the rainfall run-off model is used to simulate hydrological conditions over the time period 1961–2099.

By forcing the CRR model with downscaled output, hydrological simulations are derived for four time periods, the control (1961–1990), the 2020s (2010–2039), the 2050s (2040–2069) and the 2080s (2070–2099). Changes in monthly streamflow and catchment storage are derived for each of the ensemble runs by assessing the difference between the control and each future time period. Given the weighted averaging employed for the generation of ensembles, such data are not suitable for the examination of extremes. Therefore the simulated outputs for each GCM and each scenario are run individually in determining changes in future flood frequency and percentile analysis.

In total, nine catchments throughout Ireland are considered. These are shown in Table 3.1. The catchments were chosen so that as broad a range of

Table 3.1. Catchments studied, their location and summary statistics.

Catchment	Area (Km)	Gauge	Data (days)	Mean rainfall (mm)	Mean ET (mm)	Mean discharge (cumecs*)	Land use	Soil texture
Suir	3,556.00	Clonmel	14,610	2.7	1.27	48.2	Pasture	Loam
Blackwater	3,245.70	Ballyduff	14,610	3.1	1.5	62.3	Pasture	Loam
Boyne	2,670.50	Slane	14,610	2.4	1.22	35.4	Pasture	Clay Loam
Moy	1,980.87	Rahans	9,862	3.9	1.22	57.9	Peat Bogs	Loam
Barrow	2,956.00	Levitstown	11,688	2.5	1.27	20.9	Pasture	Sandy Loam
Brosna	1,082.50	Ferbane	14,610	2.4	1.22	17.1	Pasture	Loam
Inny	1,072.50	Ballymahon	10,227	2.6	1.22	18.7	Pasture	Loam
Suck	1,050.00	Bellagill	9,498	2.8	1.22	25.2	Pasture	Loam
Ryewater	213.90	Leixlip	14,610	2.2	1.5	2.3	Pasture	Clay Loam

*1 cumec represents a flow of 1 m^3/s.

hydrological conditions as possible was considered. Furthermore, strategically important catchments, such as the Ryewater, a major tributary of the Liffey, were included. Catchments of varying size are also represented. The largest catchment in the analysis is the River Suir with a catchment area of approximately 3,556 km^2 while the smallest is the Ryewater with an area of just over 213 km^2. The number of days of available data, the mean daily rainfall and evapotranspiration, daily mean discharge, as well as the predominant land use and soil textural properties are presented in Table 3.1. Figure 3.1 provides the location of each catchment. Baseline (1961–1990) precipitation and evapotranspiration data were obtained from Met Éireann, while daily streamflow data for each gauge were obtained from the Office of Public Works (OPW).

3.4 Rainfall Run-Off Model Overview and Application

3.4.1 HYSIM overview

The Hydrological Simulation Model (HYSIM) is a CRR model, which uses rainfall and potential evaporation data on a daily time step, to simulate river flow using parameters for hydrology and hydraulics that define the river basin and channels in a realistic way. HYSIM has been used for a variety of hydrological applications including assessing the impacts of climate change on the hydrological cycle (Pilling and Jones, 1999; Charlton and Moore, 2003; Murphy *et al.,* 2006). The complete flow diagram of the structure of the model is

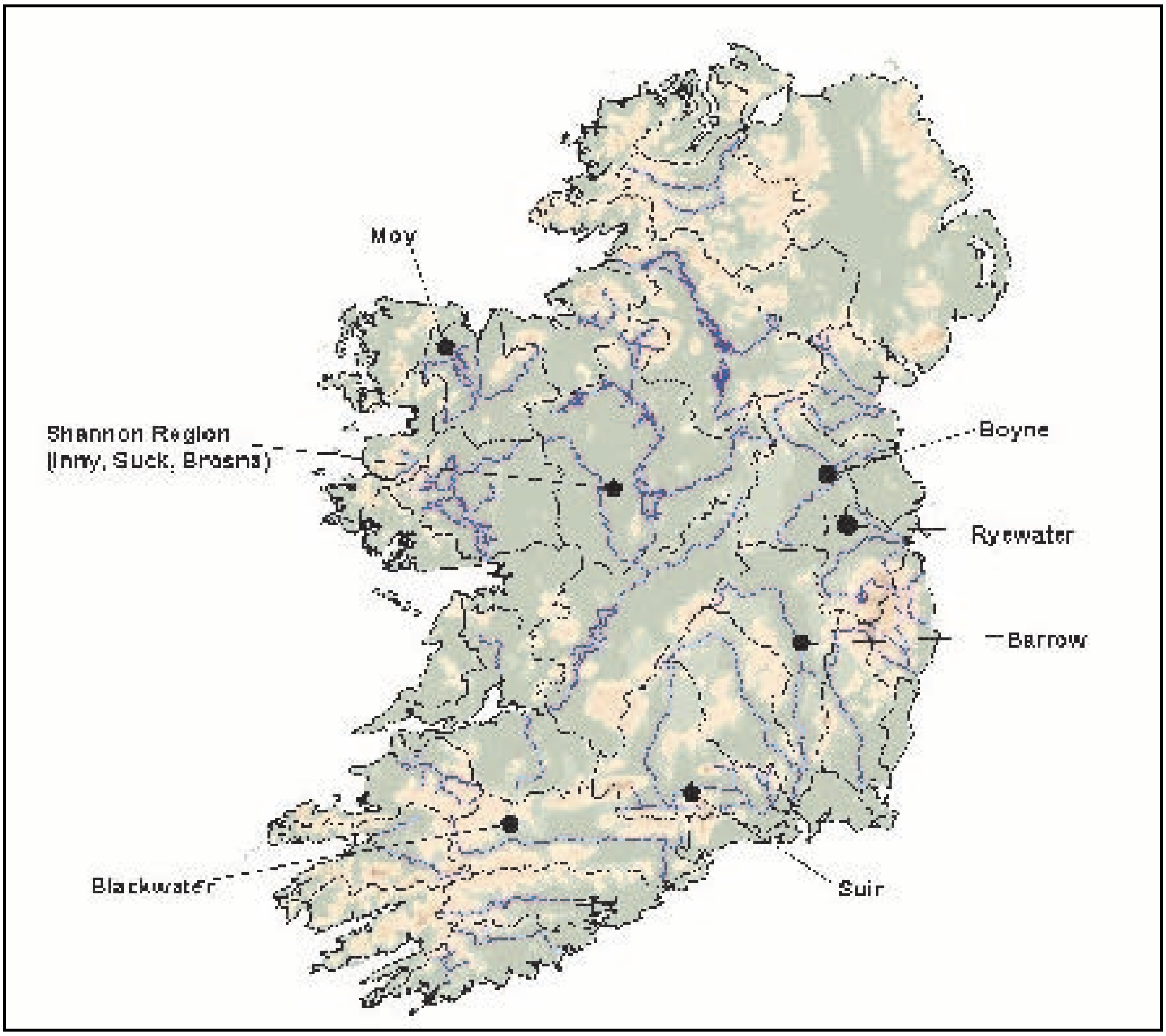

Figure 3.1. Location of each of the study catchments.

given in Fig. 3.2. Seven natural stores are employed to represent catchment hydrology. The main components of the model are the upper and lower soil reservoirs, with the works of Brooks and Corey (1964) employed to represent the variation of effective permeability and capillary suction with changes in moisture content. A full description of the model and its structure is given in Murphy *et al.* (2006).

Parameters within HYSIM can be broken down into two groups, the physical parameters and the process or 'free' parameters (Sorooshian and Gupta, 1995). The former represents physically measurable properties of the watershed, whereas process parameters represent watershed characteristics that are not directly measurable, such as the lateral interflow rate. There are two approaches to fitting the model: the first involves the specification of the physically measurable parameters, while the second involves the optimisation of process parameters. A split sample procedure was adopted for calibration and validation. The first 30 years of the baseline data set (1961–1990) were used for calibration. This period was selected so that the model could be trained on as much variability in streamflow as possible. Validation was conducted for the period 1991–2000. This decade has been the warmest globally, with 1998 being the warmest year on the global instrumental record. In Ireland, the warmest year was recorded in 1997. Furthermore, the 10 years 1991–2000 present some of the largest flood peaks on record in Ireland, such as the November 2000 floods in the Suir catchment. Thus the 1990s provide a good test of model performance, with conditions being more akin to those expected under climate change than at any other period in the baseline data set.

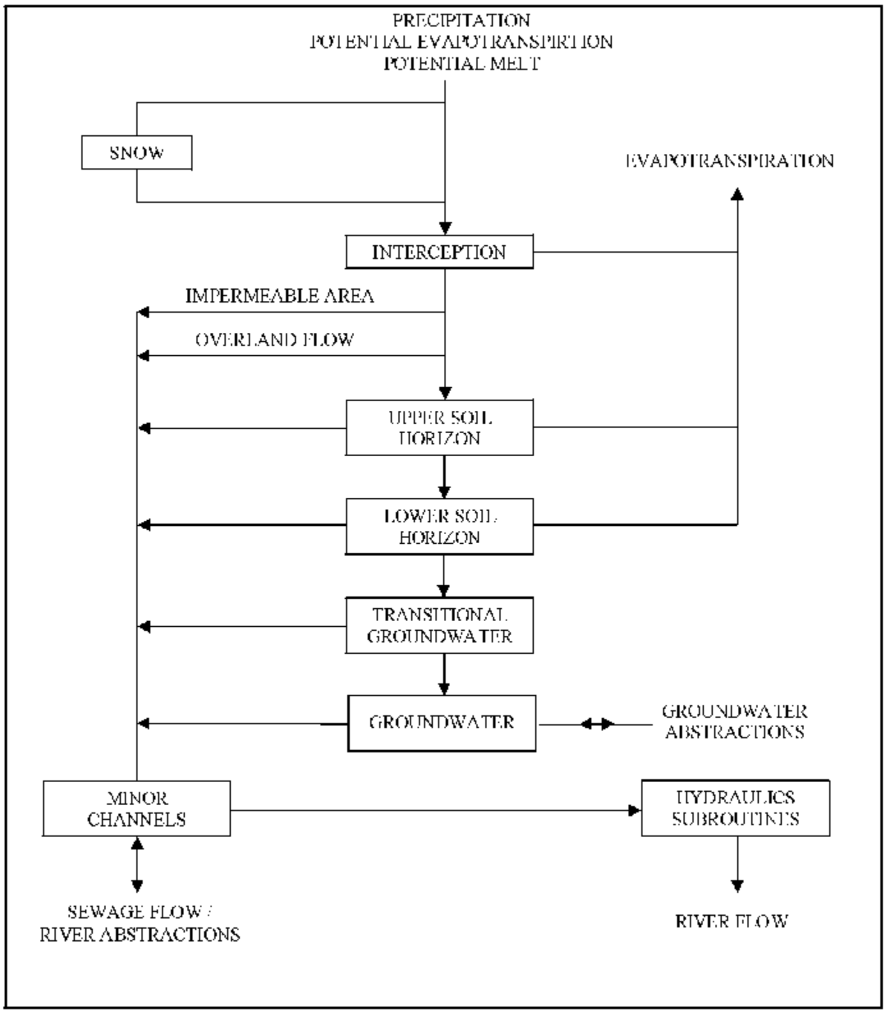

Figure 3.2. Hydrological Simulation Model (HYSIM) structure.

3.4.2 Deriving physical parameters

The first method to consider when parameterising the model was the specification of physical characteristics of each catchment. The incorporation of a Geographical Information System (GIS) has the potential to dramatically increase the speed, accuracy and reproducibility of catchment parameterisation, while in turn reducing the subjectivity of the model user (Pullar and Springer, 2000). Consequently, the use of a GIS was central to the parameterisation procedure. The first task was the delineation of catchment boundaries using the EPA's Digital Elevation Model (DEM). Automated digital terrain analysis methods are available to derive most watershed characteristics that cannot be readily derived using common GIS tools. Soil hydrological properties were calculated from the General Soil Map of Ireland (Gardiner and Radford, 1980). Once the catchment boundary was delineated it was used to extract the relevant data for each catchment. Each soil association within the catchment was examined and the proportions of the soil type and its location within the catchment were considered. The dominant soil texture was calculated by establishing the percentage sand, silt and clay in each soil association with the derived texture being used to calculate the soil parameters. Vegetation parameters were obtained using the CORINE (Coordination of Information on the Environment) data set (O'Sullivan, 1994). Again the catchment boundaries were used to cookie-cut the desired data (see Fig. 3.3). Due to the

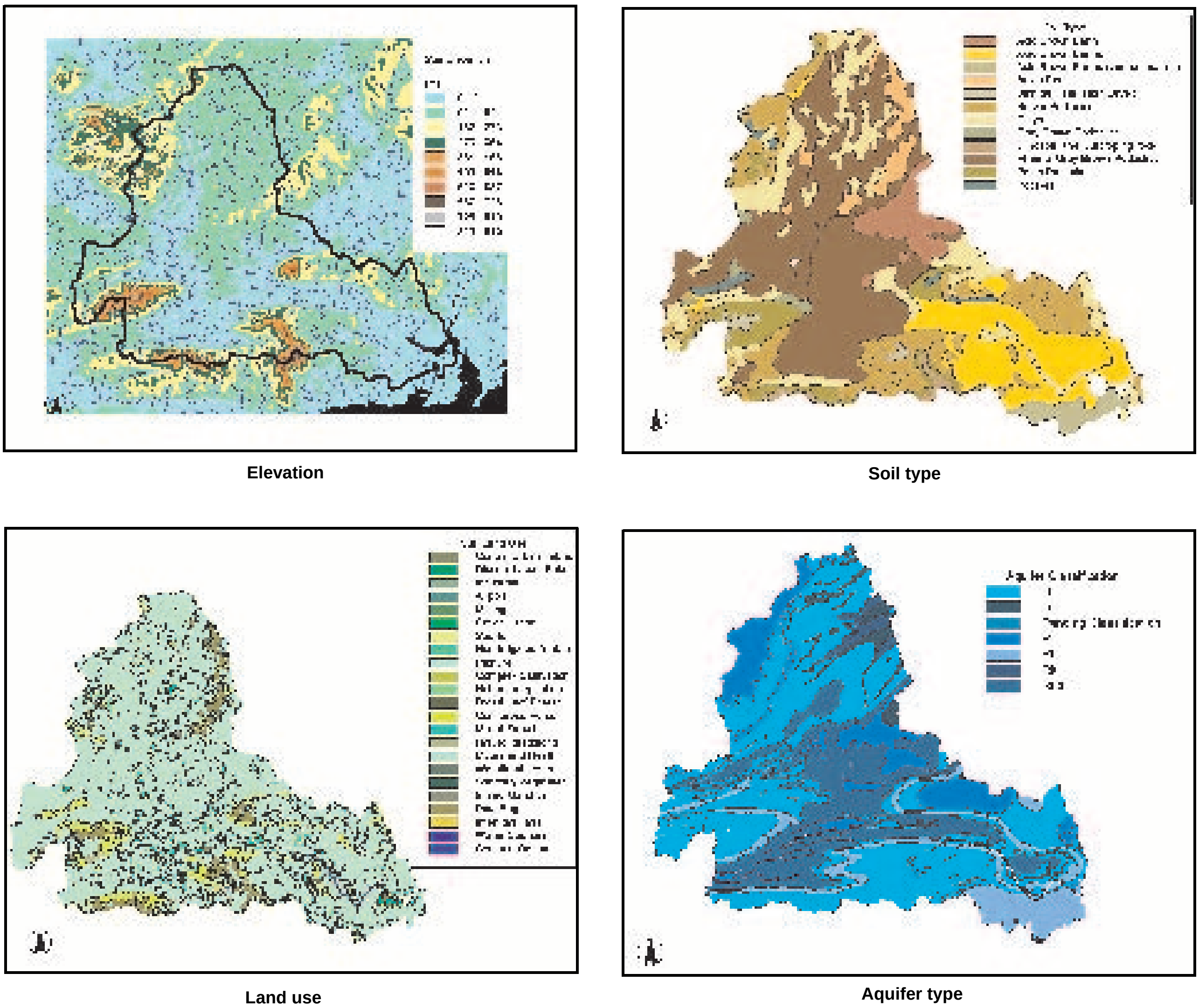

Figure 3.3. Calculation of physical parameters for the Suir catchment through the incorporation of GIS techniques.

lumped nature of the model, the land use with the highest percentage was used to derive the land-use parameters. Many of the groundwater parameters were calculated from flow records while others were estimated using the Aquifer Map of Ireland (Geological Survey of Ireland (GSI), 2003) (Fig. 3.3).

3.4.3 Process parameter estimation and uncertainty quantification

Within HYSIM, calibration is catered for by a multi-parameter optimisation procedure. HYSIM employs the Rosenbrock method, a local search algorithm using a direct search method. Blackie *et al.* (1985) provide details on the functioning of the Rosenbrock method. In order to calibrate the model, a number of objective functions were employed. These comprised the Nash–Sutcliffe (NS) efficiency criterion, the Coefficient of Determination (R^2), the Mean Actual Error (MAE) and the Percent Bias (PBIAS). Both correlation and relative error measures were included as the use of correlation-based measures alone can be oversensitive to extreme values and are insensitive to additive and proportional differences between model predictions and observations (Legates and McCabe, 1999). Only results for NS and PBIAS will be given here. For NS, values of 1 indicate a perfect fit while a PBIAS of 0% is ideal. Once the optimum parameter set was realised for each catchment, the Rosenbrock algorithm was restarted using different parameter values in order to establish whether the results relate to a local or global optimum (Blackie *et al.,* 1985). When different starting points were used, different end values were encountered due to problems related to the parameter response surface. Sorooshian and Gupta (1995) highlight a number of difficulties associated with the parameter response surfaces that are common to CRR models. These include the presence of several major regions of attraction into which the search algorithm may converge. Furthermore, where parameters exhibit varying degrees of sensitivity a great deal of interaction and compensation may be evident (Sorooshian and Gupta, 1995). These obstacles make it very difficult for a local search strategy such as the Rosenbrock method to progress towards a global optimum and results in uncertainty in model output.

Therefore, uncertainty is seen in the process of parameter estimation and, as a result, it is necessary to quantify the uncertainty derived from the estimation of the process parameters. Uncertainty evaluation generally holds that all acceptable parameters or models of a system be retained until they are disproved and consists of analysing the range of parameter sets that are acceptable for a specific application (Wagener, 2003). These plausible models are used to construct uncertainty bounds or confidence limits for model output. One established method for uncertainty analysis is the Generalised Likelihood Uncertainty Estimation (GLUE) procedure (Beven and Binley, 1992).

The GLUE procedure starts with the recognition that many model structures or parameter sets within a given model framework will simulate a required output. Given this concept of equifinality it follows that no single optimum set of model parameters can be readily identified (Beven, 1993). Consequently it is only possible to assign a likelihood value to each parameter set, indicating that it can predict the system and that the set of parameters provides an acceptable or behavioural simulation of the observed flow (Beven and Binley, 1992). The GLUE procedure has five main steps (Beven and Binley, 1992):

1. The definition of a likelihood measure, chosen on the basis of an objective function to determine model performance

2. The definition of a prior distribution for each parameter

3. Parameter sets are sampled from the defined prior distributions using sampling techniques such as Monte Carlo Random Sampling and Latin Hypercube Sampling

4. Each parameter set is classified as behavioural or non-behavioural through assessing whether it performs above or below a predefined threshold

5. Predictive model runs generate results from each of the parameter sets that yield acceptable calibration simulations. These combined simulations are in turn used to determine the weighted mean discharge and simulation

probability bounds (Melching, 1995).

In implementing the GLUE procedure for each catchment, the NS efficiency criterion was adopted as the likelihood measure. Behavioural parameter sets were taken as those with an efficiency value above 0.7. A uniform distribution was attributed to each process parameter (as proposed by Beven and Freer, 2001) and values were generated using Latin Hypercube Sampling. For more information on the techniques employed see Murphy *et al.* (2006). Using the example of the Suir catchment, these parameter sets were run for the calibration period 1961–1990 and, of these, 50 were retained as behavioural with efficiency values ranging from 0.701 to 0.825. In order to validate these parameter sets, a blind simulation was conducted on each set for the validation period 1991–2000. From the 50 behavioural parameter sets obtained during calibration, all were retained as acceptable sets in representing the period 1991–2000. For the validation period, model efficiency ranged from 0.702 to 0.852.

In order to ascertain the representativeness and thus the range of conditions provided by the 1961–1990 calibration period, the transferability of parameter sets over wet and dry periods was assessed for the validation years. The ten most skilful parameter sets were extracted and run for both the calibration and validation periods as well as for individual years within the validation period. On a decadal timescale the 1970s are representative of a relatively dry decade while the 1980s are considered to be wet. Therefore, the calibration period provides a wide range of flow conditions on which to train the model. The NS efficiency value and the PBIAS of the ten most skilful parameter sets for each catchment were analysed. Tables 3.2 and 3.3 show the results obtained for the calibration and validation period for each catchment using the NS efficiency criterion. Good results are achieved for each catchment, with efficiency values remaining high when parameter sets are transferred to the validation period. Only four catchments, the Brosna, Inny, Moy and Suck, show a general reduction in model performance during the validation period. However, the reductions in performance are only slight with values always remaining above the 0.7 threshold value. Improvements in model performance are evident for the Barrow, the Blackwater, the Ryewater and the Suir, while performance for the Boyne remains similar during both calibration and validation. Figure 3.4 shows the validation uncertainty bounds for the Suir at Clonmel.

The transferability of parameter sets for individual years as well as between wet and dry years in the validation period also proved successful. The inclusion

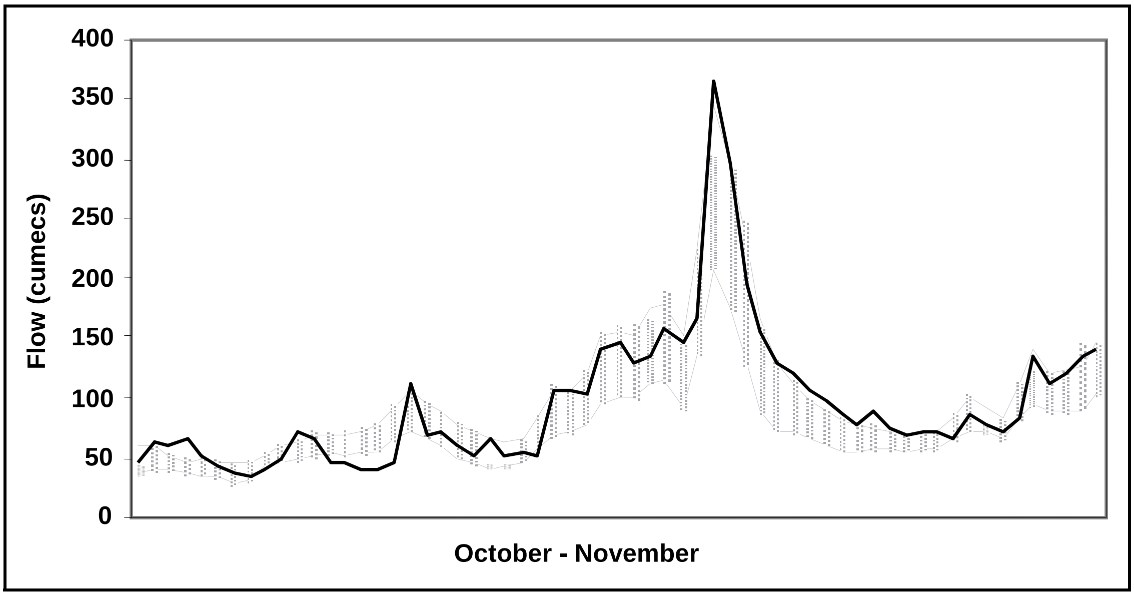

Figure 3.4. Uncertainty bounds generated for the Suir at Clonmel. The peak marks the largest flood in the validation period.

Table 3.2. Top ten Nash–Sutcliffe values obtained for each catchment during calibration.

	Barrow	Blackwater	Boyne	Brosna	Inny	Moy	Ryewater	Suck	Suir
Top ten parameter sets	80.1	77.7	85.1	83.0	85.2	89.5	73.5	72.6	79.3
	79.9	77.7	85.0	83.0	85.1	89.5	73.4	72.5	79.3
	79.9	77.6	85.0	82.9	84.9	89.5	73.1	72.5	79.2
	79.8	77.6	84.8	82.9	84.9	89.5	72.8	72.5	78.8
	79.7	77.6	84.7	82.6	84.9	89.4	72.8	72.5	78.8
	79.7	77.3	84.6	82.2	84.5	89.4	72.5	72.5	78.3
	79.6	77.3	84.6	82.0	84.5	89.4	72.5	72.4	78.2
	79.6	77.1	84.5	82.0	84.5	89.4	71.9	72.3	77.9
	79.5	77.0	84.5	81.8	84.4	89.4	71.8	72.2	77.9
	79.5	76.8	84.2	81.6	84.1	89.3	71.4	72.2	77.8

Table 3.3. Top ten Nash–Sutcliffe values obtained for each catchment during validation.

	Barrow	Blackwater	Boyne	Brosna	Inny	Moy	Ryewater	Suck	Suir
Top ten parameter sets	81.5	83.2	85.1	82.0	78.4	86.5	80.8	72.3	81.6
	81.4	82.9	84.7	81.9	78.3	86.5	80.4	72.1	81.5
	81.3	82.8	84.5	81.8	78.2	86.5	80.4	71.7	81.3
	81.3	82.5	84.4	81.7	78.2	86.5	78.3	71.5	80.2
	81.2	82.4	84.4	81.5	78.1	86.4	77.9	71.5	80.1
	81.2	82.1	84.3	81.4	78.0	86.4	77.7	71.4	80.1
	81.1	82.1	84.2	81.1	77.8	86.4	77.6	71.3	80.0
	81.1	81.8	84.0	81.1	77.8	86.4	77.5	71.3	79.9
	81.1	81.6	84.0	80.8	77.8	86.4	77.1	71.2	79.7
	81.1	81.4	83.9	80.7	77.7	86.3	76.9	71.2	79.5

of these results is beyond the scope of this report and interested readers should refer to Murphy *et al.* (2006). Given that the 10 years used for validation (1991–2000) comprise the warmest decade on the instrumental record and provide the best available surrogate for expected future conditions as a result of climate change, the results achieved indicate that the calibration period provides a representative sample of the range of hydrological conditions for the Suir.

3.5 Future Simulations

The use of different objective functions in assessing model performance results in the extraction of different optimum parameter sets for each function. Unfortunately, it is not yet clear how populations of parameter sets should be selected for operational use (Wagener, 2003). In order to overcome this, a combination of the top parameter sets, as defined by each objective function, was retained and run using the downscaled GCM data. For each catchment HYSIM was run for each GCM using both scenarios and all of the derived parameter sets. Consequently, future simulations capture a degree of the inherent uncertainty derived from data measurement, parameterisation, the use of different objective functions, GCM climate sensitivity and uncertainty due to different emissions scenarios.

3.5.1 Changes in catchment storage

Changes in temperature and precipitation will alter subsurface hydrology, with significant changes in soil moisture storage, groundwater recharge and groundwater storage likely. Gregory *et al.* (1997), show that a rise in greenhouse gas concentrations is associated with reduced soil moisture in Northern Hemisphere mid-latitude summers, while Scibek and

Allen (2005) indicate that reductions in baseflow are anticipated due to the lowering of groundwater gradients in many aquifers. Peters *et al.* (2005) contend that decreases in precipitation and increases in evapotranspiration cause low soil moisture content, which in turn causes low groundwater recharge. In order to assess likely changes in subsurface hydrology, changes in monthly soil moisture storage and monthly groundwater storage are simulated for each time period using the mean ensemble. It is important to recognise that in terms of groundwater storage, each aquifer is unique in its geology, its geometry and the nature of its connection with surface waterbodies. Given the lumped conceptual nature of HYSIM, only an indication of large-scale changes in catchment storage can be made; however, these are extremely important in highlighting the direction and magnitude of future change, as well as areas where further research is required. Figure 3.5 depicts changes in storage simulated for each catchment.

3.5.1.1 Inny

Soils within the Inny catchment include Gleys, Grey Brown Podzolics, Minimal Grey Brown Podzolics and substantial amounts of Basin Peat. Due to the greater amount of summer precipitation in the midlands and west under the current climate, the seasonal variations in soil moisture storage are not as pronounced in the Inny catchment as they are in eastern catchments such as the Ryewater. This is evident under the control period where the transition from winter to summer storage levels is quite gradual. However, this is likely to be altered as a result of climate change with decreases in spring, summer and autumn becoming more pronounced. By the 2020s, slight reductions in soil moisture storage are evident for many of the summer and autumn months; however, reductions are only in the range of –5%. By the 2050s, the greatest reductions are suggested for August (–19%) and September (–20%). By this time, 7 months show a reduction in storage, from April through to October. Reductions in soil moisture storage in the Inny catchment are likely to be most severe by the 2080s with decreases of approximately –30% likely for August and September. Substantial reductions are also evident for the summer months of June (–12%) and July (–15%).

The Inny catchment has abundant groundwater resources, with extensive faulting and karstification greatly influencing permeability. The vast majority of the catchment (75%) is comprised of locally important aquifers. Although these are less transmissive than the regionally important aquifers, they are very permeable along faults and fractures (GSI, 2003). Under the control period, groundwater storage in the Inny reaches a maximum in the months of April and May and gradually decreases through the summer and autumn months as the importance of baseflow to sustaining streamflow increases. The minimum storage is recorded in November; thereafter the amount of water in storage begins to increase. By the 2020s, there is little change in groundwater storage with slight increases and decreases evident. By the 2050s, however, there is a substantial increase in storage from March to July as a result of increased precipitation. Little change is suggested for the summer and early autumn months; however, reductions are simulated during the recharge period with reductions likely for November (–10%), December (–18%) and January (–7%). By the 2080s, increases in groundwater storage are evident from February to September, with a maximum increase of +12% in April. Again decreases are likely during the late autumn and winter with reductions of –9%, –22% and –11% in November, December and January, respectively.

3.5.1.2 Brosna

Due to its similarity in terms of physical characteristics, climatic regime and close geographical proximity, the response of soil moisture storage in the Brosna is very much similar to that in the Inny. By the 2020s, slight reductions are evident for 5 months, beginning in May and ending in September. Greatest reductions by the 2020s are likely for August with a reduction of –7% relative to the control period. By the 2050s, substantial reductions are suggest throughout the summer months and for the early to mid-autumn. Reductions in the order of –20% to –25% are suggested for August and September. Again the greatest decreases are likely by the 2080s. By this time it is likely that reductions in storage will be experienced for 6 months of the year, beginning in May (–7%) and continuing until November (–5%). Most significant by the 2080s are the simulated reductions for August (–39%) and September (–32%).

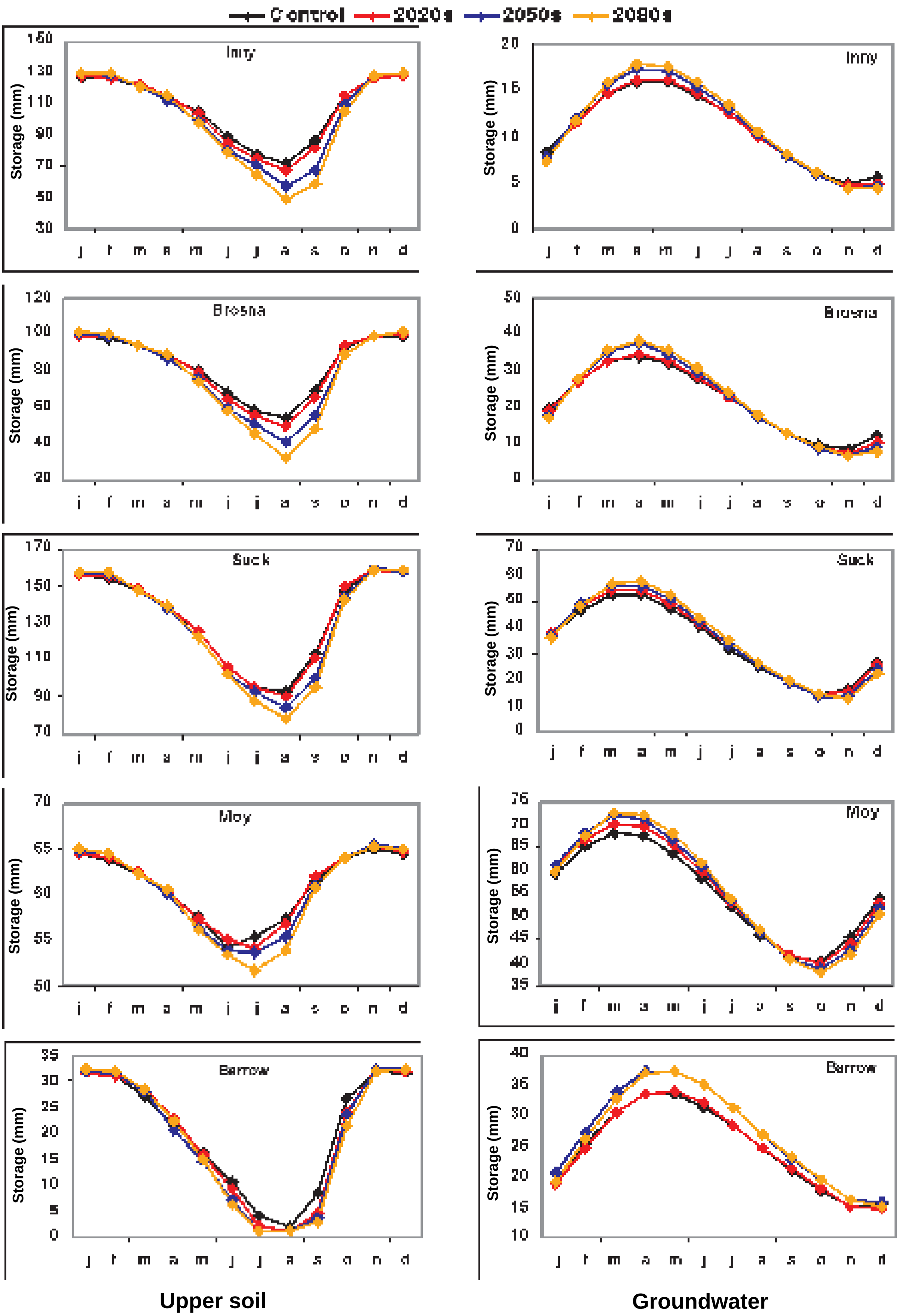

Figure 3.5. Changes in catchment storage for each future time period under the mean ensemble.

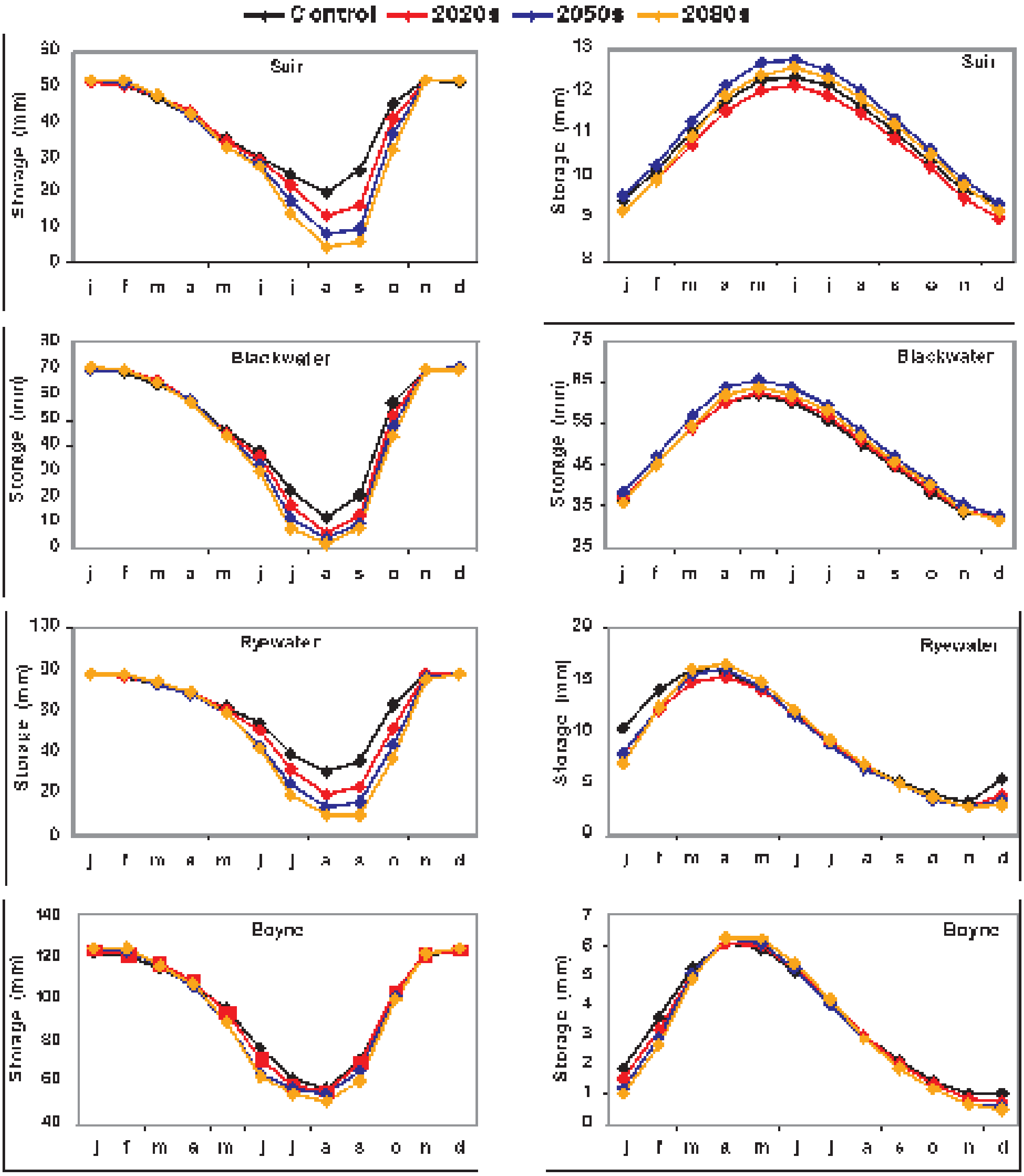

Figure 3.5 *contd.*

The remainder of the summer months also shows substantial reductions in storage of –15% and –20% in June and July, respectively.

In terms of aquifer potential, over 20% of the Brosna is comprised of regionally important aquifers. Much of the catchment is covered by limestone glacial till and morainic gravels. The dominant rock units within the catchment are pure bedded and unbedded Dinantian limestones. Under the control period, storage reaches a maximum in April and gradually decreases thereafter through the summer and early autumn, with a minimum storage reached during November. By the 2020s, there is little change in groundwater storage for the majority of the year. However, there are substantial decreases at the end of autumn and early winter, with decreases of –14% and –15% suggested for November and December, respectively. By the 2050s, increases in storage of +10% are likely during the spring and early summer. By this time, decreases are likely from August through to February, with greatest reductions again likely at the end of autumn and the beginning of winter, with the months of November and December showing decreases of –23% and –25%, respectively. Greatest change in groundwater storage is likely by the 2080s with increases of between +10% and +13% likely for the spring months. Little change is likely for the summer; however, substantial decreases are likely during the important recharge period with reductions of –25%, –33% and –11% likely for November, December and January, respectively.

3.5.1.3 Suck

Predominant soil types in the Suck are poorly drained and heavily textured. During the 2020s, slight reductions are evident for only 3 months of the year (July, August and September). By the 2050s, reductions in storage are extended to 7 months, beginning in April and extending to October. Greatest reductions are likely for the month of September, with a reduction of approximately –12% evident by this period. For the remainder of the months, reductions are all less than –10%. By the 2080s, reductions are slightly greater; however, the greatest reductions only reach –15% in August and September.

The dominant hydrogeological characteristics of the Suck catchment are the widespread coverages of Dinantian pure bedded limestone and limestone glacial tills. Almost 75% of the catchment consists of regionally important aquifers with the potential for groundwater storage being the largest among the Shannon sub-catchments considered. Under the control period, greatest groundwater storage is achieved in March and April. In the summer and early autumn, storage levels are shown to decrease more rapidly than in the Inny and the Brosna, with minimum storage reached earlier in the year (October). By the 2020s, a slight increase in storage is suggested for the majority of months, with slight decreases likely for the last 3 months of the year. By the 2050s, decreases of between –10% and –15% are likely for November and December. By the 2080s, increases in storage of approximately +10% are suggested from March to July. By this time, minimum groundwater storage is likely to occur in November with reductions of –20%. Substantial reductions are also likely for December.

3.5.1.4 Moy

Soils within the Moy are poorly drained with significant deposits of Blanket and Basin Peat. During the control period, soil storage reaches a minimum in June and increases thereafter. The timing of minimum storage is delayed until July by mid to late century as a consequence of climate change. By the 2020s, only slight reductions (all less than –3%) are suggested for the months of May, July, August and October. More consistent drying is likely by the 2050s with reductions suggested from May to October. However, these reductions remain minimal when compared to other catchments. By the 2080s, drying persists for these months with greatest reductions of –6%. The ability of soils within the Moy catchment to retain moisture may be the cause of reductions being less pronounced than in other catchments. Increases in evaporation are not as strong for the west of the country, while more energy is required to remove water from the soil due to the increased forces of capillary suction in the heavily textured soils.

The geology of the Moy catchment is extremely complex with the groundwater storage potential of rock varying hugely. In terms of aquifer potential, almost 30% of the catchment is underlain by poorly productive bodies. Subsoils within the catchment are largely comprised of limestone and sandstone glacial till. Under the control period, groundwater storage reaches a maximum in early spring, reducing thereafter to an October minimum. By the 2020s, slight reductions are likely for October, November and December. By the 2050s, the same general trend is maintained although both increases and decreases are slightly more pronounced. Greatest change is simulated for the 2080s, with increases reaching a maximum of +7% in March and April. Decreases in storage of between –5% and –7% are likely for the last 3 months of the year. It is interesting to note that the Moy catchment exhibits the most conservative changes in both soil and groundwater storage and serves to highlight the importance of catchment characteristics in determining a catchment's response to climate change.

3.5.1.5 Barrow

Soils in the Barrow catchment are permeable, well-drained mineral soils and are among the most heavily cultivated soils in the country. In terms of future changes in soil storage, little change is likely for the winter and spring months due to the suggested increases in precipitation. Substantial reductions in storage are likely by the early summer with reductions of –11% likely for June. During the 2020s, the greatest decrease in soil storage is evident for the month of July with reductions of –50% simulated, while decreases are likely to persist until October. By the 2050s, reductions in soil storage are further pronounced with maximum reductions of –65% likely for July. Reductions in storage are also evident earlier in the year than simulated for the 2020s, commencing in April and persisting until October. The most dramatic changes in soil storage are suggested for the 2080s with reductions of –39%, –75% and –51% simulated for the summer months. It is worth noting that decreases are simulated from May through to November by this time. Given the increases in evaporation and the decreases in precipitation during the autumn months, reductions in the order of –65% and –18% are suggested for September and October.

Geology in the Barrow catchment is diverse and includes fine-grained well-bedded limestones and medium- to coarse-grained sandstones, siltstones and shales. Subsoil deposits consist of sands, gravels and clays of variable extent and thickness. These deposits play a key role in the groundwater flow regime with highly permeable sands and gravels allowing a high level of recharge and additional storage to underlying bedrock aquifers. Under the control period, maximum groundwater storage occurs in March and April and gradually decreases to a minimum in November. By the 2020s, slight decreases in storage are likely for all winter and the majority of spring months, while slight increases are likely from late spring until the end of autumn. By the 2050s, increases in storage of between +6% and +10% are simulated for all months as the large storage capacity of the underlying geology offsets the reductions in precipitation in the summer and autumn. By the 2080s, increases are maintained for the majority of months with increases in the order of +10% likely from May to November. Slight decreases are suggested for December and January by this time.

3.5.1.6 Suir

Like the Barrow catchment, soils within the Suir are generally classified as highly permeable and well drained. By the 2020s, reductions in soil storage are likely from late spring (May) through to mid-autumn (October). The greatest reductions by this time are suggested for the months of August and September with decreases of –31% and –39%, respectively. By the 2050s, reductions in soil storage are likely from April to October, with the most substantial reductions again likely for August (–59%) and September (–62%). The most extreme reductions in soil storage are likely by the 2080s with reductions evident for 7 months of the year, commencing in May and persisting until November. Reductions in the order of –75% are likely for August and September.

Subsoils within the Suir catchment comprise glacial tills and sands and gravels. As with the Barrow, high permeability rates associated with sands and gravels allow a high level of recharge and provide additional storage to underlying bedrock aquifers. The bedrock geology of the catchment is extremely diverse. In terms of aquifer productivity, almost half of the catchment is underlain by moderately productive, locally important aquifers. Regionally important aquifers make up approximately 35% of the catchment area and, of these, diffuse karst aquifers are the most common. Under the control period, June is the month of maximum groundwater storage, while minimum storage occurs in December. A distinct lag between maximum precipitation and maximum groundwater storage is evident, while a large proportion of groundwater is contributed to streamflow as baseflow due to diffuse karstic conditions. By the 2020s, slight reductions in storage are evident for all months with greatest reductions likely for the important recharge months. By the 2050s, slight increases are suggested for the majority of months as a result of increased precipitation. However, increases are marginal. By the end of the century, greatest reductions are likely during the current recharge period, while December becomes the month when groundwater storage is at a minimum.

3.5.1.7 Blackwater

The predominant soil types within the Blackwater are relatively permeable. Under the control period, soil water storage is at a minimum during August and September. By the 2020s, there is a reduction in soil storage for 6 months of the year, with the greatest reduction likely for the month of August (–51%). Substantial reductions are also likely for July (–27%) and September (–41%). By the 2050s, the rate of decrease between the spring and summer is much more rapid, with further reductions in storage evident for 7 months of the year, beginning in April and persisting until October. The greatest reductions are likely for the late summer and early autumn months, with a reduction of –47% in July, –67% in August and –54% in September. By the 2080s, 8 months show reductions in soil storage with reductions being extended into November. Of these, 5 months, June to October, show reductions of more than –20%. Again the greatest reductions are evident for July (–65%), August (–82%) and September (–63%).

Subsoils within the Blackwater are diverse, with deposits comprised predominantly of sandstone and limestone glacial tills. Dominant bedrock consists of Old Red Sandstone, undifferentiated Namurian deposits and unbedded Dinantian limestones. The vast majority of the catchment is underlain by moderately productive aquifers, while regionally important aquifers make up over 16% of the catchment area. Under the control period, the groundwater storage regime is similar to that of the Suir. By the 2020s, there is little change evident for the winter and spring months, while only slight increases are suggested for the remainder of the year. By the middle of the century, increases are simulated for all months, with results ranging from +4% to +6%. By the 2080s, reductions in storage are likely for each of the winter months, most pronounced in December with a reduction of –5%. Increases in the order of +1 to +3% are likely for the remaining months.

3.5.1.8 Ryewater

The majority of the Ryewater catchment comprises soils having a heavy clay loam texture. In terms of soil storage during the control period, there is a gentle reduction throughout the spring and into the summer. As is evident in other catchments, the rate of drying during the spring and summer becomes more pronounced during future simulations for the Ryewater. By the 2020s, 7 months show a reduction in storage with the greatest changes once again evident during August (–32%) and September (–35%). By the 2050s, the reductions become more pronounced, with 7 months experiencing reductions in storage by mid-century. Five months, from June to October, suggest substantial reductions of over –20%, with August and September showing reductions of –54% and –55%, respectively. By the 2080s, further reductions are likely for all of the summer and autumn months, with major reductions in June (–22%), July (–50%), August (–68%), September (–70%) and October (–40%).

Within the Ryewater, subsoils largely comprise glacially deposited till derived from the Irish Sea, while the underlying geology is predominantly made up of impure limestone. Consequently, aquifer productivity is largely refined to being moderately productive. Under current conditions, groundwater storage reaches a maximum earlier in the year than many of the other catchments analysed, with storage peaking in March. By the 2020s, decreases in storage are simulated for each month, with substantial decreases in November (–14%), December (–28%), January (–24%) and February (–13%). By the 2050s, slight increases are simulated for April and May; however, more pronounced decreases are likely for the rest of the year. The most severe decreases are likely for December and January, with reductions of –37% and –26% simulated. By the 2080s, 5 months show an increase in storage, with greatest increases in April and May of approximately +5%. The most dramatic changes by the end of the century are the significant reductions in storage during important recharge months, with the months from November to February showing reductions of –15%, –45%, –33% and –12%, respectively.

3.5.1.9 Boyne

In relation to the other catchments involved in this analysis, the Boyne is one of the catchments with the greatest amount of soil water storage. When examining the results, it is evident that least change is shown in terms of simulated future soil moisture storage for the Boyne catchment. Over 35% of the Boyne catchment comprises poorly drained soils, which reduce the capacity of precipitation to infiltrate into the subsoil and into groundwater. By the 2020s, reductions are likely for 5 months of the year, beginning in May and persisting until September. Greatest reductions by the 2020s are suggested for June, with a reduction of –6% in upper soil storage. By the 2050s, the number of months showing a reduction in storage increases to six (April to October), with reductions of –14% and –8% likely for June and July. Because of increased precipitation earlier in the year and the ability of soils in the Boyne to retain moisture, the number of months recording a reduction in storage by the 2080s is reduced to six. Greatest reductions by this time are likely for the summer months of –16%, –10% and –10%.

Subsoils within the Boyne catchment are complex with important deposits of glacial tills of limestone and shale and till of Irish Sea origin. On the catchment scale, the infiltration of water, its movement through the soils and into groundwater, is not as rapid as in the Suir catchment where highly porous sand and gravel subsoils are dominant. Due to the impurities in limestone formation, karstification is inhibited and the transmissivity and thus the aquifer potential of the bedrock is reduced. Under the control period, groundwater storage reaches a maximum in April, while minimum storage levels are recorded in November and December. By the 2020s, slight increases are simulated for May, June and July, while decreases are suggested for the remaining months. The most significant decreases are likely for the winter months with reductions of –26%, –21% and –10%. By the 2050s, slight increases are again likely for the spring and early summer; however, by mid-century reductions become more extreme. During the autumn, reductions range from –12% to –27%, while winter decreases are in the order of –19% to –42%. By the end of the century, this trend becomes more pronounced. Again, only slight increases are simulated for late spring and early summer, with a maximum increase of +5% in May. Most problematic are the reductions simulated by this period. Reductions in autumn range from –12% to –30% while reductions of –51%, –50% and –27% are suggested for the winter months. Once again the most significant reductions are likely to occur during the important recharge season.

3.5.2 Changes in monthly streamflow

Changes in monthly streamflow are predominantly driven by changes in precipitation and temperature as well as changes in catchment storage, with the latter dependent on processes such as the infiltration capacity, the porosity and the type of subsurface material. Therefore the effects of climate change on river flow depend not only on the extent of change in climatic inputs, but also on the characteristics of the catchment itself (Arnell, 2003). In order to account for the response of basins with similar characteristics, catchments are grouped so that similarity in response is highlighted. In total, four groups of catchments are analysed:

1. The Suir, the Barrow and the Blackwater form the first group, as their response is determined by the influence of groundwater on monthly streamflow

2. The second group includes the eastern catchments of the Boyne and Ryewater

3. The third group is formed by the Shannon sub-catchments of the Inny, the Suck and the Brosna

4. The final catchment, the Moy, is analysed separately.

For each catchment the percentage change in monthly streamflow derived from the mean ensemble run using all of the behavioural parameter sets is presented (Figs 3.6–3.8). The columns represent the average results obtained using the mean ensemble, with the error bars representing the full range of uncertainty analysed. Percentage changes are calculated for each future time horizon through comparison with the 1961–1990 control period. Appendix 3.1 shows percentage changes and uncertainty ranges simulated for each catchment in tabular form for the 2020s, 2050s and 2080s. The significance of changes in monthly streamflow is calculated using the Student's *t*-test (Appendix 3.2). Figure 3.9 maps seasonal changes in streamflow for each catchment. Seasonal changes are defined as winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November).

The percentage change derived from the A2 and B2 ensembles is presented for illustrative purposes and is not discussed in the text due to the fact that the mean ensemble is a weighted average of both. In general, the B2 scenario suggests more substantial increases in streamflow for the majority of months during the 2020s, while decreases are generally less pronounced during the summer and autumn periods. On the other hand, the A2 scenario shows more pronounced decreases during summer and autumn than the B2 scenario. While increases in spring under the A2 scenario are less pronounced than the B2, there are a number of catchments in which winter increases are more significant under the A2 scenario. In many cases, the mean ensemble changes do not lie within the ranges simulated by the A2 and B2 ensembles. This is due to the thresholds and feedback present in determining a catchment's response to climate change.

3.5.2.1 The Suir, the Barrow and the Blackwater

Simulations conducted for the 2020s suggest little change for the winter months. Increases of approximately +3% are likely for December streamflow in the Blackwater, while slight decreases are suggested in the Suir for the same month. Under the mean ensemble, March and April are the months that show the most substantial increases by the 2020s in each catchment. A maximum increase of +9% in March is likely for the Blackwater, with the Suir and Barrow showing similar increases, although slightly less pronounced. In terms of streamflow response during the summer months, both the Suir and the Barrow show only slight reductions (between –1% and –8%). When the uncertainty bounds are accounted for, the direction of change in summer months in the Blackwater is uncertain with slight increases and slight decreases simulated. In each catchment, the greatest reductions by the 2020s are simulated for the autumn. The largest reduction in September streamflow is shown for the River Suir, with reductions ranging from –5% to –12%. In each catchment, decreases are most pronounced for October, with average results showing a reduction of between –20% and –23%. Significant reductions are also suggested for November. In the Blackwater and Barrow catchments, average November streamflow decreases by approximately –10%, while average decreases in the Suir approach –20%. The greatest amount of uncertainty is also evident for changes in autumn streamflow in each of the catchments.

By the 2050s, significant increases in streamflow are suggested for the winter months. In both the Suir and the Barrow, greatest increases in streamflow are likely for the month of February by this time, with increases in the order of +15% to +18% likely. Although the average response suggests a slight increase in December streamflow in the Suir, when all model runs are accounted for the direction of change becomes uncertain. In the Blackwater catchment, March remains the month displaying the greatest increase in streamflow, with an average increase of +13%. The response of summer months in each of the catchments remains conservative, with slight increases and slight decreases suggested. In all of the catchments, reductions are not as pronounced as in the 2020s due to increases in precipitation earlier in the year and the role of groundwater in each of the catchments. Indeed, slight increases in streamflow of between +2% and +3% are likely for summer months in the Blackwater catchment under the mean ensemble. As with the 2020s, the autumn months display the greatest reductions. For each catchment the month of October remains the month with most pronounced decreases. The greatest decreases are experienced in the Suir, with average October reductions reaching –27%. Reductions consistent with those simulated for the 2020s are maintained for both the Blackwater and Barrow by the 2050s. Significant decreases in streamflow are also likely for November, with reductions in the Suir ranging from –11% to –44% when the model is run with all parameter sets. Average decreases become more pronounced in November in both the Suir (–22%) and the Barrow (–12%), while they remain the same as in the 2020s for the Blackwater.

The most significant changes in streamflow are likely by the end of the century. During the winter, further increases are likely for the months of January and February by the 2080s, with February displaying the greatest percentage increase in streamflow in all catchments (Suir +22%, Blackwater +13%, Barrow +25%). Increases in December streamflow become

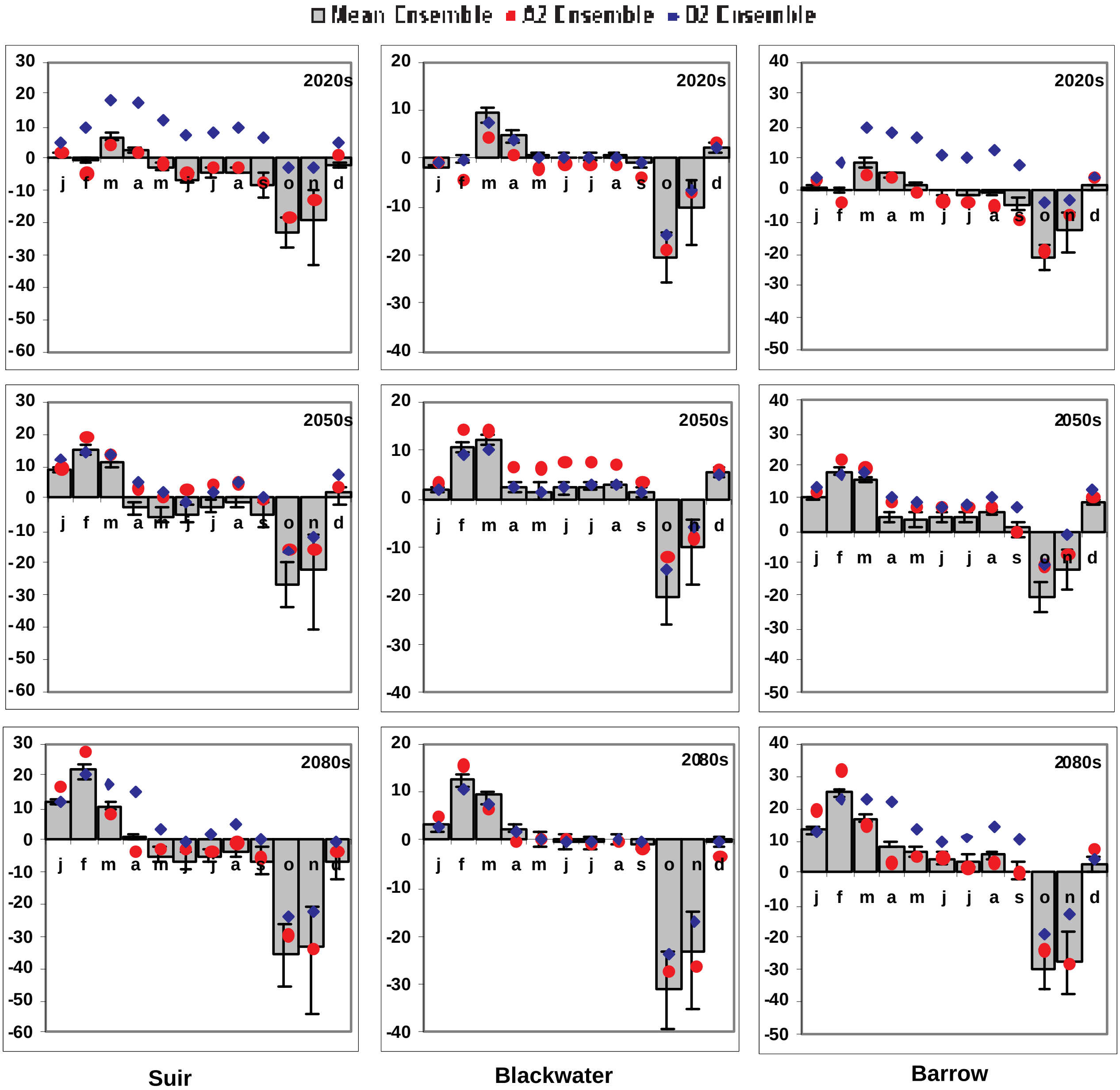

Figure 3.6. Percentage change in monthly streamflow in the Suir, Blackwater and Barrow catchments for each future time period.

less marked by this time in the Barrow while decreases are simulated for both the Suir and Blackwater. In the Suir and Barrow, spring changes remain similar to those simulated for the 2050s, while increases are not as pronounced in the Blackwater. In terms of changes in the summer months, slight decreases are suggested for the Suir (–3% to –7%), the direction of change in the Blackwater becomes uncertain, while slight increases are simulated for the Barrow (approximately +4% in June, July, August). Reductions in autumn streamflow are also greatest by this period. Reductions in both October and November become more pronounced in each of the catchments. For the Suir, average reductions of –36% and –33% are likely. In the Blackwater, October and November streamflow is suggested to decrease by –31% and –23%, while reductions of –38% and –28% are simulated for the Barrow. Again, uncertainty bounds are also greatest during the autumn with reductions of up to –54% simulated for November in the Suir catchment.

Changes in streamflow of the magnitude simulated (Fig. 3.6) would have significant implications for water resources and flood management in each of the catchments. Surprising from the analysis are the conservative changes in summer flows, as these catchments are located in the south and south-east of the country. This finding highlights the important role that catchment storage plays in offsetting the response to precipitation changes. It is also interesting to note that the greatest reductions in streamflow are likely when storage levels reach a minimum. Although increases in precipitation are simulated for December, more rainfall is diverted to storage than at present and thus a reduction in streamflow compared with the control period is likely, especially in the Suir catchment.

3.5.2.2 The Moy

The Moy catchment is the most westerly of the catchments analysed. By the 2020s, the largest changes in streamflow are likely to occur in late summer and early autumn, with average reductions of –10% in August and September (Fig. 3.7). Decreases are also simulated for the remaining summer and

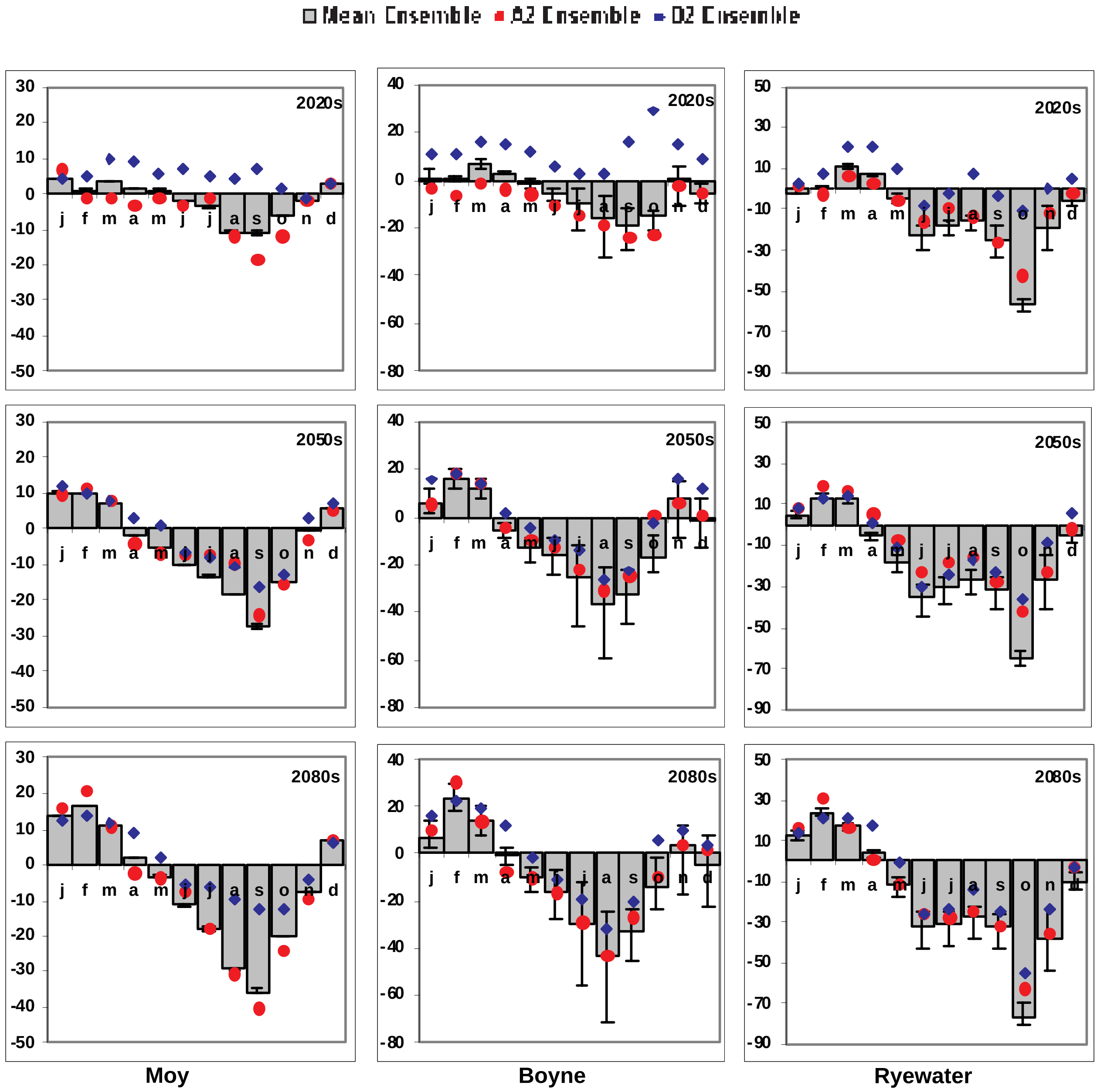

Figure 3.7. Percentage change in monthly streamflow for the Moy, Boyne and Ryewater by each future time period.

autumn months but these are only marginal. Slight increases in the order to +2% to +5% are simulated for the winter and spring months. The decreasing trend in summer and autumn streamflow is likely to continue into the 2050s, with more substantial average decreases simulated for June (–10%), July (–13%), August (–19%), September (–27%) and October (–15%). For the winter months, there are further increases suggested, with December showing an average increase of +6%, while January and February display average increases of +10%. By this time, the direction of change of some of the spring months is altered, with April and May showing decreases in streamflow. Simulations for the 2080s suggest continued increases in flow throughout the winter months, with average increases for December, January and February reaching +7%, +14% and +16%, respectively. Further reductions in flow are also suggested during the summer and autumn with reductions in July, August, September and October extending to –18%, –30%, –36% and –20%, respectively.

3.5.2.3 The Boyne and Ryewater

The Boyne and the Ryewater are located in the east of the country and are the most heavily populated of the catchments considered. While the response of each of the two catchments to climate change is quite different, they are analysed together due to their comparable strategic importance. By the 2020s, little change is suggested for the winter months in either catchment. Indeed simulations for both (Fig. 3.7) suggest slight decreases in December flow. Greatest increases in streamflow are likely for March, with an average increase of +11% in the Ryewater; increases for the same month are not as large in the Boyne. Significant reductions in summer flow are simulated for both catchments. In the Ryewater, greatest summer reductions are likely in June (–22%), while in the Boyne the greatest decreases are likely in August (–16%). In both catchments, the uncertainty bounds are greatest during the summer months. During the autumn, reductions in flow reach a maximum in both catchments. In the Boyne, September streamflow is likely to reduce by –19%. In the Ryewater, greatest average reductions are likely in October (–57%), while substantial reductions are also likely in September (–25%) and November (–19%).

By mid-century, increases in flow are likely for January and February. In both catchments, February displays the greatest change, with increases of +13% to +16%. In the Boyne, the direction of change in December streamflow is uncertain, with simulations ranging from +7% to –13%. Slight decreases are likely for December flow in the Ryewater. By the 2050s, reductions in spring streamflow are also likely. While increases in March streamflow remain largely the same as suggested for the 2020s, reductions in April (–6% and –5%) and May (–13% and –18%) are likely in both catchments. By the 2050s, the greatest reductions in the Boyne are simulated during the summer months, with average reductions of –16%, –25% and –36% in June, July and August, respectively. Uncertainty bounds are large with reductions reaching up to –60% in August. Significant decreases are also likely for the summer in the Ryewater with average reductions of –35%, –30% and –27% in June, July and August, respectively. However, greatest average reductions in the Ryewater are suggested for the autumn, with reductions of –32%, –65% and –27% in September, October and November, respectively. Uncertainty bounds are largest for November with simulations ranging from –15% to –41%.

By the 2080s, further increases are likely during the winter months, especially in February with increases of over +23% in both catchments. During the spring, increases in March become more pronounced, especially in the Ryewater where an average increase of +17% is suggested. In both catchments, decreases in streamflow for April and May are not as pronounced as in the 2050s due to increases in precipitation earlier in the year. In the Boyne, decreases in June remain the same as simulated during the 2050s. However, reductions become more pronounced during July and August with likely average reductions of –30% and –43%, respectively. Uncertainty bounds are also large for these months with streamflow reducing by as much as –56% in July and –71% in August when all simulations are accounted for. During the summer months in the Ryewater reductions are consistent, with average decreases of between –28% and –32% in

June, July and August. Unlike the Boyne, the greatest reductions in the Ryewater are displayed in autumn. Average reductions of –32% and –38% are likely for September and November, respectively. However, the greatest reductions are evident for October with an average reduction of –76% suggested by the 2080s. In the Boyne catchment, significant reductions are likely in September (–33%); however, reductions become less pronounced in October (–14%). By the end of the century, the direction of change in November streamflow is uncertain with simulations ranging from +5% to –24%.

3.5.2.4 The Inny, Suck and Brosna

The Inny, Suck and Brosna are important tributaries of the Shannon catchment. Both the Inny and the Brosna are eastern tributaries, while the Suck joins the main river from the west. Each of the catchments are similar in terms of their physical and meteorological characteristics. By the 2020s, slight increases in streamflow for winter and spring months are suggested for all three catchments (Fig. 3.8). However, these increases are all less than +6%. During the summer months no change, or very slight reductions are likely. In each of the catchments, the greatest changes by the

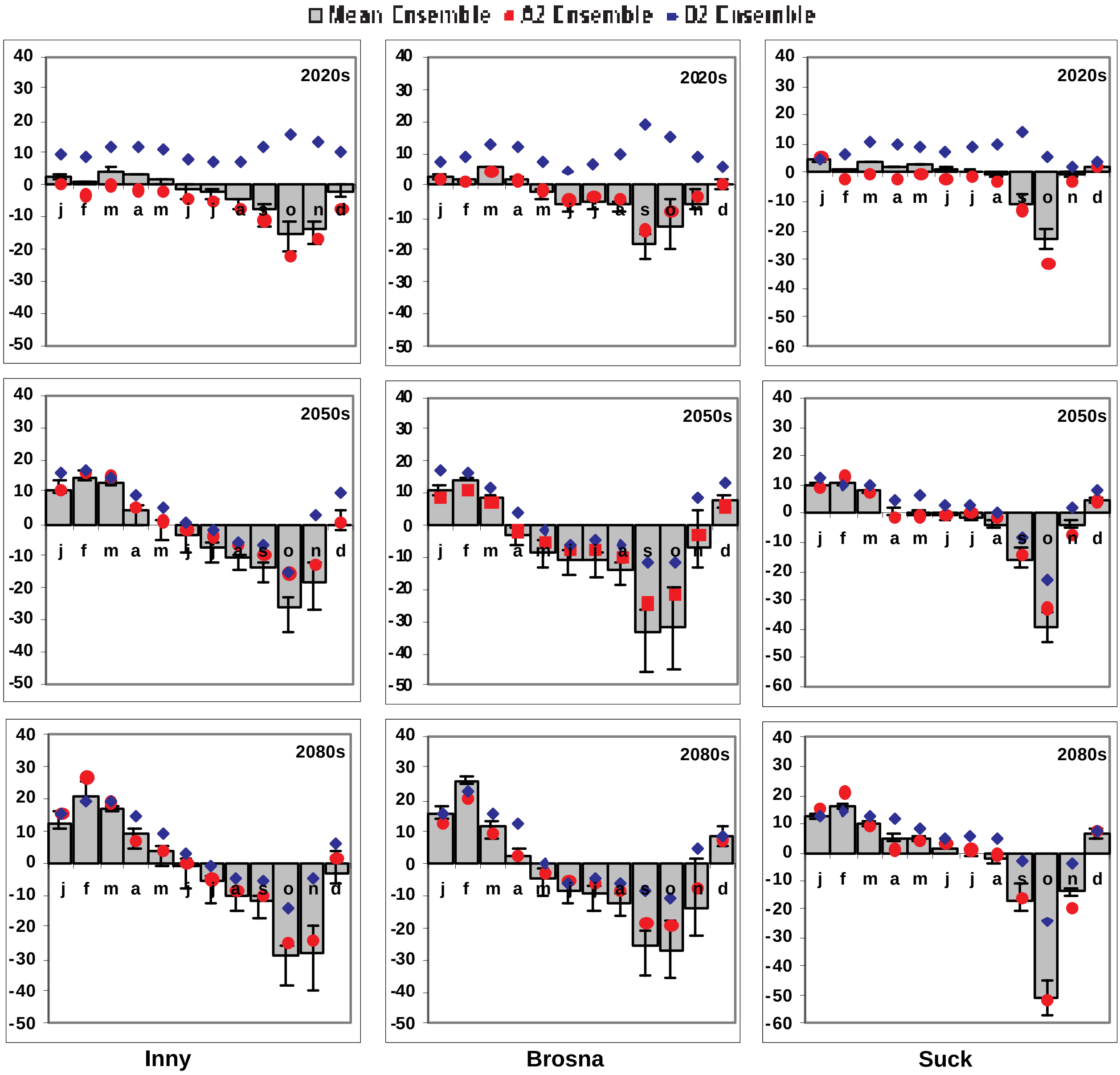

Figure 3.8. Percentage change in monthly streamflow for the Inny, Brosna and Suck by each future time period.

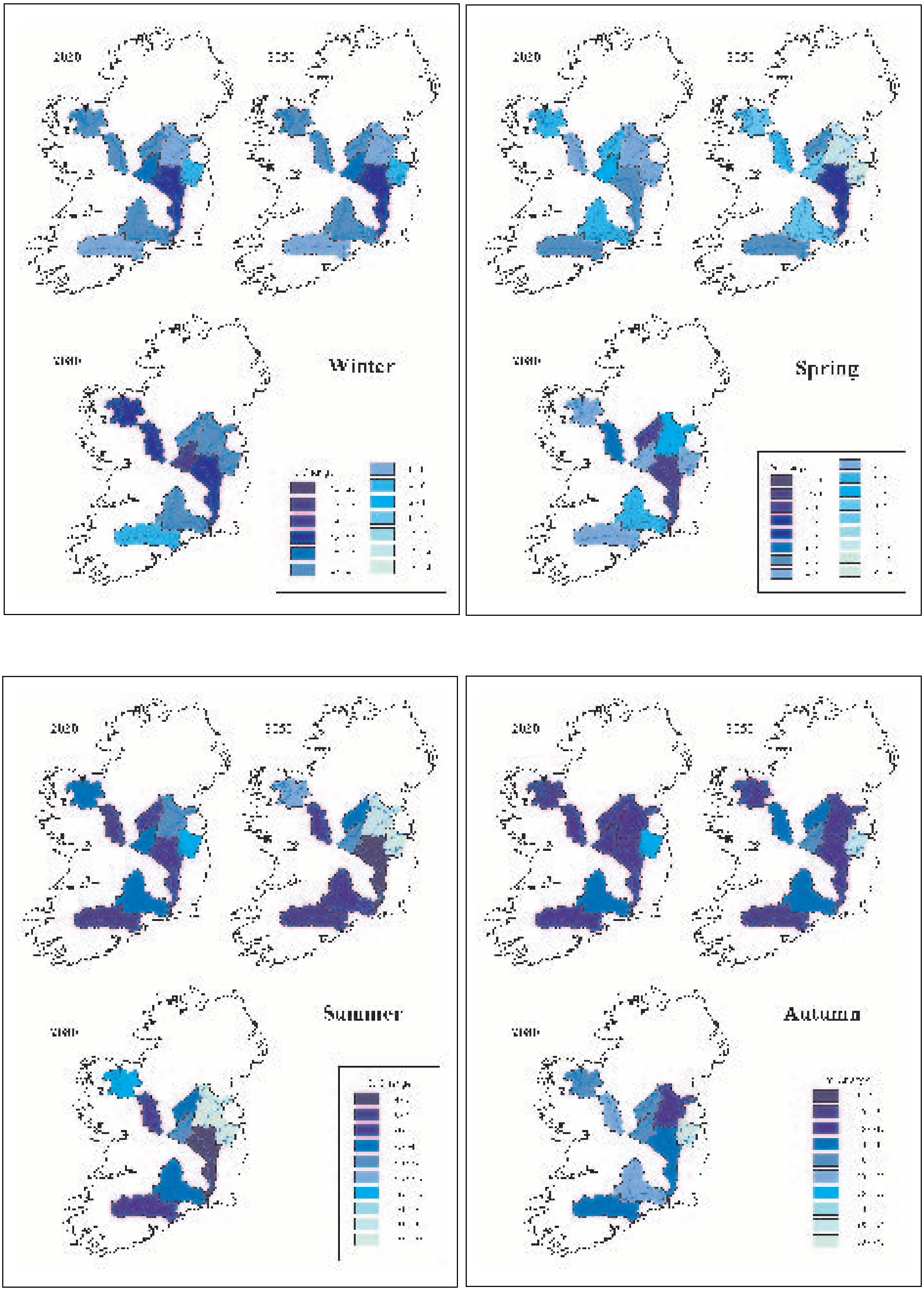

Figure 3.9. Seasonal changes in streamflow for each of the catchments analysed.

2020s are likely for the autumn months. For the Inny, average reductions of –8%, –16% and –14% are simulated for September, October and November, respectively. In the Brosna, the largest reductions are likely for September (–18%) with decreases of –13% and –6% in October and November, respectively. October shows the greatest decrease in the Suck (–22%), while little or no change is suggested for November.

By the 2050s, significant increases are likely for winter months. For each of the catchments, average increases in January approach +10%. In both the Inny and the Brosna, the greatest increases are likely in February (approximately +14%), while increases in the Suck for the same month are not as large. It is worth noting that the direction of change in December flow in the Inny becomes uncertain by the 2050s. In terms of spring streamflow, increases of between +8% and +13% are suggested for March in all of the catchments. However, for the late spring months, especially May, decreases in flow are simulated, with greatest decreases in the Brosna of –8%. Reductions in streamflow during the summer are suggested for both the Inny and the Brosna. In the Inny, minimum average summer reductions are shown for June (–4%) and extend to –11% in August. In the Brosna, average reductions of –11% are likely for June and July, with reductions slightly more pronounced in August (–14%). Only minimal decreases are simulated for the Suck catchment during the summer months. Once again, the greatest reductions in streamflow in all three catchments are likely for the autumn months. In the Inny, average decreases of –14%, –26% and –18% are suggested for September, October and November, respectively, while in the Brosna average decreases for the same months are –33%, –32% and –7%, respectively. When uncertainty ranges are accounted for, the direction of change for November in the Brosna is uncertain. Error bars are also large for September and October, with reductions reaching –45% in both months when all simulations are analysed. In the Suck, greatest decreases are again suggested for October, with an average reduction of just over –39% by mid-century.

By the end of the century significant increases are simulated for winter months. In each of the catchments, February shows the greatest increase in streamflow, with average increases of +21% in the Inny, +26% in the Brosna, and +17% in the Suck. During the winter, the smallest increases are shown for December, where in the Inny the direction of change by the 2080s is uncertain. Greatest increases in the spring are again likely for March with average increases ranging from +10% in the Suck to +17% in the Inny. Increases are not as pronounced during April and May. In the Suck catchment, little change persists in the summer months, while in the Inny and Brosna the greatest summer decreases occur in August with average reductions of –10% and –12%, respectively. Decreases in autumn streamflow are extended into the 2080s for all catchments. In the Inny, average reductions of –12%, –29% and –28% (September, October and November) are simulated, while in the Brosna reductions for the same months extend to –26%, –27% and –13%. In the Suck, average reductions of –17% and –14% are suggested for September and November, respectively. However, greatest reductions are shown for October streamflow with an average reduction of –51%. When uncertainty ranges are accounted for, reductions in October in the Suck are likely to range between –45% and –58%.

3.5.3 Changes in the variability of streamflow

The changes in precipitation highlighted in Chapter 2 are also likely to result in changes in the variability of daily streamflow. Figure 3.10 shows the likely changes in the variability of daily streamflow for each future time period. Changes are calculated as a percentage difference from the 1961–1990 control period. The columns represent the average change for each catchment, while the error bars represent the uncertainty ranges from each ensemble run using all behavioural parameter sets. By the 2020s, the majority of catchments are likely to experience a decrease in the variability of daily streamflow, with greatest average reductions suggested for the Barrow, the Blackwater and the Suir. By the 2050s, increases in variability are simulated for the majority of catchments, with greatest increases in the Brosna and Inny; slight reductions in variability are likely for the Blackwater. Uncertainty bounds are also large, with variability increasing by up to +60% in Inny and Brosna. By the end of the century, further increases in the variability of

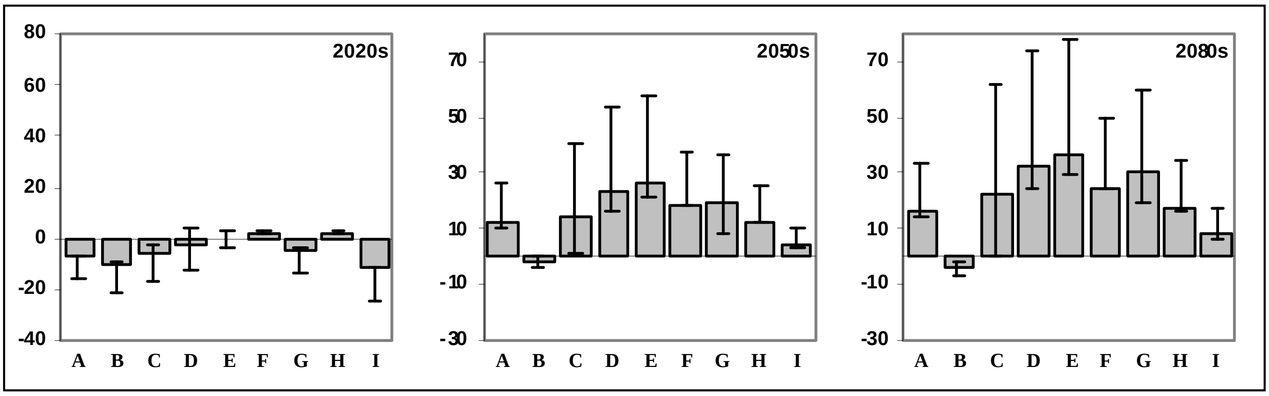

Figure 3.10. Percentage change in the variability of monthly streamflow in each catchment for each time period. A, Barrow; B, Blackwater; C, Boyne; D, Brosna; E, Inny; F, Moy; G, Ryewater; H, Suck; I, Suir.

daily streamflow are likely. The catchments showing the least change in variability are the groundwater-dominated catchments: the Barrow, the Blackwater and the Suir. Indeed, slight reductions in variability are simulated for the Blackwater by the 2080s. The catchments likely to experience the greatest increase are the Brosna, the Inny, the Ryewater and the Boyne.

3.5.4 Changes in selected flow percentiles

As a result of changes in both the variability of daily streamflow and the simulated changes in average monthly streamflow, changes associated with important flow percentiles are assessed for each catchment (Fig. 3.11). These include Q5, the flow that is exceeded 5% of the time, Q50, the flow exceeded 50% of the time and Q95, the flow exceeded 95% of the time. The latter is an important low flow statistic in water resources management. Each statistic is calculated from the full flow record in each time period considered. The changes presented are relative to the control period 1961–1990.

3.5.4.1 Q5

Q5 is a high flow statistic referring to the flow that is exceeded only 5% of the time. By the 2020s, all simulations range from +12% to –7%. The greatest increases are suggested for the Boyne under the CCCma (Canadian Centre for Climate Modelling and Analysis) B2 run, while the greatest reductions are likely for the Blackwater under the CSIRO (Commonwealth Scientific and Industrial Research Organisation) B2 run. By the 2050s, increases in Q5 are simulated for all catchments under the vast majority of model runs. The greatest increases are likely for the Boyne and the Inny under the CSIRO B2 run, with increases in Q5 of approximately +30% in both catchments. In each catchment, the smallest changes are associated with the Hadley Centre A2 run. By the 2080s, more significant increases in Q5 are simulated for each catchment. Three catchments, the Boyne, the Inny and the Brosna, show maximum increases of between +20% and +30%. In each of the catchments, the majority of model runs indicate an increase in Q5 with the greatest increases simulated under the Hadley and CSIRO A2 runs, while the smallest changes are likely under the CCCma A2 and B2 simulations. Slight decreases in Q5 are likely for the Blackwater (maximum decrease of –8%), with only the Hadley runs suggesting an increase.

3.5.4.2 Q50

Q50 refers to the flow exceeded 50% of the time. For the 2020s, there is a distinct difference between the results obtained using each of the scenarios. Reductions in Q50 are simulated under the A2 scenario while increases are generally associated with the B2 scenario. In terms of GCM, greatest reductions are simulated using the Hadley model, with the Boyne, Inny and Ryewater showing reductions of –25% under the A2 scenario. The greatest increases are simulated by the CCCma and the Hadley Centre (HadCM3) models using the B2 scenario. By the 2050s, changes in Q50 are not as pronounced in each of the catchments, with the majority of runs clustering between +10% and –10%. However, increases in the Boyne and Inny under the CSIRO B2 run are more

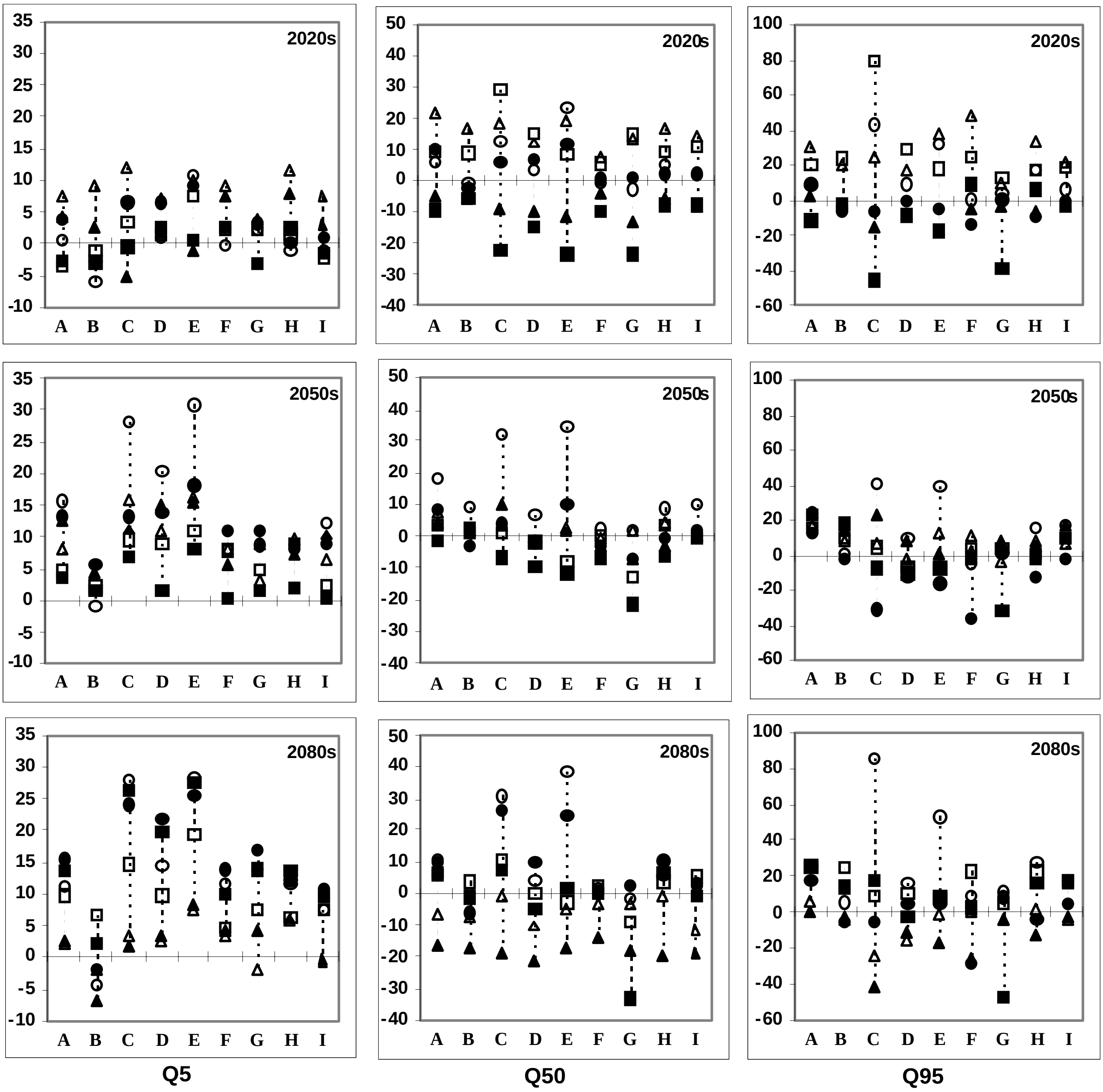

Figure 3.11. Percentage change in important flow percentiles for each catchment by the 2020s, 2050s and 2080s. A, Barrow; B, Blackwater; C, Boyne; D, Brosna; E, Inny; F, Moy; G, Ryewater; H, Suck; I, Suir.

pronounced (+35 to +40%). Again, the greatest reductions in each of the catchments are associated with the Hadley A2 run. By the 2080s, each catchment experiences decreases in the order of –20% in Q50 under the CCCma A2 run. Apart from the Ryewater, little change is likely under the Hadley runs (±10%). The greatest increases in Q50, especially in the Boyne and Inny, are associated with CSIRO A2 and B2 runs.

3.5.4.3 Q95

Q95 is an important low flow statistic referring to the flow that is exceeded 95% of the time. For the 2020s, reductions in Q95 are simulated under the majority of A2 scenario runs while increases are likely under the B2 runs. Largest increases are generally around +35% to +40% under the CCCma and HadCM3 B2 runs. However, an increase of +80% is suggested for Q95 in the River Boyne under the HadCM3 B2 run. In the majority of catchments, the greatest decreases in Q95 are simulated using the HadCM3 A2 run. In all catchments, except the Boyne and Ryewater, reductions of approximately –20% are likely. In the two eastern catchments, reductions of approximately

–40% are simulated by the 2020s under the HadCM3 A2 run.

By the 2050s, results from the A2 and B2 scenarios become more clustered. In the majority of catchments, the greatest reductions are shown for the CSIRO A2 run, while the greatest increases are evident for the same GCM under the B2 scenario. Increases in Q95 are simulated for the Barrow, Blackwater and Suir by the 2050s. By the end of the century, the greatest decreases in Q95 are suggested for the Boyne (–40%) and Ryewater (–50%). However, results are subject to large uncertainty ranges, depending on the GCM and scenario used. For the majority of catchments, the greatest reductions are likely under the CCCma A2 run. The direction of change obtained under the HadCM3 A2 run varies between catchments.

Taking account of the changes in Q95 suggested above, the total number of days with a total streamflow equal to or less than Q95 is adopted as an index to analyse the impact of climate change on low flows. Using the threshold defined under the control period, the number of low flow days in any given year is calculated for the mean ensemble run using all behavioural parameter sets for each future time period. The results are presented in Table 3.4.

By the 2020s, there is a reduction in the number of days when streamflow is less than or equal to the control Q95 in the majority of catchments. For example, in the Suir there is a reduction of between 9 and 11 days in any year when streamflow falls below Q95. The Ryewater is the only catchment to show a likely increase in the number of low flow days by the 2020s, with an increase of 3–5 days simulated. By the 2050s, only the groundwater-dominated catchments show a decrease in low flow days.

The most significant changes are suggested for the Suir, with annual low flow days decreasing by 13–15 days. The greatest increases in frequency of low flow days are simulated for the Boyne and Ryewater, with increases of between 3 and 12 days in the Boyne and 12 and 15 days in the Ryewater. This trend is continued into the 2080s, with groundwater-dominated catchments showing further reductions in low flow days, while catchments in which surface run-off plays a more important role in streamflow generation show further increases in the number of low flow days in any given year. Again, the Ryewater and the Boyne show the most significant increase in low flow days.

3.6 Flood Frequency Analysis

Increases in greenhouse gas concentrations are likely to result in increased temperatures, changes in precipitation patterns and increases in the frequency of extreme events due to an enhanced hydrological cycle. Increased winter rainfall implies an increase in winter flooding, while more intense convectional summer rainfall suggests an increase in the occurrence of extreme summer flooding (Arnell, 1998). Sweeney *et al*. (2002) show under the current climate that indications of increases in average monthly rainfall amounts are particularly strong during the winter months of December and February, while maximum 24-hourly receipts appear to be rising in October and

Table 3.4. Change in the average number of days in the year when flows are less than or equal to Q95.

	2020s		2050s		2080s	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Barrow	–7	–6	–13	–11	–16	–15
Blackwater	–10	–9	–11	–10	–12	–9
Boyne	–7	1	3	12	7	20
Brosna	–5	–5	3	6	2	8
Inny	–6	–4	1	6	–1	5
Moy	–6	–6	3	3	12	13
Ryewater	3	5	12	15	12	17
Suck	–10	–8	–4	–2	–5	–3
Suir	–11	–9	–15	–13	–17	–13

December. This section accounts for the impacts that climate change is likely to have on future flooding in each of the selected catchments. Changes in the flood regime are characterised in two ways. Firstly, changes in the magnitude of a flood event of a given frequency or return period are analysed. Secondly, changes in the frequency of floods of a given magnitude under the control period are assessed for each future time period. In total, four flood events are analysed: the flood expected every 2, 10, 25 and 50 years. Therefore flood events ranging from fairly frequent (2-year) to moderately infrequent (50-year) are analysed. Due to the limited years of data, more extreme return periods were not included. Given that the ensembles are averages of each model run and not suited to extreme value analysis, flood frequency analysis is conducted using each GCM model run for each scenario. In total, six GCM runs are analysed.

One of the key assumptions of flood frequency analysis is that the return period of a flood peak of a given magnitude is stationary with time (Cameron *et al.*, 1999). However, recent studies (Arnell and Reynard, 1996; Hulme and Jenkins, 1998) have demonstrated the variability of climate characteristics, with such variability having serious implications for statistical methods used in flood frequency analysis. Consequently, assumptions regarding the stationarity of the flood series are made. In dealing with non-stationarity in the flood series, Prudhomme *et al.* (2003) contend that it is possible to assume stationarity around the time period of interest (i.e. the 2020s, the 2050s and 2080s). Under this assumption, standard probability methodologies remain valid and are thus considered representative of the flood regime of the considered time horizon (Prudhomme *et al.*, 2003). Similar assumptions are made in this work.

In conducting a flood frequency analysis for each catchment, the maximum annual flood was extracted from each time period. In total, 30 maximum annual floods comprised each flood series. An extreme value distribution (Generalised Logistic) was fitted to each series using the method of L-moments following the methodology described in the *Flood Estimation Handbook* (Robson and Reed, 1999). The relatively short time series sampled makes it difficult to identify the true underlying distribution. Thus, confidence intervals were calculated to reflect the sampling error and the effects of natural variability on the flood distribution. For each catchment, bootstrapping was undertaken to produce a set (199) of randomly sampled flood series and the Generalised Logistic distribution was fitted to each series. The 95% confidence interval was derived from the ensemble of the resulting 199 flood frequency distributions (Prudhomme *et al.*, 2003). The 95% confidence intervals describe the limits within which the true curve is expected to lie at the 95% confidence level. Confidence intervals were calculated for the control period only and are used to assess the significance of likely future changes.

3.6.1 Changes in flood magnitude

Figures 3.12 and 3.13 present the simulated changes in flood magnitude under each emissions scenario for each of the return periods analysed. For ease of presentation, the weighted average of the results from each model run is illustrated. Due to the performance of the HadCM3 model in replicating current conditions, especially during periods of high flow, greatest weight is therefore attributed to results derived from these runs. Table 3.5 highlights the percentage change in flood magnitude compared with the control period for each future time period; changes that are significant at the 0.05 level are shaded. For each of the catchments analysed under the A2 scenario, there is a consistent signal that the magnitude of flow associated with each return period will increase for each time period.

Only two catchments, the Boyne and the Inny, suggest a decrease in flood magnitude by the 2020s; however, reductions are not significant when sampling error and natural variability are accounted for. The period in which the greatest increases in flood magnitude are simulated varies between catchments. In the Boyne, Blackwater and Suir, greatest increases in the magnitude of the 50-year return period are simulated by the 2020s. The most significant increases are suggested for the Blackwater, with the magnitude of flow associated with the 50-year return period increasing by 56%. On the other hand, only one significant change is simulated for the Suir where the 2-year flood shows a slight reduction of –1%. Large increases in the magnitude of floods are also likely for the Boyne, the Moy and the Suck. In the Boyne

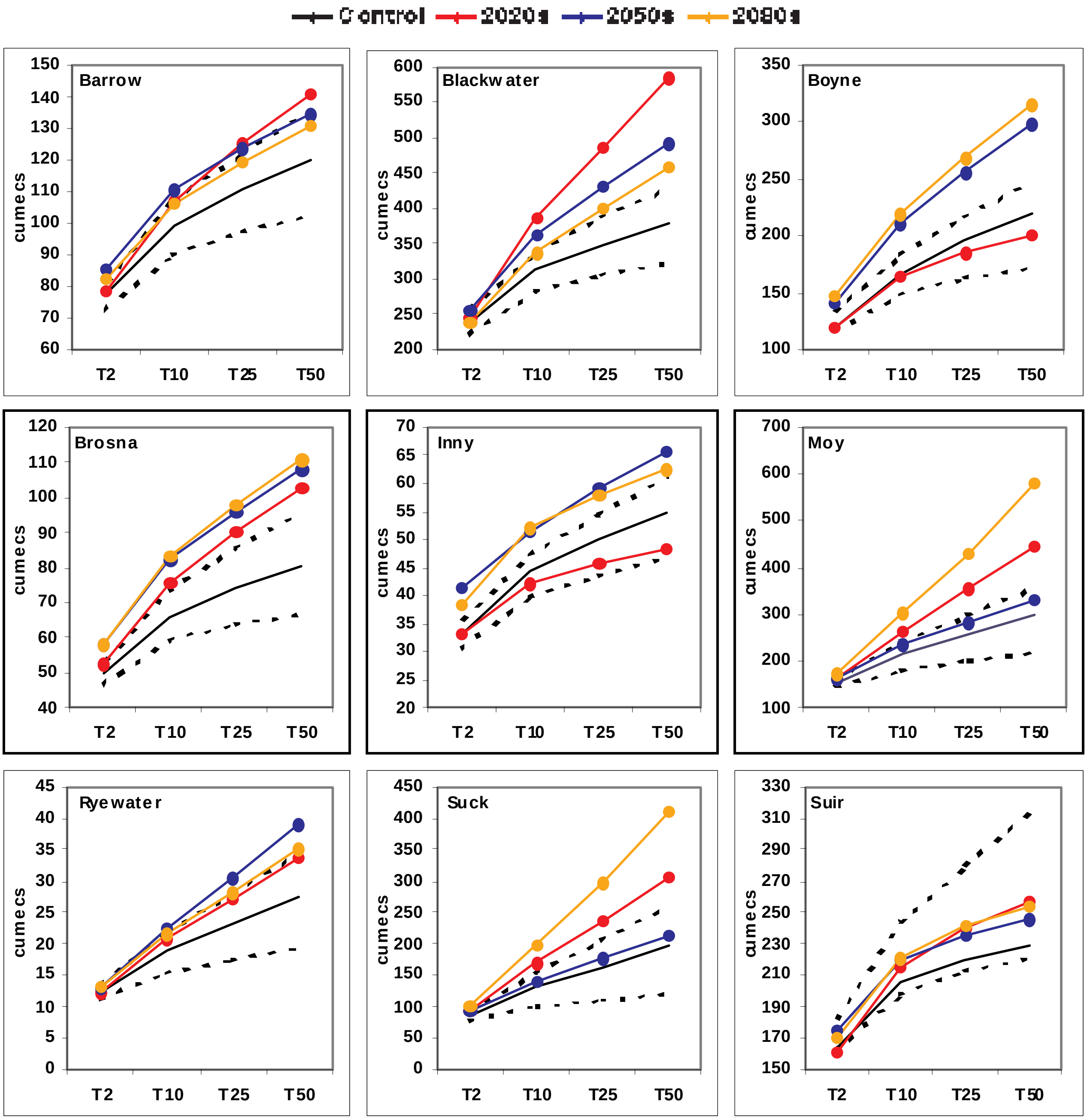

Figure 3.12. Changes in the magnitude of selected flood events for each future time period under the A2 emissions scenario.

catchment, significant increases in magnitude are likely for all return periods by the 2050s and 2080s. Greatest increases are likely for the larger return flows, with the 50-year return period showing a 47% increase by the end of the century. In the Moy, increases in flood magnitude are likely to be greatest during the 2020s and 2080s, while none of the increases suggested for the 2050s are significant at the 0.05 level. Again, greatest increases are associated with the 50-year return period, with an increase of 92% (almost double the magnitude under the control period) suggested by the end of the century. The Suck shows significant changes in flood magnitude for each return period during each time horizon. A similar trend to the Moy is evident, with the 2020s and 2080s showing the most significant increases in flood magnitude. By the end of the century the flow associated with the 25-year flood under the control period is suggested to increase by

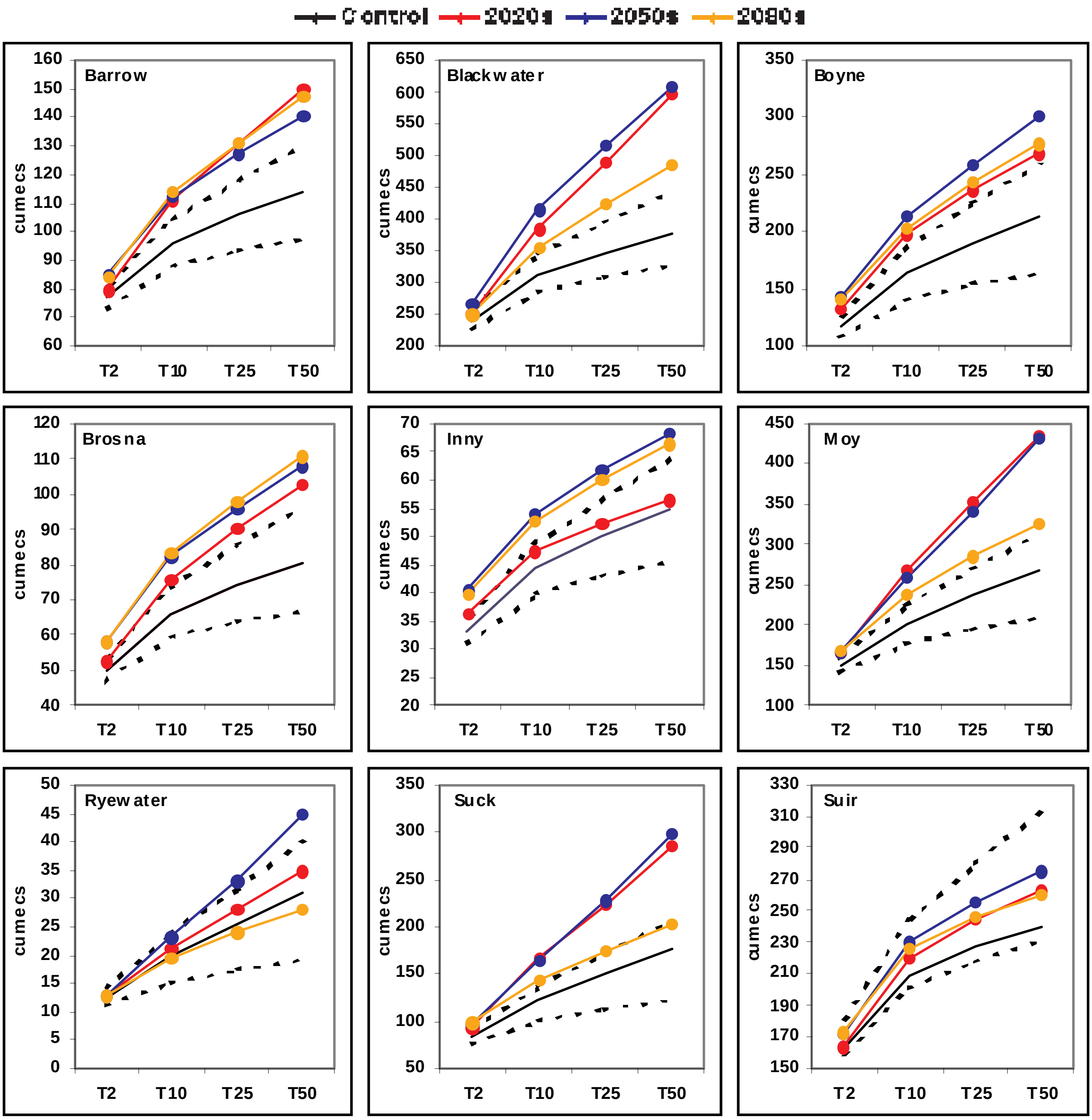

Figure 3.13. Changes in the magnitude of selected flood events for each future time period under the B2 emissions scenario.

64%, while the magnitude of the 50-year flood is likely to almost double, with an increase of 92%. Significant increases in flood magnitude are also simulated for the Ryewater and the Brosna, especially during the 2020s and 2050s; however, increases are not as large as those considered above.

Under the B2 (Fig. 3.13) scenario, greatest changes in the magnitude of flow associated with the return periods analysed are likely for the 2020s. As with the A2 simulations, the dominant signal is towards increased flood magnitude, with the greatest increases likely for flows associated with more infrequent return periods. Greatest increases in flood magnitude are suggested for the Blackwater, Moy and Suck. In the Blackwater, greatest increases are likely by the 2020s, with increases of +44% and +65% in the 25- and 50-year return periods. Increases in flood magnitude

Table 3.5. Percentage change in the magnitude of flow associated with floods of a given return period under the A2 and B2 emissions scenarios. Shaded cells show changes significant at the 0.05 level.

			Barrow	Blackwater	Boyne	Brosna	Inny	Moy	Ryewater	Suck	Suir
T2	A2	2020s	1	3	1	–3	1	6	1	6	–1
		2050s	11	7	18	12	18	7	8	7	7
		2080s	7	0	11	14	22	13	8	13	4
	B2	2020s	3	5	13	4	9	9	5	9	1
		2050s	10	10	22	15	21	11	3	11	6
		2080s	9	3	21	15	19	12	5	12	6
T10	A2	2020s	8	24	–3	–2	–5	24	12	24	5
		2050s	11	16	26	25	17	8	21	8	7
		2080s	7	9	26	16	17	39	15	39	8
	B2	2020s	15	24	21	15	6	29	9	29	5
		2050s	16	33	30	24	21	28	17	28	10
		2080s	18	13	25	25	18	17	0	17	8
T25	A2	2020s	13	40	–6	–2	–9	39	20	39	9
		2050s	12	23	32	34	19	9	34	9	7
		2080s	8	16	37	17	16	64	22	64	10
	B2	2020s	23	44	26	22	5	44	13	44	8
		2050s	20	49	36	30	23	46	33	46	13
		2080s	24	21	28	32	19	20	–3	20	9
T50	A2	2020s	18	56	–8	–1	–11	54	28	54	12
		2050s	12	30	36	42	21	11	46	11	7
		2080s	9	23	47	17	16	92	30	92	11
	B2	2020s	31	65	30	28	4	57	17	57	10
		2050s	23	63	40	34	25	65	49	65	15
		2080s	29	27	32	38	21	23	–6	23	9

become less pronounced through the 2050s and 2080s, although changes remain significant for all but the 2-year return period.

In the Moy catchment, increases in flood magnitude are not as pronounced as those simulated under the A2 scenario. Increases are suggested to be greatest for the 2020s and 2050s. All changes in flood magnitude are significant for each time period. In the Suck catchment, changes during the 2020s and 2050s are very similar, with increases greatest for the 25- and 50-year return periods by the 2050s. Although increases in magnitude are not as pronounced by the 2080s, changes remain outside the limits of sampling error and natural variability. For the remainder of the catchments, the most significant changes are likely for the Barrow, the Boyne, the Inny and the Brosna, with greatest increases suggested for the 2050s and 2080s.

Under the B2 scenario, the least significant changes are for the Ryewater and the Suir. In the latter, while increases are suggested for each return period during each future time horizon, none are significant at the 0.05 level. In the Ryewater, increases are suggested for the 2020s and 2050s, with only the magnitude of the 25- and 50-year return periods showing significant increases. Reductions in the majority of return periods are suggested by the 2080s; however, these remain within the error limits and are thus not significant.

3.6.2 Changes in flood frequency

Because the relationships between return period and flood magnitude is unlikely to be linear, it is important to analyse how the frequency of fixed magnitude events may change in the future (Prudhomme *et al.*, 2003). With this in mind, the frequency of flows associated with each return period during the control was assessed for each future time period. Only the HadCM3 model runs are presented with changes in flood frequency simulated for both the A2 and B2 scenarios. Table 3.6 presents the results for each catchment.

By the 2020s, under the A2 scenario, seven of the catchments show an increase in the frequency of the 2-year flood, with the same flood expected every 1.5 to 1.9 years. The greatest increase in frequency is suggested for the Suck, with a return period of 1.5 years likely by this time. Only the Brosna and the Inny suggest a decrease in frequency, with new return periods of 2.1 and 2.5 years likely. By the 2050s, the

Table 3.6. Changes in the frequency of floods of a given magnitude for each future time period. Results are based on the Hadley Centre climate model (HadCM3) global climate model using both A2 and B2 emissions scenarios.

			Barrow	Blackwater	Boyne	Brosna	Inny	Moy	Ryewater	Suck	Suir
T2	**A2**	**2020s**	1.8	1.8	1.9	2.1	2.5	1.6	1.6	1.5	1.8
		2050s	1.6	1.5	1.4	1.5	1.4	1.5	1.4	1.4	1.7
		2080s	1.3	1.4	1.2	1.3	1.2	1.3	1.5	1.2	1.5
	B2	**2020s**	1.8	1.5	1.4	1.8	1.6	1.4	1.4	1.4	1.8
		2050s	1.6	1.5	1.4	1.4	1.3	1.4	1.7	1.4	1.8
		2080s	1.5	1.5	1.3	1.3	1.3	1.4	1.6	1.4	1.6
T10	**A2**	**2020s**	4.8	3.6	7.1	13.9	12.7	4.2	3.4	4.4	4.4
		2050s	4.8	4.2	3.4	3.4	4.5	4.4	3.3	4.5	6.9
		2080s	3.4	3.4	1.8	2	2	2.2	4.1	2.1	3.2
	B2	**2020s**	3.7	2.6	2.3	4	4.1	2.2	3.5	2.4	4.1
		2050s	4	2.6	3.5	3	3.5	4.6	5.5	5.5	4.1
		2080s	2.9	3.8	2.2	2.1	2.3	3.9	5.4	4.6	2.8
T25	**A2**	**2020s**	8.3	5.1	15.1	39.3	26.4	7.7	5.3	8.8	6.5
		2050s	10.1	7.3	5.6	4.9	7.5	8.5	5.5	9.7	16.9
		2080s	6.7	5.3	2.3	2.8	2.7	3.1	6.9	3	4.7
	B2	**2020s**	5.5	3.2	3	5.6	6.6	3	6.4	3.5	5.8
		2050s	7.7	3.4	6.9	4.5	6.1	10.3	11	14.2	5.8
		2080s	4.6	6.6	3.2	2.6	3.2	8.2	12.8	13.8	3.7
T50	**A2**	**2020s**	12.6	6.5	26.8	85.1	26.4	12.3	7.6	8.8	8.4
		2050s	18.3	11.1	8.2	6.4	10.6	13.9	8.1	17.8	34.4
		2080s	11.5	7.3	2.9	3.8	3.3	4	10.2	4	6.2
	B2	**2020s**	7.4	3.8	3.7	7.2	9.4	3.9	10.2	5.2	7.2
		2050s	13.2	4.1	12	6.1	9.1	19.6	18.5	29.7	7.2
		2080s	6.8	10.1	4.2	3.1	4.1	15	25.5	35.9	4.5

current 2-year flood is expected to occur more frequently in all catchments, with new return periods ranging from 1.4 years in the Boyne, Ryewater and Suck to 1.7 years in the Suir. The frequency of occurrence is further increased by the 2080s, where return periods range from 1.2 years in the Boyne and Inny to 1.5 years in the Ryewater and Suir catchments. Under the B2 scenario, the frequency of occurrence of the current 2-year flood is also likely to increase for all catchments, with a return period of around 1.3 years suggested for the Boyne, Inny and Moy by the 2080s.

Substantial changes in the frequency of the current 10-year return period are also likely. By the 2020s, under the A2 scenario the majority of catchments indicate an increase in the frequency of occurrence, with return periods ranging from 3.4 years in the Ryewater to 7.1 years in the Boyne. Again, both the Inny and Brosna show an increase in the return period, with the current 10-year flood expected once every 13.9 years by the 2020s in the Brosna. The signal becomes more consistent by the 2050s, with increased frequency of occurrence likely in all catchments, with return periods ranging from 3.3 years in the Ryewater to 6.9 years in the Suir. Further reductions in return period are likely by the 2080s, where the current 10-year flood is reduced to a 1.8-year flood in the Boyne. The smallest reductions in return period are likely for the Barrow and Blackwater, where a return period of 3.4 years is simulated. Under the B2 scenario, increases in frequency are not as pronounced. The greatest increases in frequency are indicated for the 2080s, where return periods range from 2.1 years in the Brosna to 5.4 years in the Ryewater.

A similar trend is suggested for the current 25-year flood under the A2 scenario, with an increasing frequency of occurrence likely for all but the Inny and Brosna catchments by the 2020s. For the remainder of the catchments, the return period associated with the same flow ranges from 5.1 years in the Blackwater to 15.1 years in the Boyne. By the 2050s, the return periods are further reduced, with all catchments showing an increase in frequency of occurrence. By the 2080s, the return periods range from 2.3 years in the Boyne to 6.9 years in the Ryewater. Under the B2 scenario, the 25-year flood is likely to increase in frequency for all catchments by each future time period. By the end of the century, return periods range from 3.2 years in the Boyne and Inny to 13.8 years in the Suck.

The final return period considered is the flood expected once every 50 years under current conditions. Unlike the results for the smaller return periods, the frequency of occurrence of the current 50-year return period is likely to increase in all but one catchment by the 2020s under the A2 scenario. Only the Brosna indicates a decrease in frequency, with a return period of 85.1 years suggested. For the remainder, the return periods simulated range from 6.5 years in the Blackwater to 26 years in the Boyne and Inny. By the 2050s, further reductions in return period are indicated, ranging from 6.4 years in the Brosna to 34.4 years in the Suir. By the 2080s, the return period of the current 50-year flood is reduced to less than 10 years in seven of the catchments. Greatest reductions are suggested for the Boyne, Brosna and Inny, with return periods ranging from 2.9 years to 3.8 years. Both the Barrow and Ryewater show reductions of 11.5 and 10.2 years, respectively. The frequency of the 50-year flood is also suggested to increase significantly under the B2 scenario, with all catchments again showing reductions in the return period for each future time horizon. By the end of the century, the return period is reduced to less than 10 years in five catchments, with return periods ranging from 3.1 years in the Brosna to 35.9 years in the Suck.

3.7 Key Future Impacts and Vulnerabilities

3.7.1 Catchment storage

The impact of climate change on subsurface hydrology presents results that vary greatly between catchments and that are largely driven by individual catchment characteristics, with infiltration rates and the ability to hold water limited by the infiltration capacity, the porosity and the type of subsurface material. Reductions in soil moisture storage throughout the summer and autumn are simulated for each catchment. The extent of decreases in storage are largely dependent on the soil characteristics of each individual catchment, with the water-holding capacity of soil affecting possible changes in soil moisture deficits: the lower the capacity, the greater the sensitivity to climate change. The highly permeable soils of the Suir, the Barrow, the Blackwater and the Ryewater all experience substantial reductions in storage, while reductions are not as pronounced for the less permeable Boyne and Moy catchments. This finding is best illustrated through the comparison of results for the Boyne and the Suir. In the Suir catchment, soils are characterised as well drained, with a highly permeable sand and gravel subsoil. Given the poor ability to retain water, large reductions in soil moisture occur during the summer and are extended well into the autumn months. On the other hand, over 35% of the soils in the Boyne catchment are poorly drained and underlain by a less permeable limestone and shale till subsoil. Reductions in soil moisture are not as pronounced and recover much earlier than in the Suir. Reductions in soil moisture of the scale simulated in many of the catchments will have huge implications for agricultural practices, while increased winter and spring precipitation as well as more frequent wetting and drying may affect the nutrient status of many soils. From the results obtained it can be inferred that soil moisture deficits will become more pronounced, as well as begin earlier and extend later in the year than currently experienced. Such projected changes in soil moisture storage may affect key soil processes such as respiration and thus key ecosystem functions such as carbon storage. Furthermore, the increased duration of soil moisture deficits will reduce the proportion of the year that soils act as a carbon sink.

In terms of groundwater storage, lower levels of recharge and thus lower groundwater levels are likely to result in a shift in the nature of groundwater–surface water dynamics for entire rivers (Scibek and Allen, 2005). For each of the catchments, elevated water levels persist into the early summer months. However, from late summer to the end of the year, water levels are generally lower than at present. Given the magnitude of changes for many of the catchments analysed, the possibility exists for low-lying streams to become perched above the water table during times of low groundwater storage and thus lose water to groundwater. Under current conditions, the late autumn and winter recharge period is critical to sustaining groundwater levels throughout the year. For each of the time periods considered, all catchments show longer, sustained periods of low groundwater levels. By mid to late century significant reductions in storage during the recharge period will increase the risk of severe drought as the failure of winter or spring precipitation may result in prolonged drought periods where the groundwater system is unable to recover from previous dry spells. Such impacts would be greatest in catchments where groundwater attenuation is greatest (e.g. the Suir, Blackwater and Barrow).

Changes in the characteristics of winter precipitation may also have significant implications for groundwater recharge. Prolonged rainfall is more effective at recharging groundwater levels; however, climate change is likely to result in shorter, more intense, periods of intense precipitation becoming more frequent, thus decreasing the amount of water that is infiltrated to storage (Arnell and Reynard, 1996). Furthermore, changes in storage within catchments are likely to be highly variable and there is a need to assess impacts for individual regionally important aquifers.

3.7.2 Changes in streamflow

From the results outlined above it can be concluded that the impact of climate change on streamflow is largely determined by catchment characteristics. In general, there are two types of response evident, with the main distinction drawn between catchments with high infiltration rates, where the impacts are dampened by large groundwater storage capacities, and catchments with prevailing surface run-off. Similar results have been highlighted by Arnell (2003), Boorman (2003) and Gellens and Roulin (1998). Characteristic of groundwater-dominated catchments are the small changes in summer streamflow simulated for the Barrow, the Blackwater, the Suir and, to a lesser extent, the Shannon sub-catchments. In catchments where surface run-off is more dominant (the Boyne, the Ryewater and the Moy), changes in summer are much more pronounced.

In each of the catchments, the greatest reductions in streamflow are likely for the autumn months and are thus consistent with the modelled changes in precipitation and evaporation. Although the pattern of change is similar in each of the catchments, there are large differences in the magnitude of change between catchments. For example, average reductions in November range from –26% in the Brosna to –76% in the Ryewater. Largest increases in streamflow are suggested for the winter and spring months. The month of February shows the most significant increases of between +10% and +25%. As a result, flow seasonality is suggested to increase with higher flows in winter and spring, while extended dry periods are likely for summer and autumn. Furthermore, changes in precipitation tend to be amplified within the catchment system with larger percentage changes suggested for streamflow due to the non-linear nature of catchment response.

Changes in the variability of streamflow are also influenced by the role of groundwater in individual catchments. Smallest changes in variability are simulated for the Blackwater, Barrow and Suir. In terms of changes in flow percentiles, there is a large amount of uncertainty depending on the GCM and scenario employed. In general, Q5 is likely to increase under the majority of model runs by the end of the century. However, while the direction of change is largely consistent, there are large differences in the magnitude of change between catchments. Such increases in Q5 are likely to result in increased flooding. Reductions in Q95 are likely to result in more extreme low flows. While considerable uncertainty is evident, greatest reductions in Q95 are suggested for the Ryewater, the Boyne and the Moy. Furthermore, changes in the number of low flow days are likely to have considerable implications for water resources management. In groundwater-dominated catchments, increased contributions to streamflow from groundwater in the summer are likely to decrease the number of annual low flow days. However, where reductions in summer and autumn streamflow are greatest, a significant increase in the number of low flow days is simulated. Such impacts are likely to be problematic for water quality, with less water available to dilute pollution, and for water supply.

3.7.3 Changes in flood characteristics

One of the most high-profile impacts of climate change is on flood frequency and risk, with major areas of concern relating to the integrity of flood defences, planning and development control, urban storm drainage and the implications for the insurance industry (Arnell, 1998). Recent flood events in Ireland have been highly publicised due to the severe economic losses and personal hardships experienced during events such as the November 2000 floods in the east and south-east. From the above analysis, an increase in both the magnitude and frequency of flood events is suggested over the coming years.

Although the results presented above are representative of output from the HadCM3 model or a weighted average response from each of the GCMs, there is a consistent indication that the magnitude of future flood events will significantly increase in the majority of catchments under all model runs and scenarios. Generally, there is little regional variation present in the results, with changes being driven by increases in precipitation and individual catchment characteristics. However, the greatest increases in flood magnitude are suggested for the two most westerly catchments analysed, the Moy and the Suck, where by the 2080s under the A2 scenario, the magnitude of the 50-year flood is suggested to almost double. Greatest changes in the magnitude and frequency of flood events are suggested under the B2 scenario, especially during the 2020s and 2050s. However, by the 2080s there is less difference between scenarios and, indeed, in many cases the most significant increases in flood magnitude and frequency are suggested under the A2 scenario. Greatest change in flood magnitude is associated with the largest floods, with the greatest percentage increase in magnitude suggested for the 50-year flood in the majority of catchments, while the smallest changes are associated with the more frequent 2-year flood.

There are substantial variations between catchments in terms of the time period representative of most significant changes in flooding. Under the A2 scenario, the 2020s represent the most significant increases in flood magnitude in the Barrow and Blackwater, while in the Inny and the Ryewater the 2050s show the most significant increases. In the remainder of the catchments (the Boyne, Brosna, Suck, Moy and Suir), the most substantial increases in flood magnitude under the A2 scenario are suggested for the 2080s. Under the B2 scenario, the time period showing the greatest increase in flood magnitude remains the same for the Brosna, Inny and Ryewater. Under the B2 scenario, the majority of catchments (Blackwater, Boyne, Inny, Ryewater, Suck and Suir) are likely to experience the greatest increases during the 2050s.

The suggested increases in the magnitude and frequency of flood events may have significant impacts in a number of areas such as property and flood plain development, the reliability of flood defences, water quality and insurance costs. Locating development in areas that are susceptible to flooding has led to property damage, human stress, and economic loss in the past. Increases in flood frequency and magnitude in areas currently prone to such damages is likely to increase in the future. Furthermore, given the scale of changes that is suggested, it is likely that areas that are not currently prone to flooding may become at risk in the future, especially areas that are located close to the confluence of major rivers. Furthermore, flood defences are built to design standards based on the probability of occurrence of floods under the current climate. The significant increases in flood magnitude and the increased frequency of occurrence of larger flood events may cause flood defences to fail, resulting in increased flood risk in many areas.

Increases in the magnitude and frequency of flood events as a result of climate change also have the potential to degrade water quality. Increased flood magnitude is likely to result in greater levels of erosion, especially following prolonged dry spells. Consequently, increased sedimentation and greater suspended loads may alter the quality of river water and prove problematic for aquatic life. Furthermore, sedimentation may reduce the capacity of impoundment reservoirs through decreasing the amount of water that can be stored for water supply. Flooding also provides problems for foul sewer systems and the effective functioning of water treatment plants. During times of flood such infrastructure can become overburdened and result in the release of pollutants into watercourses. As well as extreme flow events, precipitation extremes may also impact on water quality through increased soil and fluvial erosion, increasing the amount of suspended solids and altering the nutrient loads of rivers.

3.7.4 Water resources management

In Ireland, both surface water and groundwater are important resources for drinking water supply. On a national level groundwater provides between 20% and 25% of drinking water supplies. However, many counties rely substantially more on groundwater resources, with 90%, 86% and 60% of drinking water in counties Cork, Roscommon and Offaly, respectively, derived from groundwater (DOELG, 1999). Furthermore, in many rural areas not served by public or group water schemes, groundwater is the only source of supply, with many thousands of wells and springs in operation throughout the country (DOELG, 1999). Reductions in groundwater of the magnitude simulated may have significant implications for groundwater supplies. Unfortunately, it is the areas where reliance on groundwater supplies is greatest that the most significant reductions in groundwater storage are suggested. The Blackwater, draining large parts of north Co. Cork, the Suck draining large areas of Roscommon and the Brosna draining large areas of Co. Offaly are all likely to experience substantial reductions in groundwater storage by the middle of the current century, with greatest reductions occurring when groundwater storage is at a minimum.

In terms of surface water, simulations indicate that all catchments will experience decreases in streamflow, with greatest decreases in the majority of catchments likely to occur in the late summer and autumn months, when water provision is already problematic in many areas. However, the degree to which water supply will be impacted will be determined by adaptation measures taken locally. The most notable reductions in surface water are simulated for the Ryewater and Boyne. Unfortunately, these catchments are the most heavily populated in the analysis and comprise a substantial proportion of the Greater Dublin Area. Significant reductions in the Boyne are suggested by the 2020s in early summer and autumn, with reductions becoming more pronounced for each time period considered. By the 2080s, reductions begin in May and persist until October, with greatest decreases of up to –70% in August streamflow by the 2080s. In the Ryewater, reductions are more extreme and persist for longer, with significant implications for water supply by the 2020s, where reductions of approximately –20% are simulated for summer months, while October streamflow is more than halved. By the end of the current century, reductions of –30% are likely in summer, with autumn reductions ranging from –30% to –80%. Such reductions are likely to pose serious problems for efficient and sustainable water supply within the region.

Non-climatic drivers such as changes in population, consumption, economy, technology and lifestyle predominantly govern water use. Over the past decade or so, the Greater Dublin Area has been successful in catering for unprecedented demand growth. However, due to the extent of population growth, water provision within this area is coming under increasing pressure. Taking account of projected population growth, with the population of the region projected to double by 2031, existing primary sources of water supply from the Liffey at Ballymore Eustace and the Ryewater at Leixlip will be unable to cope with projected demands over the coming years. Work is currently under way to supplement sources of water supply in the medium term through the extraction of water from Lough Ree to increase resources in the Greater Dublin Area. Added to this is the fact that non-climatic drivers of water demand in the past will be supplemented by climate change. Herrington (1996) in studying the impact of climate change on water consumption in the UK suggests that a rise in temperature of about 1.1°C would lead to an increase in average domestic *per capita* demands of approximately 5%, with increased demand greatest for personal washing and gardening. Peak demands are likely to increase by a greater magnitude, while the frequency of occurrence of current peak demand is also likely to increase (Zhou *et al*., 2001). From the simulations conducted, it is during times of the year that demand is greatest (summer and autumn) when the greatest reductions in surface water resources are likely. Furthermore, increases in evaporation are likely to result in increased losses from storage reservoirs. It is also important to note that it is not just the domestic sector from which pressures are likely to increase, with agricultural demand being particularly sensitive to climate change. Reductions in soil storage of the extent suggested in many catchments may require the implementation of irrigation practices for particular crops. Furthermore, industrial demands are likely to increase, especially where water is used for cooling purposes. Therefore, increased competition between sectors for declining resources is likely. Obvious then is the fact that water provision is likely to become an increasingly complex task, where even under current conditions demand is projected to be at the limit of projected supply capacity in the Greater Dublin Area by 2015. Serious long-term plans need to be initiated for the sustainable development of water supply within all regions.

Closely linked with issues of water resources management are the likely impacts of climate change on water quality, with the contamination of aquifers, rivers and lakes posing problems for water supply and the sustainability of freshwater ecosystems. The IPCC Third Assessment Report asserts that water quality is threatened from both direct and indirect effects of climate change (IPCC, 2001). Direct effects include issues such as increasing water temperatures and the associated reduction in the dissolved oxygen concentrations of surface waters and the contamination of coastal aquifers from saline intrusion as a result of changes in the water table. Indirect effects are linked to the increased pressure exerted on the hydrological system from anthropogenic factors, such as increased abstractions and discharges from watercourses. In the Irish context, the greatest effects on water quality are associated with drying during the summer and autumn months. Reductions in groundwater storage of the scale simulated in many catchments increases the vulnerability of aquifers to contamination from saline intrusion in coastal areas as well as from the application of domestic, industrial and agricultural effluents to the ground. Shallow, unconfined aquifers are most susceptible to contamination. However, where increased soil moisture deficits result in decreased percolation to the water table, contamination may be prevented (Cunnane and Regan, 1994). Furthermore, the introduction of irrigation practices in many areas is likely to increase the nutrient load and salinity of groundwater.

In terms of surface waters, the reduction in low flows in many catchments will decrease the amount of water available to dilute pollution from both point and non-point sources, while there is a strong relationship between increased water temperatures and the occurrence of coliforms (Peirson *et al.*, 2001; Chigbu *et al.*, 2004). It is therefore essential that effluents to watercourses be closely monitored, especially during the months in which reductions in streamflow are suggested. Indeed reductions in Q95 values in many catchments may require the adjustment of flows used in Integrated Pollution Prevention Control (IPPC) discharge licensing. The increased duration of low flow events will serve to exacerbate the problems mentioned above and may have significant implications for wetland habitats and ecosystems.

3.8 Conclusions

The impacts of climate change on hydrology and water resources are diverse and complex, while each catchment's individual characteristics play a pivotal role in determining the hydrological response to climate change. Although the results for individual catchments should be referred to, a number of general conclusions can be made:

- For each catchment, reductions in soil moisture storage throughout the summer and autumn months are likely. However, the extent of decreases are largely dependent on the soil characteristics of individual catchments: the lower the capacity of soils to hold moisture, the greater the sensitivity to climate change.

- Reductions in soil moisture of the scale simulated may have serious implications for agricultural practices, while more frequent wetting and drying may alter the nutrient status of many soils.

- From the results obtained, it can be inferred that soil moisture deficits will begin earlier and extend later in the year than currently experienced. Increases in the magnitude and duration of soil moisture deficits may affect key soil processes such as respiration and thus key ecosystem functions such as carbon storage.

- Reductions in groundwater recharge and lower groundwater levels during critical times of the year are likely to alter the nature of groundwater–surface water dynamics for entire rivers.

- By mid to late century, significant reductions in groundwater storage during the recharge period will increase the risk of severe drought, as the failure of winter or spring precipitation may result in prolonged drought periods where the groundwater system is unable to recover.

- Greatest reductions in streamflow are likely for the autumn months in the majority of catchments, while greatest increases are suggested for the month of February. However, large differences exist in the magnitude of change simulated between catchments. The greatest reductions are suggested for the Boyne and the Ryewater in the east, while greatest increases are likely for the two most westerly catchments, the Suck and the Moy.

- The seasonality of streamflow is also likely to increase in all catchments, with higher flows in winter and spring, while extended dry periods are suggested for summer and autumn in the majority of catchments.

- In all catchments, Q5 is likely to increase while Q95 is likely to decrease. Changes in the number of low flow days are likely to have considerable implications for water resources management.

- The magnitude and frequency of flood events are shown to increase, with the greatest increases associated with floods of a higher return period. Such changes may have important implications for property and flood plain development, the reliability of flood defences, water quality and insurance costs. There are substantial variations between catchments in terms of the time period representative of the most significant changes in flooding.

- Water quality is likely to be threatened from both direct and indirect impacts of climate change. Direct effects include increased water temperatures and the contamination of coastal aquifers from saline intrusion, while indirect effects relate to increasing demands placed on limited resources from human pressures, especially during times of low flow.

3.9 Adaptation

Water is central to sustainable development. Changes in the quantity and quality of water resources, as well as changes in the frequency, magnitude and duration of extreme events may have considerable implications for society, ecology and the economy, with sectors such as forestry, agriculture, industry, construction, energy, tourism and insurance being highly dependent on a reliable water supply and effective defence from extreme events. Thus, climate change presents both significant challenges and potential opportunities for water management in Ireland. From the impacts and vulnerabilities highlighted above, it is likely that the hydrological response to climate change will be appreciably determined by the capacity of individual catchment characteristics to buffer the suggested changes in precipitation and evaporation. Therefore, in order to successfully adapt to projected changes, strategies must be capable of accounting for the complex processes and interactions that occur at the catchment scale.

Modern approaches to water management have been founded on the ability to react and adapt to changing pressures and demands, with adaptation historically based on reactive measures that are triggered by past or current events, or anticipatory measures where decisions are based on some future assessment of future conditions. While such decision-making practices are unlikely to change in the future, increasing importance must be placed on the anticipation of impacts. Traditionally, such anticipatory measures have been built on the premise that the past is the key to the future. Changing trends in many important hydrological time series, such as rainfall intensity and maximum flood peaks, have introduced non-stationarity, with the result that past events can no longer be relied upon in driving future decision making. Therefore, adaptation to climate change presents new challenges to water resources management, requiring innovative approaches to complex environmental and social problems. In Ireland, there are a number of opportunities for efficient adaptation, some of which are already at the initial stages of implementation and others for which the capacity to adapt is greatly aided by the institutional structures already in place. Over the coming decades, the management of future water resources and the capacity to adapt to a changing climate is dependent on the ability to incorporate both technological and scientific advances into the decision-making processes in an integrated and environmentally sustainable fashion. With this in mind, adaptation should be focused on reducing the sensitivity and increasing the resilience of water resources systems, as well as on altering the exposure of the system, through preparedness, to the effects of climate change (Adger *et al*., 2005)

3.9.1 The role of technology

In the past, the role of technology has been essential in water resources management and is likely to remain so into the future. The emphasis placed on technology in adaptation is largely dependent on economic conditions, policy initiatives and future scientific breakthroughs, with perhaps the greatest potential in water supply management. At present, options such as improved water treatment and reuse, deep well pumping, the transfer of resources between catchments and desalinisation are becoming ever more accessible. Indeed, in anticipation of future resource needs in the Greater Dublin Area, the transfer of water from the Shannon to the east is already under way and provides a novel option to supplement water resources in the medium to long term. At present, the economic cost of desalinisation is too high for it to be feasible on a large scale in Ireland; however, this is likely to change in the future. It is of prime importance that the employment of technology in adapting to climate change be environmentally sustainable, with equity fairly distributed between all resource stakeholders.

3.9.2 Integrated assessment and decision making

Historically, water management has been largely concentrated on the physical control of water and economic cost–benefit analysis, where the allocation of economic worth to many natural resources has been underestimated. On the whole, environmental and social effects have at best been given token consideration, as has the involvement of local communities in the decision-making process (Jakeman and Letcher, 2003). Internationally, the recent shift towards the integrated assessment of natural resources and environmental modelling has resulted in a less narrowly focused and disjointed approach to environmental management. Integrated resource management offers considerable potential to decision making in adapting to climate change. Characteristic of such an approach is the consideration of multiple issues and multiple stakeholders, the ability to further understand the interaction between nature and society, as well as the ability to model the impact of critical decisions over a range of scales. Given the increased availability of spatial data sets, integrated management offers the potential to manage water in a way that meets a broad range of demands and expectations. Furthermore, integrated analysis allows for the quantification and reduction of uncertainty in determining system response. Natural systems, even without human intervention, present considerable difficulties for modellers due to the complexity of natural systems, spatial heterogeneity and the inability to comprehensively measure internal system variables (Jakeman and Letcher, 2003). Integrated assessment allows the perturbation of the system, its inputs and parameters, using likely scenarios of change, so that the impact of decisions can be anticipated and assessed, therefore offering a robust methodology to aid decision making, describe policy impacts and prioritise research needs in adapting to climate change.

3.9.3 Decision making in the face of uncertainty

While the role of integrated assessment is indispensable in adapting to climate change, critical gaps still exist between environmental assessment and the provision of robust information for decision makers and risk managers. Burton *et al.* (2002) highlight a number of reasons for this, with the central issues being the wide range of potential impacts derived from uncertainty in modelling climate change. Such uncertainty exists at every scale and is visible in areas such as likely future development pathways and future emissions of greenhouse gases, uncertainty in modelling complex environmental systems from the global climate system to individual catchment processes, as well as a mismatch in scales between global change and local impacts. In an effort to deal with such uncertainty, impact assessment has evolved to deal with scenarios of change so that a number of possible realisations can be accounted for. Where different scenarios lead to divergent results, decision making in adapting to climate change becomes challenging, with traditional decision-making tools proving inadequate. The focus of international research has thus turned to bridging the gap between impacts and the information required by decision makers. Central to this task is the role of probability through the determination of likelihoods and the construction of confidence intervals for simulated impacts. The ability to attribute probabilities to impacts offers huge potential to decision-making approaches, with risks defined as the probability of hazard times the vulnerability. The use of probabilities in this way offers the potential for decision makers to account not only for the most likely impacts, but also for low probability, high impact surprise events while accounting for the vulnerability of individual stakeholders. The application of probability is especially useful in the water resources sector where managers and engineers already use probabilities in everyday decisions.

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Appendix 3.1

Table A3.1a. Percentage change (%) in monthly streamflow simulated for each catchment in the 2020s using the mean ensemble. Upper (+) and lower (–) uncertainty bounds are also provided.

	Barrow			Moy			Suir			Blackwater			Boyne			Ryewater			Inny			Brosna			Suck		
2020	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**
Jan	0.7	0.5	0.4	4.5	0.1	0.1	0.6	0.8	0.7	–1.4	0.3	0.5	1.0	4.0	1.9	–1.4	1.0	1.2	2.6	0.9	0.5	2.5	0.9	1.1	4.6	0.2	0.2
Feb	–0.3	0.7	0.7	0.9	0.1	0.1	–0.6	1.0	1.0	0.2	0.7	0.8	0.9	1.1	1.1	0.6	0.6	0.5	0.8	0.1	0.1	1.6	0.3	0.3	1.2	0.3	0.3
Mar	8.9	1.0	1.4	3.6	0.0	0.0	7.1	0.7	1.2	9.4	1.4	1.8	7.0	1.6	1.7	11.0	1.9	1.4	4.4	1.5	0.5	5.5	1.0	0.6	4.3	0.2	0.2
Apr	5.2	0.8	1.0	1.7	0.0	0.0	3.0	0.7	0.5	4.9	1.2	1.3	3.1	0.7	0.8	6.9	0.9	1.0	2.9	0.1	0.1	2.1	0.3	0.7	2.5	0.1	0.1
May	1.8	0.5	0.6	0.8	0.2	0.2	–2.3	1.0	1.0	0.9	0.6	0.6	–0.9	1.7	2.0	–4.4	1.5	2.7	1.5	0.4	1.0	–2.0	1.2	2.5	3.1	0.2	0.2
Jun	–0.6	0.8	1.0	–2.5	0.2	0.2	–6.4	2.1	1.0	0.4	1.0	1.2	–5.1	2.4	3.4	–22.3	4.7	8.2	–1.1	0.9	3.3	–6.2	1.6	2.0	1.3	0.5	0.4
Jul	–1.2	1.0	0.8	–4.0	0.5	0.5	–4.6	1.6	1.3	0.4	0.6	0.5	–10.0	7.2	11.7	–17.6	2.5	5.1	–2.4	0.7	2.5	–5.0	1.1	2.3	0.9	0.4	0.4
Aug	–0.7	0.6	0.8	–10.9	0.2	0.3	–3.8	1.0	0.6	0.7	0.5	0.5	–16.1	9.6	16.4	–15.8	2.7	5.0	–4.7	0.6	2.5	–5.9	0.9	2.1	–0.9	0.7	0.5
Sep	–4.4	2.0	2.3	–11.0	0.4	0.4	–8.1	3.7	4.1	–0.6	0.9	0.8	–19.1	7.3	10.3	–24.9	6.3	8.4	–8.0	1.5	4.8	–18.1	3.2	4.9	–11.1	3.7	2.5
Oct	–21.3	3.6	3.4	–6.0	0.0	0.0	–23.0	4.5	4.5	–20.3	5.0	5.2	–15.4	3.2	6.2	–56.8	2.3	3.8	–15.7	4.1	4.8	–12.8	8.1	7.1	–22.4	3.5	3.3
Nov	–12.7	5.9	6.9	–1.9	0.1	0.1	–19.0	8.9	14.1	–10.0	5.2	8.0	0.6	5.2	11.3	–19.2	10.0	11.0	–14.1	2.9	4.5	–5.6	4.8	2.0	–0.6	0.6	0.8
Dec	1.0	0.7	0.7	2.8	0.0	0.0	–1.9	1.2	1.2	2.5	0.6	1.1	–5.5	4.1	4.2	–5.3	3.2	2.5	–2.4	2.3	1.1	0.8	1.5	1.9	2.5	0.3	0.4

Table A3.1b. Percentage change (%) in monthly streamflow simulated for each catchment in the 2050s using the mean ensemble. Upper(+) and lower (–) uncertainty bounds are also provided.

	Barrow			Moy			Suir			Blackwater			Boyne			Ryewater			Inny			Brosna			Suck		
2050	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**
Jan	10.2	0.5	0.4	10.2	0.1	0.2	8.8	0.7	0.6	2.1	0.3	0.5	5.4	6.1	3.3	5.0	1.9	2.0	10.5	2.7	1.0	11.0	1.2	1.2	9.7	0.4	0.6
Feb	17.9	1.0	0.9	10.0	0.1	0.1	15.2	1.4	1.4	10.7	1.0	1.0	15.5	4.5	3.7	13.6	1.3	0.9	14.4	2.3	0.7	14.2	0.6	0.3	10.2	0.1	0.4
Mar	15.8	0.8	0.7	7.4	0.2	0.2	10.7	1.0	0.8	12.5	1.0	1.5	11.4	4.2	4.4	12.6	1.1	1.2	12.9	0.7	0.6	8.4	1.0	2.5	7.5	0.4	0.3
Apr	3.9	1.6	1.7	–1.8	0.1	0.1	–3.1	2.4	1.7	2.3	1.2	1.2	–5.5	2.4	3.7	–4.8	1.7	2.9	4.2	1.5	4.5	–3.1	2.4	3.2	0.0	1.7	1.0
May	3.4	2.5	2.0	–5.2	0.3	0.3	–5.5	3.1	1.5	1.4	1.9	1.6	–12.5	3.7	6.2	–17.9	3.6	5.5	–0.3	1.4	4.7	–8.1	3.4	4.9	–0.1	1.3	0.7
Jun	3.8	1.4	1.4	–10.1	0.1	0.1	–4.9	3.0	2.1	2.5	1.2	1.6	–15.7	7.5	9.0	–34.9	5.8	10.0	–3.7	1.7	5.9	–10.9	3.1	4.7	–1.0	1.3	0.8
Jul	4.5	1.4	1.5	–13.4	0.4	0.4	–2.9	2.4	1.3	2.7	0.8	0.9	–25.3	13.7	20.9	–30.3	4.4	8.2	–7.2	1.4	5.1	–10.9	2.3	5.0	–1.7	1.0	0.7
Aug	5.7	0.7	0.9	–18.6	0.2	0.3	–1.0	1.6	1.3	3.1	0.7	0.8	–36.2	15.6	23.4	–26.8	4.2	7.5	–11.0	1.2	3.7	–13.8	2.4	4.8	–3.9	1.3	0.9
Sep	0.8	2.3	2.7	–27.3	0.6	0.4	–5.2	4.3	4.0	1.3	1.0	0.9	–32.2	9.2	12.7	–31.6	6.1	8.9	–13.6	1.7	4.9	–33.4	7.0	12.5	–16.3	4.7	3.1
Oct	–20.6	4.7	4.4	–15.0	0.2	0.2	–27.0	7.3	6.7	–20.1	5.5	5.7	–16.3	8.2	7.5	–65.1	4.1	3.4	–26.4	3.0	7.1	–31.7	12.5	13.8	–39.4	4.9	5.1
Nov	–11.8	6.3	6.9	–0.3	0.1	0.1	–22.0	10.9	18.2	–9.6	5.2	8.4	7.4	7.6	16.8	–27.0	12.2	13.5	–18.4	5.8	8.6	–6.6	11.4	6.9	–3.5	0.7	1.4
Dec	8.6	0.7	0.9	5.6	0.1	0.1	1.5	1.6	3.3	5.7	0.8	1.0	–1.5	8.5	11.0	–4.6	4.0	3.5	–0.6	5.1	1.6	7.5	1.9	1.8	5.0	0.6	1.3

Table A3.1c. Percentage change (%) in monthly streamflow simulated for each catchment in the 2080s using the mean ensemble. Upper (+) and lower(–) uncertainty bounds are also provided.

	Barrow			Moy			Suir			Blackwater			Boyne			Ryewater			Inny			Brosna			Suck		
2080	%	+	–	%	+	–	%	+	–	%	+	–	%	+	–	%	+	–	%	+	–	%	+	–	%	+	–
Jan	13.8	0.8	1.2	13.6	0.2	0.2	12.3	0.6	1.0	3.0	0.6	1.2	6.7	7.3	3.8	12.9	2.9	2.8	12.4	4.3	1.3	16.0	2.0	1.6	13.0	0.7	1.3
Feb	25.0	1.4	1.4	16.3	0.1	0.2	21.7	2.0	2.4	12.5	1.3	1.5	23.7	6.0	4.8	24.0	1.9	1.4	21.0	4.4	1.4	25.7	1.6	0.9	16.6	0.5	1.2
Mar	16.9	1.1	0.9	10.8	0.2	0.2	10.7	1.5	1.2	9.3	0.9	1.5	14.6	5.8	6.1	17.3	1.2	1.3	17.2	0.9	0.9	11.6	1.5	3.7	10.1	0.6	0.4
Apr	8.4	1.0	0.8	2.1	0.0	0.0	0.6	1.0	0.6	2.4	0.7	0.7	–0.8	2.6	3.7	4.1	1.4	2.1	8.8	1.5	4.3	2.2	2.0	2.5	4.6	1.3	1.0
May	6.3	1.9	1.5	–3.4	0.4	0.4	–4.9	2.9	1.7	0.1	1.7	1.5	–9.5	4.0	6.9	–11.5	3.5	5.7	3.9	1.5	4.8	–4.4	3.5	5.4	4.2	1.2	0.5
Jun	4.4	1.6	1.5	–11.3	0.2	0.2	–6.8	3.3	2.2	–0.5	1.5	1.6	–16.3	9.1	11.2	–31.8	6.4	11.0	–0.7	2.1	7.0	–8.3	3.1	4.2	1.7	1.6	1.0
Jul	3.7	1.8	1.9	–17.9	0.6	0.6	–5.7	2.9	1.4	–0.6	1.3	1.3	–29.9	17.6	25.8	–31.1	5.6	10.6	–5.6	1.9	6.6	–9.3	2.5	5.2	0.0	1.5	1.1
Aug	5.5	1.1	1.1	–29.5	0.3	0.3	–3.2	2.0	1.6	0.1	1.0	1.0	–43.3	19.1	27.4	–27.5	5.4	10.1	–10.3	1.6	4.3	–11.7	2.5	4.2	–2.0	1.7	1.4
Sep	0.9	2.7	2.9	–35.8	0.8	0.6	–6.8	4.5	4.1	–0.9	1.2	1.0	–32.9	9.4	12.9	–32.4	6.4	10.2	–11.9	2.0	5.2	–25.5	4.9	9.0	–16.7	5.6	3.6
Oct	–29.8	6.5	6.2	–20.0	0.2	0.2	–36.0	9.9	9.4	–30.9	7.7	8.3	–14.3	12.0	9.3	–76.0	6.6	4.6	–28.8	2.8	9.0	–26.8	8.8	8.8	–50.9	6.2	6.5
Nov	–27.5	9.4	9.9	–7.4	0.1	0.1	–33.4	12.6	20.4	–23.1	8.4	11.8	3.7	8.9	20.8	–38.0	14.5	16.1	–27.9	8.0	12.1	–13.4	15.1	8.7	–13.6	0.8	1.4
Dec	2.8	1.8	2.4	6.6	0.1	0.2	–6.7	2.6	5.6	–0.2	1.0	1.4	–4.7	12.5	17.1	–9.9	4.6	4.0	–3.6	7.3	2.8	8.8	3.5	3.5	6.9	1.1	2.3

Appendix 3.2

Table A3.2. Student *t*-test results for monthly streamflow simulated using the mean ensemble. The asterisk highlights months for which changes in streamflow are significant at the 0.05 level.

	Barrow			Blackwater			Boyne			Brosna			Inny			Moy			Ryewater			Suck			Suir		
2020	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080
Jan		*	*			*		*	*		*	*	*	*	*	*	*	*		*	*	*	*	*		*	*
Feb		*	*		*	*		*	*		*	*		*	*		*	*		*	*		*	*		*	*
Mar	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Apr	*	*	*	*	*	*	*	*			*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	
May		*	*		*			*	*		*	*			*		*	*	*	*	*	*		*	*	*	*
Jun		*	*		*		*	*	*	*	*	*		*		*	*	*	*	*	*			*	*	*	*
Jul		*	*		*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*		*	*	*
Aug		*	*		*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*		*
Sep	*						*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Oct	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Nov	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*		*	*	*	*		*	*	*	*	*
Dec		*			*		*		*		*	*			*	*	*	*	*	*	*	*	*	*			*

4 Impact of Climate Change on Irish Agricultural Production Systems

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4.1 Introduction

4.1.1 Background

Previous work evaluating climate change impacts on agriculture in Ireland focused on first-order interactions (Fig. 4.1) and mainly considered impacts on plant growth and resulting crop yields (Government of Ireland, 1991; Holden and Brereton, 2003b). While such studies are valuable and are contributing towards global knowledge of potential climate change impacts, they do not offer great insight into the impact climate change may have on agricultural production systems, and consequently the direct impact on peoples' lives.

Evaluating agricultural production systems in the present day is difficult, but making predictions regarding the future is plagued by uncertainty about the climate change forecast, the reliability of simulation model predictions and the socio-economic framework that shapes how we interpret the results. One approach taken is to use stochastic simulation of a farm system in order to look at distributions of possible responses. Gibbons and Ramsden (2005) analysed possible distributions of crop yields with climate change and then found farm management plans that maximised profit for a given yield. They concluded that examining variation is necessary when making recommendations for farmer adaptation to climate change (as is done in this study), but also note that it may not actually be possible to state what the best adaptation to climate change may be. The major difficulties that arise come from the complex interaction of multiple plant species and animal management that constitutes modern agriculture. The approach of Parsons *et al.* (2001) was similar to that taken in this study, but their composite model lacked a dynamic grass model designed for grazing systems and did not consider the role of soil in influencing system interaction with climate change. Their conclusion was that livestock production systems in the UK should be able to adapt with relatively small changes to climate change impacts as forecast at the time of writing (2001).

Modelling a single plant or animal species in terms of its role in an agricultural system is possible (e.g. the

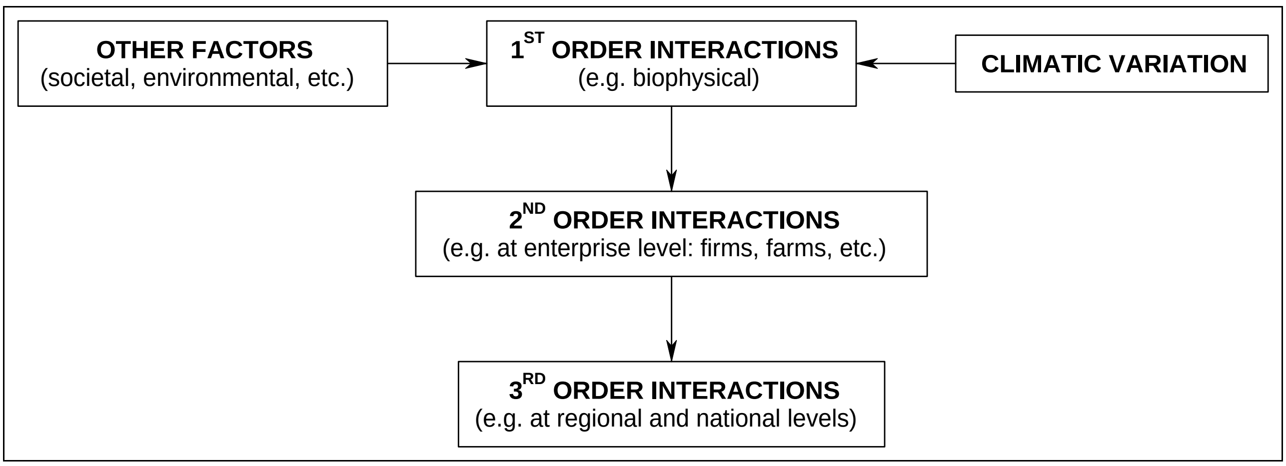


Figure 4.1. The levels of interaction for assessment of climate change in conjunction with other factors (Parry and Carter, 1988).

work of Holden and Brereton listed in the References for this chapter), but trying to formulate a system model that accounts for interactions of the biological, chemical and physical is a much more complex task. In this work, the focus has being on clearly defined problems and attention has being restricted to simulating those aspects of production systems that can be robustly modelled using existing simulation techniques, and to questions that can be addressed with some certainty. The authors have tried to avoid 'general ideas' and 'possibilities' with regard to their analysis of climate change impacts on agricultural systems. Where necessary new model components were developed to facilitate better simulation of climate change impacts and adaptations.

4.1.2 The approach taken

The approach taken in this work was to select example enterprises, with the dominant focus on dairy production, and to look at system impacts rather than primary impacts on yield. A defined hierarchy of levels of interaction was suggested in previous work (Holden and Brereton, 2003b), and initial investigations into climate change impacts considered first-order interactions (Fig. 4.1). For the work presented here, second-order interactions at the production system level were considered, thus focusing not on yield changes but rather on how the change in climate drives adaptation of the system.

The various sections of this chapter present details of:

1. Nitrogen (N) and water interaction, for example arable crops, the results of which are explained in biological terms, which help define the nature of system adaptation that may be required for arable crop production

2. The formulation and testing of a dairy system simulation model, focusing on the production aspects (much emphasis is placed on this phase of the work as the future prediction results are only as good as the system simulation model)

3. Evaluation of the uncertainty associated with driving the dairy system model with data derived from different climate change scenarios and global climate models

4. Integration of the effects of elevated CO_2 into the grass growth component of the system model to better simulate climate change impacts, and integration of a variable soil type model to predict impacts at sites with well-drained and poorly drained soils. The soil component in the system model also allows environmental aspects of the system to be considered, such as restrictions on grass growth, availability of slurry spreading opportunities, volumes of slurry being stored, field access limitations causing additional animal housing requirements and the potential occurrence of drainage events, and

5. Evaluation of adaptations to strategic and tactical system management choices in order to have a viable and productive system of low-cost, grass-based milk production. Consideration was also given to replacing grass forage with maize forage as an adaptation strategy.

4.1.3 The selection of sites for impact and adaptation assessment

The approach taken in previous work undertaken to examine the impact of climate change on crop yields in Ireland (Holden and Brereton, 2003b) was to drive crop models using monthly climatic data (low temporal resolution) with high spatial resolution (10 × 10 km grid over Ireland). For the work presented in this report the climate change data were largely going to be daily data (high temporal resolution) with low spatial resolution (i.e. for a limited number of sites). In order to identify which sites would be useful from an agricultural perspective, a hydrothermal analysis was undertaken to establish a number of agro-climatic zones (Holden and Brereton, 2004). The aim was to derive agro-climatic regions of Ireland using data for the period 1961–1990. The approach taken was to use hydrothermal climate (as expressed by monthly rainfall and mean temperatures) and crop yields in conjunction with a statistical clustering technique. The method integrated crop yield data, estimated using mathematical simulation models for grass, barley, maize, potato and soybean (Holden and Brereton, 2002, 2003a; Holden *et al.*, 2003) with site hydrothermal climate data (Sweeney and Fealy, 2003) in order to derive generalised agro-climatic regions. Sites associated with extremes of growing season conditions and extremes of yields were identified. The climate extreme and average sites were those with:

1. Maximum summer rainfall
2. Minimum summer rainfall
3. Maximum summer temperature
4. Minimum summer temperature
5. Minimum deviation from mean annual precipitation, and
6. Minimum deviation from mean annual temperature.

The sites with minimum and maximum yield for grass, barley, maize, potato and soybean were also identified. After initial analysis of the climographs derived for these sites, locations with February rainfall nearest 48 mm, 70 mm, 76 mm, 93 mm, 108 mm, 120 mm and 150 mm were found in the data set and used as seed values for k-means clustering (Johnson and Wichern, 1992) and a map with seven climate regions was created.

The clusters created from the February rainfall seeds (Fig. 4.2) occupy distinct geographical regions and have clear climate and crop response characteristics:

Cluster 1. East Ulster, East Leinster.
Warm (*c.* 9.5°C) and relatively dry (75 mm) causing water stress in grass, barley and potato, and to a lesser extent in maize.

Cluster 2. Central Connaught.
Moderate temperatures (8.5–9.0°C) and average rainfall (86 mm) resulting in moderate to good yields of grass, barley, maize, potato and soybean. Average conditions with few extremes, little (if any) water stress and few growing season length limitations.

Cluster 3. Intermixed with Cluster 4 in Central Ulster.
Moderate temperatures (8.5–9.0°C) and dry to average rainfall conditions (82 mm) lead to moderate to good barley yield but poor to moderate grass, maize and potato yield. Some water stress limitations.

Cluster 4. Intermixed with Cluster 3 in Central Ulster.
Cool (<8.5°C) and average to wet (92 mm) conditions (cooler and wetter phase of the intermixture of Clusters 3 and 4) result in relatively poor grass, maize and soybean yield, but good barley yield and moderate potato yield. There are some growing season length limitations.

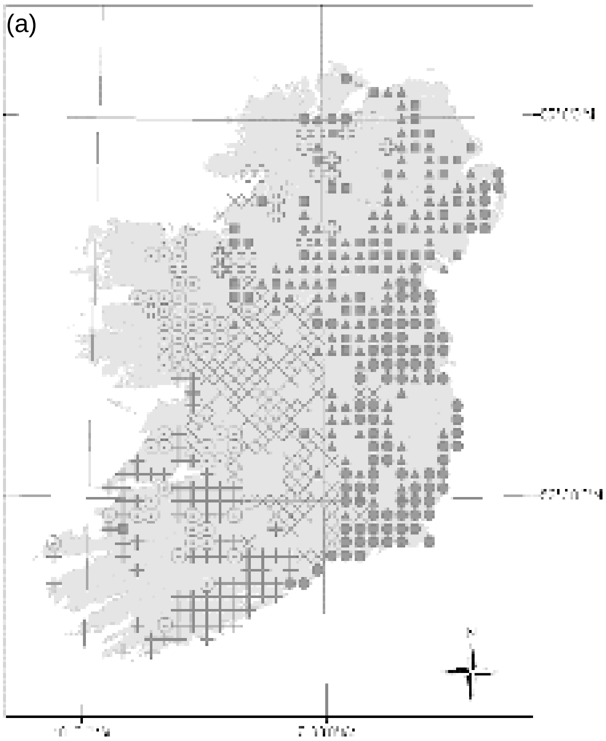
Cluster 5. West Ulster.
Cool temperature (<8.5°C) and relatively wet (105 mm) conditions lead to poor grass, maize and soybean yields but good barley and potato yields. There are some growing season length limitations.

Cluster 6. South and south-west Munster.
Warm temperatures (9.5–10.0°C) and relatively wet conditions (106 mm) lead to good grass, barley and maize yields and provide conditions with potential for crops such as soybean. Potato yield is limited.

Cluster 7. North-west Connaught.
Moderate temperatures (*c.* 9.0°C) and wet conditions (107 mm) permit moderate yields of grass, maize and soybean but good yields of barley and potato. There is a possible temperature/season length limitation.

The climatic mean monthly temperature and rainfall for each of the seven agro-climatic classes (clusters) was compared with similar data for each of the Met Éireann synoptic weather stations (locations marked on Fig. 4.2) as published on the Met Éireann website (http://www.met.ie). Root mean squared error (RMSE) was used to find which synoptic stations most closely represented the climatic distribution of rainfall and temperature. Perfect geographical correspondence was not achieved.

For Cluster 1, Dublin Airport recorded far greater rainfall than was characteristic of the cluster (RMSE = 15 mm/month). Shannon Airport showed the closest correspondence at RMSE = 4.7 mm/month due to the known anomaly of unusually low rainfall for its geographical region. Roche's Point, Rosslare and Kilkenny all showed reasonable correspondence. The



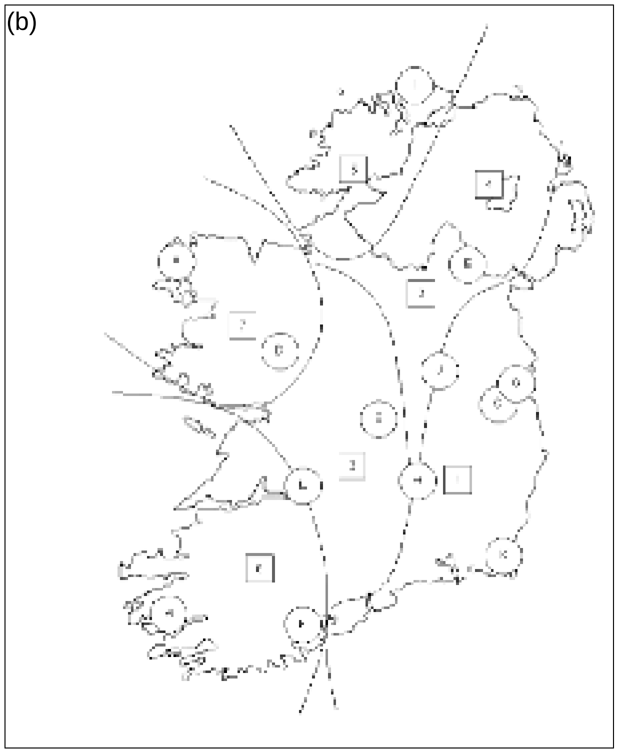


Figure 4.2 Seven agro-climatic regions defined by February rainfall: (a) derived from k-means clustering (● Cluster 1; × Cluster 2; ▲ Cluster 3; ■ Cluster 4; · Cluster 5; + Cluster 6; ⊙ Cluster 7); and (b) generalised interpretation (A, Belmullet; B, Birr; C, Casement; D, Claremorris; E, Clones; F, Cork Airport; G, Dublin Airport; H, Kilkenny; I, Malin Head; J, Mullingar; K, Rosslare; L, Shannon Airport; M, Valentia).

Dublin Airport temperature was most closely related to the Cluster 1 mean monthly temperatures (RMSE = 0.2°C). Likewise for Cluster 2, the rainfall was not well reflected by observation records within the cluster area but temperature was well represented by Birr and Kilkenny. Cluster 3 was well represented by Clones for both temperature and rainfall and Cluster 4 by Malin Head for rainfall and Clones/Mullingar for temperature. A lack of data for the north-west means that this is an incomplete comparison. Cluster 5 rainfall was most closely related to Belmullet and Claremorris (RMSE = 10.6 mm) but was poorly related to the Malin Head record (RMSE = 17.1 mm). Temperature was also problematic, being most closely related to the Claremorris, Clones, and Mullingar records (RMSE = 0.4°C in all cases). Cluster 6 was well represented by Cork Airport, but the rainfall record for Dublin Airport was in fact most closely related. The rainfall and temperature records at Claremorris were in close agreement with the mean values for Cluster 7.

It would be unreasonable to draw specific conclusions from the correspondence between mean monthly values averaged over extensive areas and those from specific observation locations. The general degree of correspondence was reasonably good; however, the results do suggest that the current Met Éireann observation network is perhaps not as well suited to providing data for agricultural applications as it might be. The possible anomalies associated with observations at Shannon and Dublin Airports are particularly worrying in this respect. From these results it was concluded that using baseline and climate change data for the Met Éireann observation network would be acceptable for most of the remaining work presented in this report, but airports have generally been excluded as being non-representative of their geographical locations.

4.2 The Focus on Dairy Production

The main focus of this report in terms of agricultural impacts and adaptations to climate change is dairy production systems. Within the agri-food sector in Ireland, livestock production systems based on grass account for the majority of agricultural land use (Department of Agriculture, Food and Rural Development, 2001) and dairying has been the most profitable farming enterprise for the last 40 years. At the end of 2003, there were almost 1.1 million dairy cows representing over half of the EU dairy herd. Almost all dairy cows are Friesian, averaging about 4,800 l of milk a year (Casey and Holden, 2005). For these reasons most effort was focused on analysis of system impacts and adaptations to climate change with respect to dairy production. One of the most important changes in arable crop management will be centred on fertiliser and water management, so the interaction of these two aspects of tillage farming was investigated in an Irish context.

4.2.1 Irish dairy production

The recommended system of best practice, referred to as the National Dairy Blueprint (the NDB is not formally documentated but described in detail by O'Donovan, 2000) is based on late-winter/early-spring calving with grazed grass as the main source of nutrition during lactation. Silage is harvested in the first half of the growing season for winter feed. The system is essentially closed; only a tenth of nutrients consumed are obtained off-farm (McFeely *et al.*, 1977). Climate has implications for the management system used, such as length of the grazing season and summer soil water deficit influencing stocking rate. In Ireland there is significant regional agro-climatic variation (Holden and Brereton, 2004).

A dairy unit on well-drained soil in the south of Ireland with a stocking rate of 2.5 cows/ha (NDB) using 400 kg N fertiliser/ha annually to produce 13 t of dry matter (DM) grass herbage (silage and grazing) and supplemented by 500 kg purchased concentrates per cow, can yield 16,000 l of milk. Within this system, cows calve in late-winter/early-spring and concentrates are needed to compensate for restriction in cow appetite post-calving and to supplement nutrition from silage until grazing begins in February or March. Grazed grass herbage is the main source of nutrition until October but grazing continues into November, with silage and concentrate supplementation as required. On average, the amount of silage produced in two harvests (May and July) is sufficient to satisfy herd requirements for a 120-day winter housing period. The relative cost of concentrate, silage and grazed grass is approximately 5:3:1, so costs are least when the proportion of grazed grass is greatest. This system represents a strategy for low-cost milk production, and an essential feature is feeding to achieve a target milk yield. Within the system, inter-annual variation in grass availability during the grazing season makes it necessary to adopt tactical feeding responses using concentrates and silage. In the Irish context, an optimum enterprise may be defined as one where, over a period of several years, herd nutrient demand is met by herbage produced on the farm (a function of stocking rate and N fertiliser use), and concentrate use is limited to the amount required to compensate for the physiological limitation of cow appetite after calving. From this definition, the amount of surplus silage accumulated is kept to a minimum as production of excess silage is expensive and reduces profit. A deficit of silage has even more impact because nutrients must be purchased outside the farm system. The proximity of the silage balance to zero (i.e. production meeting but not much exceeding demand) and the amount of tactical concentrates (close to 500 kg/cow/annum) fed over several years provide a measure of how close the enterprise is to optimum performance.

The NDB has been defined for well-drained soil and close to ideal climatic conditions. In order to understand something of the regional impact of climate change on dairy production, it is necessary to examine interactions with:

1. Elevated CO_2
2. Soil type, particularly poorly drained soils, and
3. Spatial variation of climate.

Further to examining whether the system can produce milk efficiently, it is also necessary to examine whether it is viable in terms of the infrastructure requirement (water storage, slurry storage), potential changes in animal diseases, opportunity for nutrient management (absence of pollution transport vectors) and access to land for the purposes of nutrient management (machine trafficability) and grazing (poaching risk). It is also necessary to examine the sensitivity of the system simulation model to the climate scenario data being used to drive the predictions.

4.3 Interactions between Nitrogen and Water Management for Two Example Arable Crops

The impact of possible climate change on the yields of spring barley (*Hordeum vulgare*) and potato (*Solanum tuberosum*) in Ireland has been assessed using statistical and simulation modelling methods (Holden *et al.*, 2003). Model predictions indicated that spring barley would remain a viable crop but that potato might suffer from summer water stress with a resultant loss of yield (Holden *et al.*, 2003). Apart from the impact of climate change on potential yields in Ireland there is a need to understand something of the changes in management that may arise as a result of climate change. Specifically, the demand for nutrient inputs and irrigation water throughout the growing season needs to be assessed because it has significant implications for how production is managed in light of potential yield changes and environmental legislation. The approach taken in this work was to focus on the spatial variability in crop yields that would result from spatial patterns of climate derived from a moderate scenario as opposed to examining the uncertainty associated with predictions from a range of climate change scenarios (IPCC–TGCIA, 1999).

The objective was to investigate, using simulation models, the interaction between changes in water and N demand for two indicative tillage crops that may arise with possible climate change in Ireland. The approach taken was to compare yield responses to N and water supply for baseline (1961–1990) and 2055 (2041–2070) climate scenarios, in areas of Ireland that currently have the highest percentage area of barley and potato production according to Lafferty *et al.* (1999), and then to try to find, using simulation, changes in demand that might occur.

For this work, eight areas sown to spring barley and eight sown to potato that corresponded with the high growing density areas on the maps of Lafferty *et al.* (1999) (locations are indicated on Fig. 4.3) were used. The scenario data used were the best downscaled data available for Ireland at the time of writing (Sweeney and Fealy, 2003). The cells chosen have >16% barley and >9% potato production on an area basis according to Lafferty *et al.* (1999). These areas are currently the most important places for growing barley and potato in Ireland and were selected because any impact of climate change will probably be of most immediate significance to farmers at these locations.

An elevation in CO_2 was assumed by 2055 to 581 ppm CO_2 compared with 365 ppm CO_2 for baseline, which is compatible with the IS95a emission scenario. The simulations of plant growth assumed a relative growth rate at 330 ppm CO_2 of 1 (i.e. growth rate as simulated). Assuming 365 ppm CO_2 during baseline, growth rates were increased by 1.05 for spring barley and 1.02 for potato. The growth rate at 581 ppm CO_2 was increased by 1.2 for spring barley and 1.08 for potato (Tsuji *et al.*, 1994), which represent moderate increases relative to the range of values published in the literature. For the simulation modelling, we assumed no pest and disease effects and no limitations to field access, or significant changes in planting dates (the same approach was taken by Wolf and Van Oijen (2002, 2003)). The results therefore have to be viewed in light of these assumptions; they cannot be regarded as predictions of the future but as indicators of the magnitude of the impact that might occur.

The dominant soil type at each location was estimated by Holden and Brereton (2003b) based on the General Soil Map of Ireland (Gardiner and Radford, 1980). All the barley-growing sites, and most of the potato sites are in areas dominated by well-drained soils, and so a single soil parameterisation was chosen for most of the simulation modelling. The parameterisation was based on the Kellistown Series, a deep sandy loam soil described by Conry and Ryan (1967) as a well-drained grey–brown podzolic (classified as a Hapludalf using *Soil Taxonomy* (Soil Survey Staff, 1999)).

The models used were integrated into the Decision Support System for Agricultural Technology Transfer (DSSAT; http://www.icasa.net/dssat; Tsuji *et al.*, 1994). Having parameterised and calibrated the models, a series of N response curves was simulated using current and future climate data and no irrigation

Figure 4.3. Maps showing the barley (A) and potato (B) crops as a percentage of area farmed. Darker areas represent higher percentages with maximum barley = 57% and maximum potato = 81% (maps adapted from Lafferty *et al.*, 1999). The eight sites where each crop is most commonly grown are labelled.

in order to evaluate the impact of possible climate change on N fertiliser demand. Trials were then undertaken to examine the sensitivity of the crop model auto-irrigation routines to amounts of water applied per irrigation and soil depth for irrigation management. The combination giving maximum yield was then used to evaluate the interaction between irrigation and N under baseline and possible future climates. It was assumed that this approach was compatible with producing high-quality tubers because an ample water supply was always available during the tuber-bulking phase (Shock and Feibert, 2000). Both the spring barley and potato models have automatic irrigation routines that can simulate a range of irrigation options. These work by applying fixed depths (in mm) of water to the simulated soil when conditions within a specified depth of soil fall outside of user-defined ranges. In order to identify the maximum possible irrigation response, each model was tested using various magnitudes of the fixed water depth (5–10 mm) and management depths (150–1,000 mm). The irrigation efficiency was assumed to be 100% and irrigation was triggered when the soil water content in the management depth fell below an average of 50% of the saturated water content. Sprinkler irrigation was assumed in all cases. The automatic procedure uses more water than is perhaps necessary but indicates the magnitude of response that could potentially be achieved by irrigating the crop. Where relevant, a stepwise manual irrigation simulation was performed to estimate the minimum irrigation required in conjunction with N to achieve a potentially profitable yield in the future. This approach to irrigation simulation is analogous to deficit irrigation management, where some water stress is permitted when water is scarce (or competition is high), and an acceptable economic gain might be achieved but maximum yield per unit water is forfeited (Shock and Feibert, 2000). Finally, some simulations were run with a modified soil parameterisation to represent a heavier (non-ideal) soil.

4.3.1 Non-irrigated nitrogen response curves

The spring barley N response curves for most sites were quite similar (Fig. 4.4). The baseline climate response curves were similar to those of Conry (1997). Yields at higher applications rates were similar for both field observations and model prediction. In general, there were relatively small differences between the N response curves predicted for baseline climate and 2055 climate except for Sites 1, 3 and 8, which have more marked increases in yield than elsewhere at N rates greater than 50 kg/ha. The response in these areas can be attributed to the relatively high growing-season rainfall that is maintained in these locations. At 125 kg N/ha the spring barley yield response to growing season rainfall was very similar to that found by Holden and Brereton (2004); the sites with the lowest rainfall have the lowest grain yield. With climate change, the response is to achieve a similar yield with less rainfall because of elevated CO_2 (Sœbø and Mortensen, 1996). The N response curves indicate that where growing season rainfall is not too low, a reduction in recommended N rate may be possible without increasing the risk for farmers, and elsewhere the N management guidelines will be unaffected by climate change. A similar conclusion can be drawn from the results of Kleemola and Karvonen (1998) from a modelling study in Finland.

The potato N response curves (Fig. 4.5) (very similar to the data of Shepherd (2000) for typical UK production) indicate three types of response to climate change:

1. Little change, with a good yield response as found at Site 1 in Donegal
2. Little change with a poor yield response as found at Site 7 in Wexford, and
3. A marked decline in yield.

Site 8 in Cork falls between that of Donegal and the marked yield decline found elsewhere in the country. The available rainfall in the growing season can explain the N response; as available water decreases so does crop yield. At Site 1 in Donegal, there is a decrease in rainfall but there is still sufficient for a good yield. In Wexford at Site 7, there is little yield response to climate change because the yield is low under baseline conditions. In Cork at Site 8, there is a decrease in rainfall that only has an influence when there is a good supply of N to ensure full canopy development.

With climate change the target of 30 t/ha (wet weight) or 6 t/ha (dry weight) of tuber yield will be very difficult to achieve in the eastern and southern parts of Ireland without irrigation. Any potential gains in yield from elevated CO_2 (Finnan *et al.*, 2002) are negated by the water stress that occurs (van Loon, 1981). Alva *et al.* (2002) found between 10 and 25% tuber yield decrease in the Pacific Northwest region (USA) as a result of water stress, which is broadly consistent with the results of this simulation study.

4.3.2 Irrigation response

Testing of the auto-irrigation component of both models indicated that the depth of water applied at a given time step had no influence. This was because the soil was parameterised to be free-draining, with a large pore volume. An application rate of 10 mm/step was used. The soil depth for irrigation management for maximum yield response was found to be 300 mm for spring barley and 500 mm for potato. While irrigation is not necessary for spring barley, the irrigation response (Fig. 4.6), averaged over the eight areas investigated was established to help understand what role irrigation could play in future spring barley management. The N response curve showed a marked change with irrigation, the most important feature of which was a loss of sensitivity to N application rate. This suggests that if small amounts of irrigation were used in the future then the amount of N needed could be significantly reduced. The curves for irrigation response in potato (Fig. 4.7) indicate why it was difficult to achieve a calibrated yield without irrigation and why the N rate had to be greater than recommended. A marked irrigation response can be seen, but unlike spring barley the N response is still clearly visible. Meyer and Marcum (1998) found that the N response with irrigation was dependent on the soil N from the

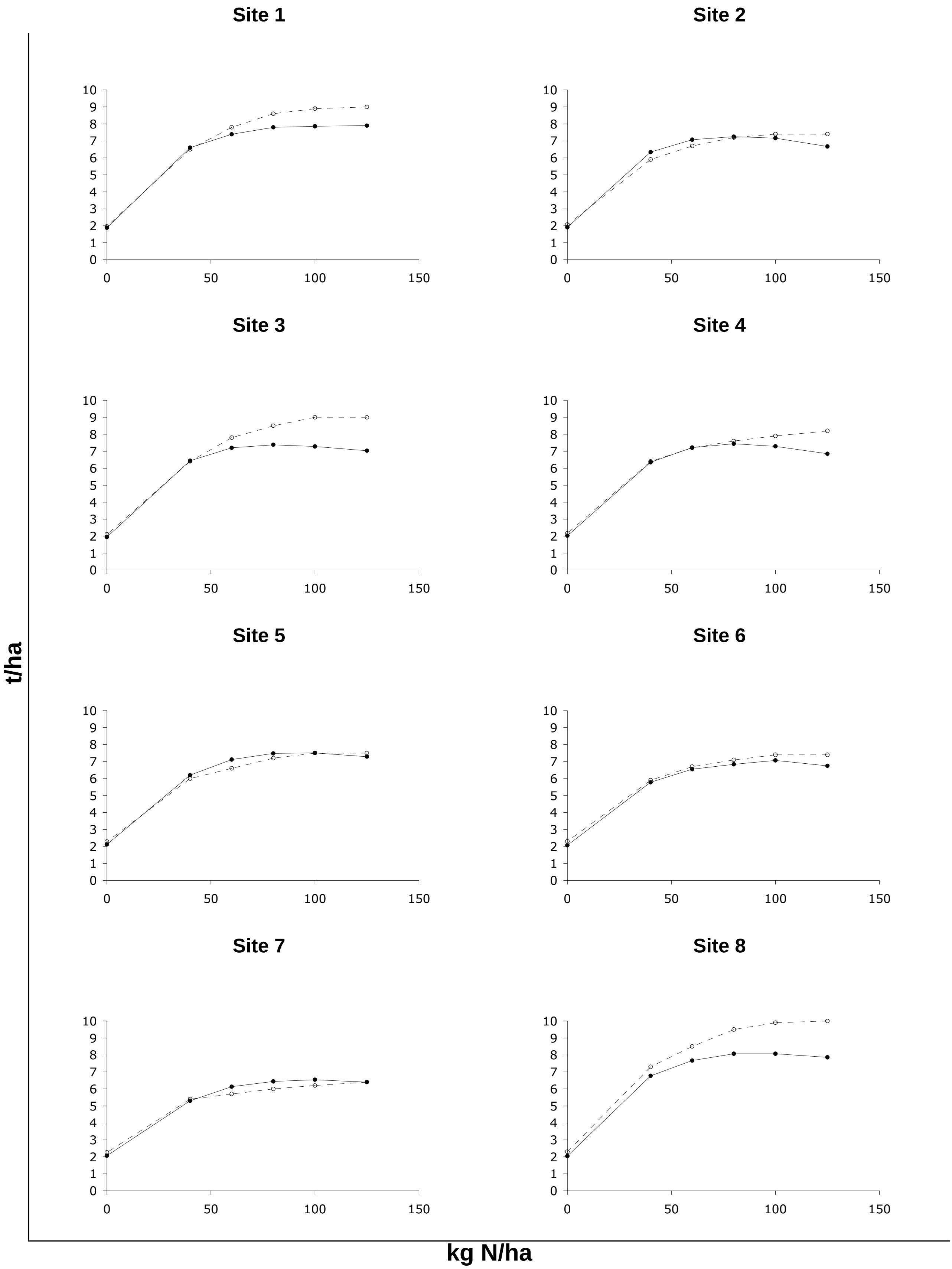


Figure 4.4. Non-irrigated, barley yield (t/ha) nitrogen (kg N/ha) response curves for eight sites with high rates of spring barley production – baseline (●) and 2055 (○).

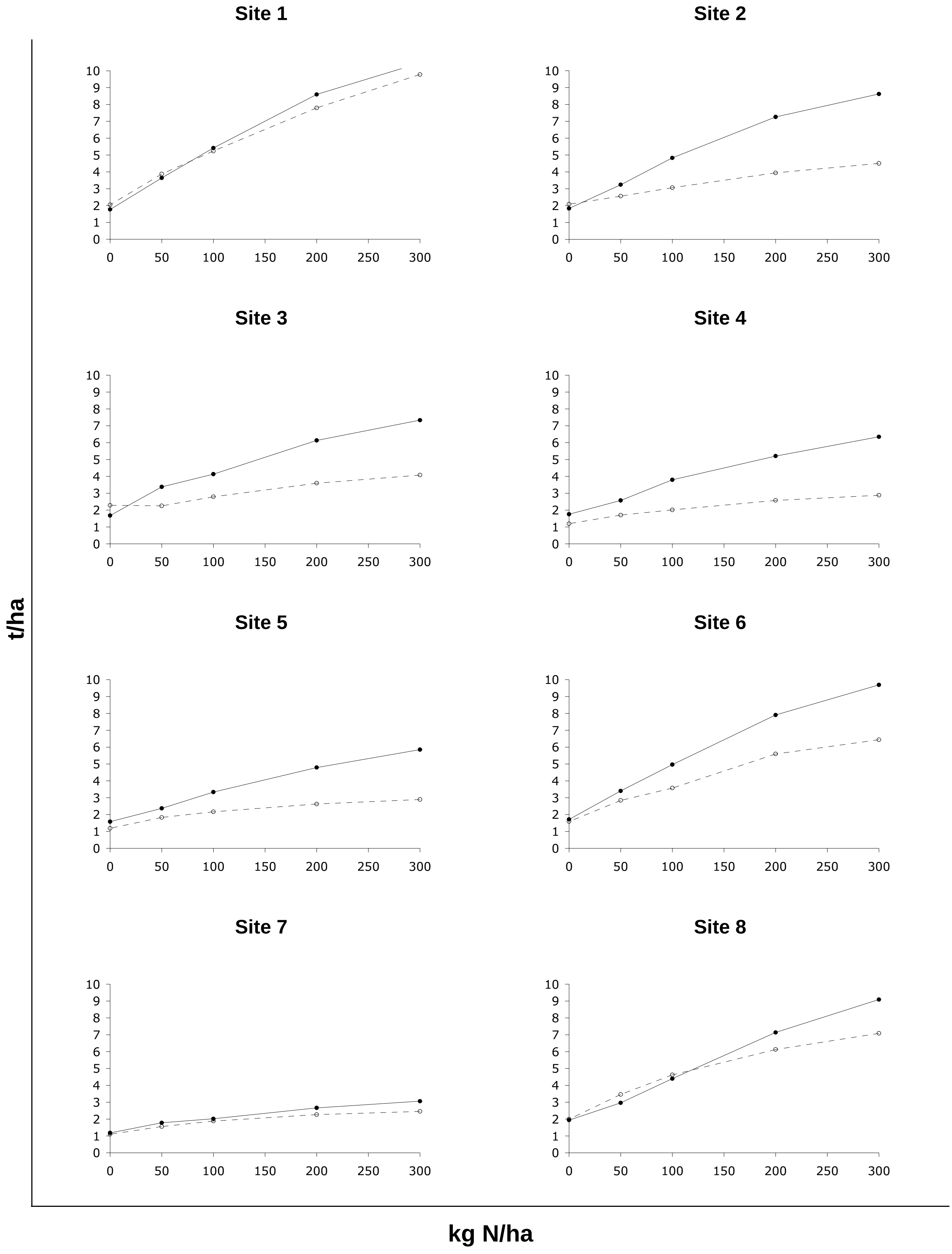


Figure 4.5 Non-irrigated, potato yield (t/ha) nitrogen (kg N/ha) response curves for eight sites with high rates of potato production – baseline (●) and 2055 (○).

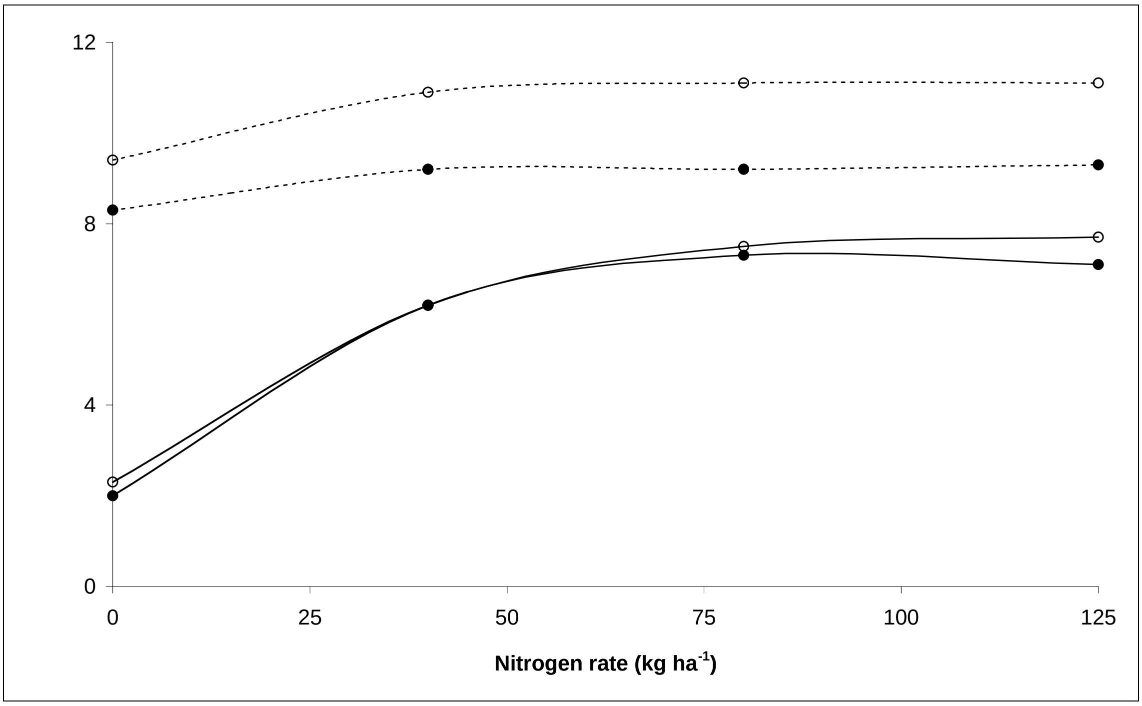


Figure 4.6. The nitrogen response with and without irrigation for barley averaged over the eight sites where the crops are most commonly grown. (Baseline: solid circle; 2055: open circle; irrigated: dashed line; non-irrigated: solid line.)

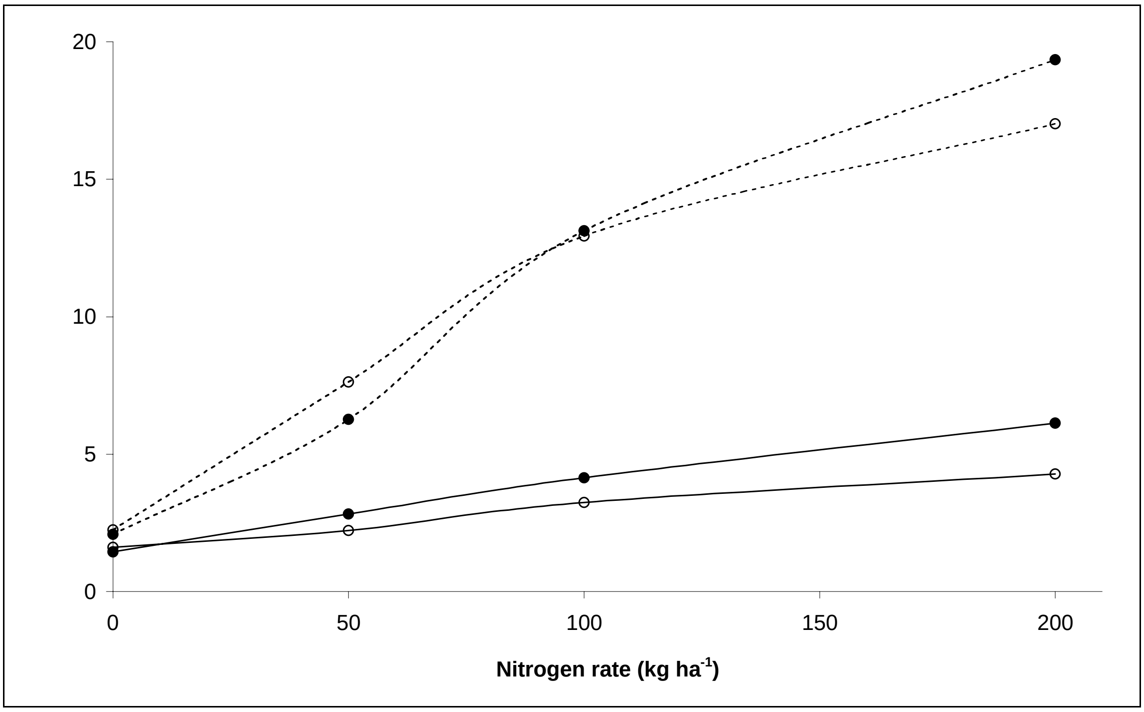


Figure 4.7. The nitrogen response with and without irrigation for potato averaged over the eight sites where the crops are most commonly grown. (Baseline: solid circle; 2055: open circle; irrigated: dashed line; non-irrigated: solid line.)

previous year. In the simulations of potato at sites in Ireland, the soil N index was always assumed to be for low available soil N, so a clear N response with irrigation is consistent with expectation. These results should be viewed in light of the assumptions stated at the outset. There is a possibility that changes in planting date, pests and diseases could influence detail of water demand during the growing season, but are unlikely to negate the results.

The reason why N application can be reduced with climate change and irrigation is related to elevated CO_2. There is more efficient assimilation of CO_2 to plant structures with elevated CO_2, which results in a lower relative leaf N content (Penuelas and Matamala, 1990). This response is simulated in the models as a growth rate change with elevated CO_2, and means that for a given amount of N uptake there will be a greater amount of carbon stored in the yield component of the plant. Therefore to achieve a profitable yield it is possible to use less N provided the plant is not limited in other ways. With climate change, if water stress occurs there will be reduced active root uptake of water and thus a wilting response (possibly including heat stress due to closed stomata) will occur that overrides the growth rate response and will cause a reduction in the yield component of the plant due to a reduced fully functioning leaf area and possible acceleration of reproduction. Therefore to benefit from reduced N fertiliser rates it is necessary to ensure that water stress is not an issue. The difference in response between spring barley and potato is also related to their seasonal cycles. Spring barley has a good resistance to water stress because it has early development and an extensive root network so by summer has the ability to utilise limited water supplies throughout a relatively large volume of soil (Lopez-Castaneda and Richards, 1994), thus maintaining an increased growth rate relative to N uptake. Potato on the other hand has a demand for water during tuber bulking, which is when water stress is more likely to occur and thus the yield component of the plant suffers restricted development.

Examination of the site-specific detail of irrigation response indicates that there are marked differences in response to irrigation in the various areas where spring barley is currently most commonly grown. In general, an improvement in water-use efficiency (WUE) was found in line with general expectation (van de Geijn and Goudriaan, 1996). At 125 kg N/ha, the irrigation response under baseline climate was most marked for areas that can suffer summer water stress (Sites 5, 6, and 7). Elsewhere the return per mm of irrigation provided was around half the efficiency of the water supplied by rainfall. At the lower N rate (60 kg/ha), a benefit of irrigation was simulated for each area, and the irrigation WUE was up to twice that of the rain-fed crop. A substantial benefit from irrigation is simulated when only 60 kg N/ha are used; in fact the simulated yield with irrigation at the lower fertiliser application rate is equal to the yield at the higher fertiliser rate without irrigation. This suggests that with climate change the combination of elevated CO_2, leading to improved WUE (Kimball *et al.*, 2002), and the supply of irrigation water would permit large reductions in fertiliser use.

Based on the simulations in the eight areas where barley is currently most commonly grown, if the relative value of the spring barley crop remains similar to present, then production will remain viable in all these areas. There is a likelihood that Area 7 will become subject to more frequent water stress however, and this could lead to increased risk of poor yields. In the other areas, the yield of spring barley will increase above the current economic threshold and in these areas a reduction in N usage could be viable even without resorting to irrigation.

Site-specific evaluation of the simulated automatic irrigation of the potato crop indicated that even under baseline conditions the potato crop is not operating at best WUE. The change in WUE is not as marked as for spring barley. There was a marked improvement in yield for both fertiliser rates under both baseline and 2055 climate. An examination of the yields suggested that the potato growing areas in Donegal and Cork could still maintain viable yields without irrigation provided a high rate of N is applied. However, if some irrigation is used, the N rate could be reduced by half to maintain good, viable yields (relative to the current economic threshold suggested by Bell (1999)). Increasing the N rate to 200 kg/ha improves the WUE, but raises the issue of the environmental desirability of high N application rates in conjunction with the supply of irrigation water that could lead to excess run-off or leaching (e.g. Peralta and Stockle, 2002). The site in Wexford appears to be unsuited to potato because of the water demand even under baseline conditions.

In the case of potato production with limited water stress and adequate N availability (200 kg N/ha), the effect of CO_2 fertilisation combined with change in climate is to increase yield by 1–2 t DM/ha, but when N rates are lower little effect is seen, except at Sites 1 and 8. The results suggest that management will be very important if any benefit from climate change is to be accrued (as found by Meyer and Marcum, 1998). When compared with data presented by Miglietta *et al.* (2000) the reduction in yield predicted for non-irrigated potato in Ireland is more marked than that predicted for elsewhere in Europe but the response to irrigation is broadly similar to that predicted for sites in northern Europe (as compared with southern Europe).

The regional changes that are predicted to occur range from little change in Donegal, where summer water stress does not become an issue, to signs of water stress in spring barley in Wexford and a likely exclusion of potato because of the excessive water demand linked to poor utilisation efficiency. In north Dublin, Meath and Louth there is evidence to suggest that potato may suffer water stress but spring barley will survive well.

The introduction of a common European water pricing policy as an economic instrument to regulate the environmental impact of water extraction (Water Framework Direct 2000/60/EC of the European Parliament) could have a significant impact on irrigation management by imposing an increased cost for the use of irrigation water (Gómez-Limón and Riesgo, 2004). In the south-east of the country there will be a marked decrease in summer rainfall (Sweeney and Fealy, 2003) so infrastructure will be required to store winter rainfall if irrigation were to be used. The economic viability of such investment will depend on the market value of the spring barley in 25–50 years time compared with other production costs and water pricing.

4.3.3 Management changes with climate change

The simulation data suggest that for both spring barley and potato a reduction in N usage will be possible with the change in climate. The data suggest that the fertiliser application rate for spring barley could perhaps be halved by 2055 thus resulting in:

1. A reduction in leaching losses (Peralta and Stockle, 2002)
2. A reduction in greenhouse gas emissions (Kramer *et al.*, 1999)
3. A reduction in the fertiliser trade, specifically of imports (there is evidence in Coulter *et al.* (2002) that this trend is already starting), and
4. Less difficulty complying with environmental legislation due to a decrease in N required to achieve an acceptable crop.

For the potato crop, a halving of N application rates could be achieved but only if irrigation water is used. The important question is: what is the minimum irrigation amount (minimising run-off risk) needed to achieve a viable reduction in N application while maintaining a profitable crop yield?

A stepwise manual irrigation strategy was used to estimate the irrigation requirements for potatoes grown with 100 kg N/ha in the 2055 period. From a situation where no site in the country could achieve a viable yield (assumed to be 6.0 t DM/ha, Bell (1999)), with just 90 mm irrigation viable yields were achieved in Donegal (Site 1), south Kilkenny (Site 6) and south Cork (Site 8). In Meath (Sites 2 and 3) 160 mm of irrigation resulted in sufficient yield and for north Dublin (Sites 4 and 5) 220 mm were required. For the area in south Wexford (Site 7), 310 mm of irrigation were needed to achieve a viable yield. In general it can be concluded that of the areas where potatoes are commonly grown, production is unlikely to be sustainable in Wexford, but in Donegal and Cork production will be possible without irrigation provided that high N rates are used. Elsewhere production can shift to a lower N usage when supplemented by irrigation.

Simulation trials using parameterisation for a heavier soil conducted for the north Dublin area (typified by heavy soils, see Table 4.2) suggest that even with 310 mm of irrigation, yields will be as low as 5.6 t/ha with 100 kg N/ha or 7.6 t/ha at 200 kg N/ha. This is because of a large increase in run-off loss (*c.* 260 mm compared with 10 mm for the ideal soil) as simulated by the soil model used. To achieve continuing viable yields field drainage will have to be carefully managed, and because of the greater seasonality of rainfall (Holden and Brereton, 2003b), in order to extract the harvest from the field it will perhaps be necessary to harvest earlier in the year.

4.3.4 Conclusions

It can be concluded that there will be no major changes necessary in order to maintain spring barley production with similar spatial distribution as currently found. It is possible that water stress risk in the south-east could make spring barley a less desirable crop in this region. Where rainfall remains adequate by the 2050 climate period it is probably going to be possible to reduce the N application rates currently recommended, perhaps by as much as half.

For the potato crop the simulations result in the conclusion that irrigation is going to be essential in most areas where potatoes are currently grown. Donegal and perhaps south Cork may not need irrigation but N application rates will be high to compensate. For most places where potatoes are currently grown between 150 and 300 mm of irrigation water will be required every year, but this will mean that the N application rates can probably be halved. In areas where potatoes are grown on heavier than ideal soils (e.g. north Dublin), lower yields can be expected and if irrigation is used, run-off losses could be greater thus increasing pollution risks. If heavy soils are used, significant investments in drainage and soil structure management will be required to achieve viable yields without undue water wastage and possible pollution.

4.4 Dairy System Simulation

4.4.1 Background

In order to simulate a low-cost grass-based dairy production system three main process models are required:

1. Animal nutrient demand
2. Herbage production, and
3. Herbage utilisation.

These have to be integrated using a number of management controls. The main components of the system simulation (outlined below) were combined into a dairy system simulation model called *Dairy_sim*. The herbage model (the Johnstown Castle Grass Model) has been shown to reliably predict herbage growth of grass in Ireland (Brereton *et al.*, 1996; Brereton and O'Riordan, 2001). The model is based on the equation by Penman (1971). The formulation of the model is described in Brereton (1981). The herbage utilisation model (Grazedown) is described in detail by Brereton *et al.* (2005). In a rotational system of pasture utilisation, the herbage mass in each paddock is progressively decreased by grazing over a period of days. As the herbage mass is depleted, the state of the sward changes. Sward height is reduced, sward bulk density increases and the proportion of leaf lamina in the herbage mass decreases. The feed demand model was based on the metabolisable energy (ME) system developed in the UK for allocating energy allowances for ruminants (MAFF, 1984). It estimates very well the nutrient requirements of the typical Friesian cow, which is most commonly used in Irish grass-based dairy production. Complete descriptions of the model components can be found in Fitzgerald *et al.* (2005) and Brereton *et al.* (2005).

4.4.2 Management control

When using *Dairy_sim* there are four types of information required before the simulation can begin. These are:

1. Farm location
2. Farm layout
3. Herd data, and
4. Farm management.

The geographical location of the farm determines climate. The locations used in this study were those of synoptic weather stations. Farm layout is not spatially explicit, rather farm area is subdivided into paddocks by the user. The starting date for simulation and initial paddock herbage mass are also defined. In the herd data section, the stocking rate, lactation yield, live weight post-calving and daily feed demand as herbage DM equivalent (ME = 12.1 MJ/kg) are defined.

February calving has been assumed. The management data section defines the fertiliser programme for the farm throughout the year and the silage management, i.e. the area devoted to first- and second-cut silage and the dates of silage harvest. The simulation time step is a half-day. The sequence of events during the simulation cycle is illustrated in Fig. 4.8. Important simulation assumptions include:

1. Only milking cows fed to achieve full lactation milk yield are considered

2. The grazing paddock with greatest herbage mass is always the next one used during a rotation

3. When mean daily intake falls to less than 1.2 times the rate of the current daily herbage intake demand, the herd exits a paddock

4. Silage paddocks are never grazed until they are reallocated after harvest, and

5. Exploitation of paddocks is never limited by soil trafficability (this assumption is addressed later in the report).

The **strategic management** options available in *Dairy_sim* are stocking rate, N application rate and silage management. These are set by the user, and mimic the annual plan developed by a farmer.

The criteria that govern **tactical management** are set at the start of the simulation. These are short-term management options in response to fluctuations in herbage availability, which is governed by day-to-day weather. Mean herbage mass (always representing mass above 5 cm in *Dairy_sim*) in the grazing area of the farm determines the level of supplementation, housing in periods of herbage deficit and harvesting of baled silage from the grazing area in periods of herbage surplus. The decision-making process means that when mean herbage mass falls below a critical value for supplementation (500 kg DM/ha by default),

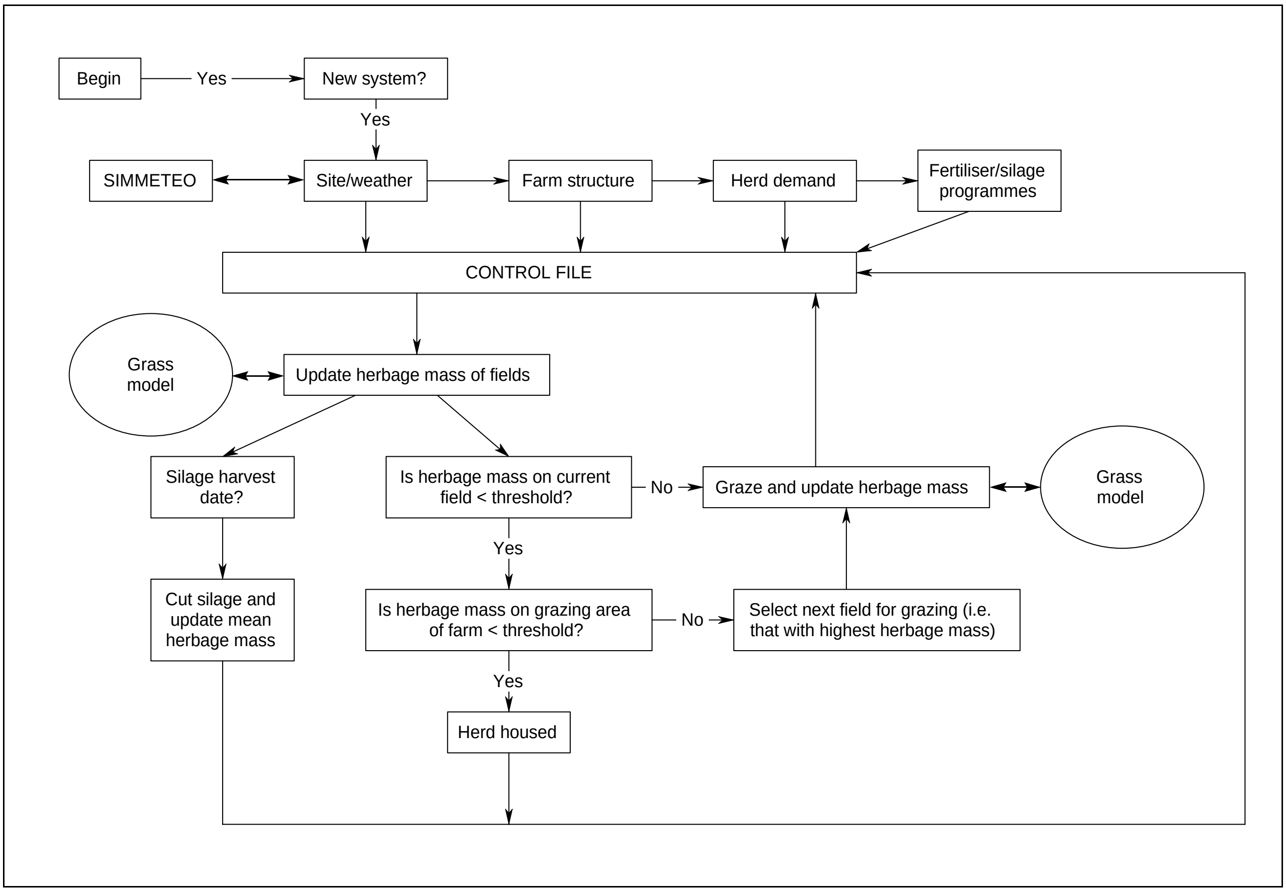


Figure 4.8. Sequence of events during dairy system simulation in *Dairy_sim*.

supplementation is introduced as a fraction of the current feed demand. If supplementation exceeds 0.75 the herd is moved. If current milk yield is less than 10 l/cow daily then the supplement is provided as silage, otherwise the supplement is provided as equal quantities of silage and concentrates. When mean herbage mass in the grazing area exceeds a selected critical value (1,750 kg DM/ha by default), baled silage is removed from the paddocks with greatest herbage mass until mean herbage mass falls below the critical value. The herd is housed during the grazing season if mean herbage mass of the grazing area and the herbage mass on the paddock selected for grazing are both less than critical values. The default critical value of mean herbage mass of grazing area is 500 kg DM/ha and for critical paddock herbage mass is 0.5 of the current daily herd feed demand.

To avoid intermittent grazing during winter as herbage accumulates and the mass on individual paddocks increases, the housing criteria may be overridden and housing 'forced' for a period. The period is defined according to the pattern of availability of herbage at the end and beginning of the grazing season.

4.4.3 *Parameterisation, testing and sensitivity analysis*

Dairy_sim was parameterised by setting up the NDB system (Table 4.1) (O'Donovan, 2000) in the model, i.e. a farm system with the stocking rate, fertiliser applications and silage management recommended by the NDB was simulated and the management parameters (area dedicated to silage, dates of silage harvest, pattern of fertiliser application throughout the year and stocking rate) and the tactical response criteria (minimum average grass herbage mass before animals are housed and the period for which winter would be 'forced') were adjusted until there was good agreement between the outputs of the simulated system and the outputs of the system that operates at the Teagasc Research Centre, Fermoy, Co. Cork (O'Donovan, 2000). This was a delicate balance involving expert intuition to adjust the tactical response criteria involved in the model without compromising the dairy production system. The object of these adjustments was to balance stocking rate and silage harvest without compromising grass supply during the spring and summer months just as a farmer would.

Table 4.1. The National Dairy Blueprint (NDB) as described by O'Donovan (2000) as the basis for dairy unit rotational grazing management in Ireland.

Location	Fermoy, Ireland
Paddocks	20
Farm area	20 ha
Closing date	26 November
Stocking rate	2.6 cows/ha
Milk yield	6,400 l/cow/year
Live weight	610 kg
Total nitrogen applied	360 kg N/ha
Area of farm used for first-cut silage	9 ha
Area of farm used for second-cut silage	7 ha
Date of closing for first-cut silage	1 April
Date of closing for second-cut silage	28 May
Date of Cut 1	27 May
Date of Cut 2	15 July

The fine-tuning of the parameterisation was achieved by calibration after setting the strategic management variables to values equal to the NDB and by progressively adjusting the thresholds for field supplementation, housing and for removal of surplus herbage as baled silage. The inputs and outputs of the production system at Fermoy as described by O'Donovan (2000) and the average inputs and outputs of 30 years simulated by *Dairy_sim* were very similar (Table 4.2). All parameters had realistic values after calibration, and the simulation was a good reflection of dairy management practised in the Fermoy area of Co. Cork.

The system simulation was then tested by comparison with field data from four system trials carried out at the Teagasc research farm at Solohead in Co. Tipperary (Humphreys *et al.*, 2002). There were major differences in management between the systems. Nitrogen use varied fourfold and stocking rate and area allocated to second silage cut varied twofold between systems. Herbage production per hectare and the quantity of silage stored per cow varied between the systems.

Table 4.2 Comparison of calibrated *Dairy_sim* system with the National Dairy Blueprint (NDB).

	NDB	*Dairy_sim*
Number of paddocks	20	20
Turnout	Early March	29 February
Close	Mid–late November	26 November
Winter	100 days	98 days
Close for first silage cut	1 April	1 April
Date first-cut silage	28 May	28 May
Proportion of area for first-cut silage	0.45 (variable)	0.45
Date second-cut silage	15 July	15 July
Proportion of area for second-cut silage	0.35	0.35
Concentrate (kg/cow)	500	543
Milk (l/cow)	6,359	6,400
Silage (t DM/cow)	1.4	1.53
Total herbage production (DM t/ha)	12–15	13 (non-irrigated) 15.8 (irrigated)
Silage yield (DM t/ha)	5.4	4.8
Silage fed housed (kg DM/cow)	–	1,400
Silage supplement at pasture (kg DM/cow)	–	205
Nitrogen (mineral + organic) (kg N/ha)	360	360

Table 4.3. Observed and simulated feed and grass results for the four systems tested at Solohead farm.

System		Concentrates[a] (t/cow)	Grazed herbage (t DM/ha)	1st Silage cut (t DM/ha)	2nd Silage cut (t DM/ha)	Silage fed[b] (kg DM/cow/day)	Silage stored (t DM/cow)
Limited	Observed	0.6	5.8	7.2	3.8	10–12	1.8
	Simulated	0.5	6.4	8.7	–	11	1.7
Extensive	Observed	0.6	6.8	7.1	4.7	10–12	1.4
	Simulated	0.5	7.3	7.4	4.5	11	1.5
Moderate	Observed	0.6	7.7	7.2	5.0	10–12	1.2
	Simulated	0.6	8.3	7.7	4.3	12	1.3
Intensive	Observed	0.6	9.6	7.3	4.8	10–12	1.5
	Simulated	0.6	8.1	7.5	4.3	13	1.5

[a]Concentrates fed within each of the separate grazing systems were not determined at the farm. The value reported is the average across all four systems.
[b]The exact silage fed within each treatment was not recorded, but the range of feed rates for the whole farm was estimated by the farm manager.

Dairy_sim described well the four Solohead farm trial systems (Table 4.3). Pasture production increase from the least-intensive to the most-intensive system followed the same pattern in the field and in the simulations. The amount of silage stored per cow agreed well with the reported values. Humphreys *et al.* (2002) reported that the moderate system produced less silage than demand and the limited system produced excess. In simulations, the moderate system experienced a silage deficit in 3 out of 4 years, whereas the limited system was in surplus every year. The number of days of housing increased with intensification. The field trials set a target for silage of 120 days of indoor feeding. In the intensive and moderate systems the housing days were 117 and 122, respectively. In all simulations a housing period of 105 days was 'forced' (from late-November to early-March) and the simulation results suggest that a shorter period would have been possible in the extensive and limited systems in most years.

Sensitivity analysis was carried out on the parameterisation for the NDB at Fermoy. Each parameter was proportionally adjusted by ±0.5 and ±0.1. The sensitivity to the strategic management parameters revealed that the system was most sensitive to stocking rate, as this had a large influence on silage surplus and to a lesser extent the system was also influenced by milk output per cow and date of harvest of the second cut of silage. Nitrogen fertilisation rate had the most influence on supplementation at pasture. The results of the sensitivity analysis indicated that the tactical management parameters provide ample scope to calibrate *Dairy_sim* for specific sites and situations without having to resort to radical deviations from the NDB. Therefore *Dairy_sim* can be used to identify sites that require adjustment of the strategic management parameters relative to NDB in order to achieve optimum production.

4.4.4 Analysis of regional management variations

Five synoptic weather stations were selected that were representative of the agro-climatic regions of Ireland described by Holden and Brereton (2004). The selected locations were:

1. Fermoy (52.5° N, 8.96° E) south, central, mild and humid
2. Kilkenny (52.4° N, 7.2° E) inland, south-east, cool
3. Rosslare (52.2° N, 6.2° E) coastal, south-east, dry
4. Clones (54.1° N, 7.1° E) north, central, cold, and
5. Claremorris (53.4° N, 8.6° E) west, mild and wet.

The winter forage requirement is an important determinant of the carrying capacity of a farm (Topp and McGechan, 2003) and, for each location, the simulator was used to identify an optimum system by adjusting strategic and tactical management parameters in order to obtain a close to neutral silage balance (<5 t DM/year) and minimum days of winter housing (<110 days). The objective of the adjustment of the system to regional climate variation was to maintain grass availability in the grazing area of the farm similar to the level at Fermoy and to achieve no more than a small annual silage surplus. The purpose in achieving a surplus was to ensure that a surplus was more probable than a deficit. The objective in maintaining a minimum average availability of grass was to limit the probability of a need to supplement the grazing herd with silage or concentrates. In each case, the simulation was run for 30 years using daily weather data stochastically generated from monthly mean values (Sweeney and Fealy, 2003).

The results of the regional management variations required to operate a stable production system with balanced silage demand and minimum days winter housing are presented in Table 4.4. The only site that

Table 4.4. Modification of strategic management parameters (compared with the National Dairy Blueprint (NDB) devised at Fermoy) necessary to achieve an optimum production system at various regional locations in Ireland on a 20-ha farm.

	Location				
	Fermoy	Claremorris	Clones	Kilkenny	Rosslare
Stocking rate (cows/ha)	2.6	2.5	2.45	2.35	2.6
Area of first-cut silage (ha)	9	7	8	9	10
Area of second-cut silage (ha)	7	9	8	7	0
Housing (days)	98	93	90	80	72
Silage deficit (years in 10)	4.3	4.3	5	4.3	3

required a radical deviation from the NDB was Rosslare, where the system had to operate with a single silage cut and a short winter period. In the adjustment of the NDB for regional climate variation (Table 4.4), there was a limited range of options. The option to increase stocking rate was not available because the grass production elsewhere was always less than at Fermoy. A reduction in stocking rate was regarded as practical because land area is often in excess of an intensive system's requirements. At Rosslare and Kilkenny, where the main restriction in grass availability was summer drought, a transfer of the application of N fertiliser from early in the season to the later summer drought period was regarded as undesirable due to possible volatilisation of the N (Coulter, 2004). At Claremorris and Clones, where the grass herbage availability was restricted early in the grazing season, a transfer of N from the summer to the spring period was less effective then the manipulation of the silage area. The length of the winter housing period is a major factor in the operation of the NDB. In the simulations, the winter housing period was determined by the availability of herbage for grazing at both ends of the season. In all simulations, housing was 'forced' in the period from December to mid-February, a period of 80 days.

4.4.5 Conclusions about the usefulness of **Dairy_sim** *for climate change evaluation*

The testing of the simulation system using field data indicated that *Dairy_sim* is a reliable tool for the simulation of management systems using perennial ryegrass pasture and Friesian cows. The sensitivity analysis indicated that the system was most sensitive to factors influencing grass herbage supply and utilisation. Nitrogen fertiliser rate determines total grass herbage production and stocking rate and milk yield determine herbage demand. This sensitivity to grass herbage production and demand was reflected in the adjustments made to the NDB for the effects of regional climate variation on total grass herbage production.

4.5 Integration of CO_2 and Soil Effects into the System Simulation

4.5.1 CO_2 effects on grass growth

Previous simulation work on climate change effects conducted in Ireland (Holden and Brereton, 2002) has not explicitly considered the impact of elevated CO_2 on grass yields. This is because the grass model used for this work (the Johnstown Castle Grass Model, Brereton *et al.*, 1996) does not contain an explicit CO_2 response.

The effect of CO_2 enrichment on the growth of plants generally varies between species. It is also affected by the ontogenetic stage of growth of the plant and its ambient environment (Kimball *et al.*, 2002). The fractional shoot biomass response to CO_2 enrichment is greater at higher soil water deficits (Idso and Idso 1994; Casella *et al.*, 1996), though not in all experiments (Kimball, 1993; Mauney *et al.,* 1994), and in adverse conditions generally (Warrick *et al.,* 1986; Morrison, 1988; Riedo *et al.*, 2001).

In most cases, CO_2 doubling increases DM accumulation rates by 10–50%. For C3 crops, Parry and Duinker (1990) reported the mean DM accumulation rate increase as 26%. Newton (1991) reported a mean yield response of 44% for pasture species and between 29 and 35% for perennial ryegrass. In another C3 grass, *Dactylis glomerata*, the response to CO_2 enrichment was on the same scale, a 25% mass response was recorded (Gunn *et al.*, 1999). Schapendonk *et al.* (1997) also reported similar responses in perennial ryegrass and similar annual responses were obtained for perennial ryegrass in computer simulation studies under UK conditions (Topp and Doyle, 1996; Thornley and Cannell, 1997). In open-top chamber experiments in Ireland perennial ryegrass annual yield responses were 16% and 28% in 2 successive years (Jones *et al.,* 1996). The response varied seasonally (between greater than 60% and less than 10%). Similar annual responses and seasonal variation in response were reported in perennial ryegrass grown in ventilated plastic tunnels in France (Casella *et al.,* 1996). The response in the reproductive phase of perennial ryegrass has been reported to be greater than in the vegetative phase (Daepp *et al.,* 2001).

The reported scale of the CO_2 effect on annual grass yield indicates that livestock systems based on grazed grass will be significantly affected by CO_2 enrichment of the atmosphere. In the particular context of the dairying system practised in Ireland, where management is closely linked to the seasonal pattern of herbage growth, seasonal variation in grass response to CO_2 enrichment (between reproductive and vegetative phases and in periods of growth stress) has special significance. In the present study, the limited available published data have been used to generate quantitative estimates of the seasonal pattern of the effect of CO_2 enrichment in perennial ryegrass.

In the simulation of a system where the grass is a perennial ryegrass monoculture and where nutrition is not restricted, the factors affecting the magnitude of the CO_2 effect during the annual cycle are:

- The seasonal change between the reproductive and vegetative states
- Variations in soil water deficit
- Stresses imposed by variations in radiation and temperature.

The seasonal production data published by Jones *et al*. (1996) for irrigated perennial ryegrass grown at ambient and double-ambient CO_2 concentrations provide a basis for making a quantitative estimate of the effect of the change between reproductive and vegetative states and the effect of variations in stress imposed by seasonal changes in temperature and radiation. The data published by Casella *et al.* (1996) for perennial ryegrass, also grown at ambient and double-ambient CO_2 concentrations and where irrigation level was an experimental treatment, additionally provide a basis for estimating the effect of soil water deficit. In the analysis of the two data sets, it has been assumed that variation in herbage growth rate between harvests in the ambient CO_2 treatments may be used as a measure of the variation in temperature/radiation stress. It is also assumed that in the period before mid-June the swards were in the reproductive state and subsequently were in the vegetative state.

Relationships between the CO_2 effect and sward were based on linear regressions of the fractional response of herbage DM growth to CO_2 enrichment on herbage growth rate (DM, kg/ha/day), on soil water deficit (mm) and on grass state (reproductive/vegetative). The data used in the regression analyses were derived from Fig. 2 of Jones *et al*. (1996) and from Fig. 2 of Casella *et al*. (1996). In the analysis of the data of Jones *et al*. (1996), because the swards were irrigated, soil water deficit was not included. In the case of the data of Casella *et al*. (1996), there were insufficient data for the reproductive period and the sward state factor was omitted.

Although the analysis is based on a limited set of data, the variation in responses to CO_2 discovered within a season to reproductive state, water deficit and growth stress are in harmony with the reported responses generally. Furthermore, the coherence between the two data sets was good, although they come from significantly different climatic environments and although the perennial ryegrass varieties were different. Implicit in the use of regression analysis is the assumption of linear relationships between the CO_2 response and water deficit and growth stress. The relationships are possibly non-linear so the parameters discovered are probably only relevant within the environmental range of the experimental data and, even then, should be regarded as rough estimates. From the regression of the two data sets combined, the parameters of the relationship between percent response of growth to CO_2 enrichment (Y) and growth stress (X_1), reproductive status (X_2) and soil water deficit (X_3) were estimated as:

$$Y = 0.6377565 - 0.00150188X_1 - 0.196545X_2 + 0.00382885X_3$$

It should also be noted that it was assumed that doubling of CO_2 concentration would have little influence on the soil water status of temperate grassland. As the resistance to water flow in grass is significantly greater than the leaf stomatal resistance (Nosberger *et al*., 2000), any changes in stomatal resistance in response to CO_2 doubling would be small compared with the total resistance of the plant.

The mean of the cumulative 28-day regrowths derived from the locations (Fermoy, Kilkenny, Rosslare, Clones and Claremorris) is shown in Fig. 4.9. The 2055 fixed 20% (b) and fractional response (c) scenarios resulted in much greater simulated grass growth than the no-CO_2 response scenario (a). The result shows that the elevated CO_2 response cannot be ignored in the system simulations. The difference between the b and c scenarios underlines the significance of using a seasonally variable CO_2 response instead of a fixed response across all circumstances. In this work the variable CO_2 response is used throughout.

4.5.2 The soil model

Soil moisture conditions are an important interface between agriculture and the environment, as they impact on the length of the grazing season, grass growth rates and nutrient uptake, and the loss of nutrients to the wider environment. Moisture conditions are conveniently quantified by the soil moisture deficit (SMD) but diverging methods for deriving SMD have been applied in Ireland to date, and in the initial version of *Dairy_sim*, a single well-drained soil condition was assumed. A simple hybrid model (Schulte *et al.,* 2006) for computing SMD, which accounts for differences in drainage regimes between soil types, was calibrated for contrasting soil types in Ireland. This hybrid model accurately predicted the temporal patterns of SMD during a 3-year time period on well-drained and poorly drained soils. Three soil drainage classes were defined, which satisfactorily describe the differences in drainage between soils. Once tested, the model was integrated into *Dairy_sim* as a component of the grass growth model, and as a driver of environmental responses.

The soil model is a water mass-balance model with a daily time step, calculating SMD from the cumulative balance of precipitation, evapotranspiration and drainage:

$$SMD_t = SMD_{t-1} - Rain + ET_a + Drain$$

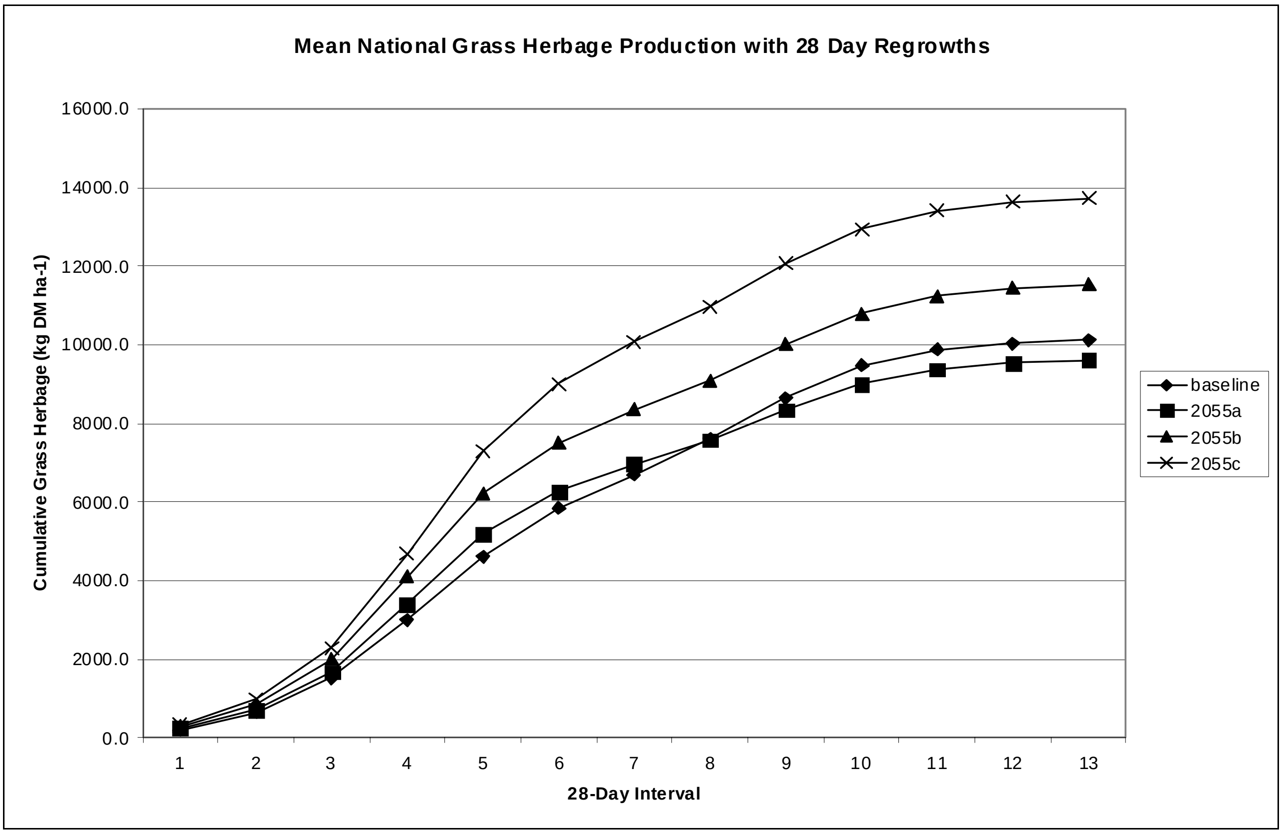


Figure 4.9. National average of cumulative 28-day regrowths in baseline years and 2055. Average based on simulations at five locations with (a) no-CO_2 response, (b) uniform 20% increase in growth with elevated CO_2, and (c) fractional CO_2 response.

where SMD_t and SMD_{t-1} are the SMD values on Day t and Day t–1, respectively (mm), *Rain* is the daily precipitation (mm/day), an input variable of the model, ET_a the daily actual evapotranspiration (mm/day), and *Drain* is the amount of water removed daily by percolation and/or overland flow (mm/day).

The actual evapotranspiration ET_a is a function of the potential or reference crop evapotranspiration ET_0, and the current SMD. Largely based on Aslyng (1965), ET_a is assumed to equal ET_0 when soil moisture conditions are not limiting grass growth, i.e. when the current SMD is between 0 (field capacity) and a critical value SMD_c. When SMD exceeds SMD_c, the grass leaf stomata close progressively to reduce the transpiration rate. As a result, the actual evapotranspiration ET_a will progressively be reduced and be less than ET_0 (Allen *et al.*, 1998). It is commonly assumed that the relationship between ET_a and ET_0 is linear between SMD_c and SMD_{max}, the maximum SMD (Aslyng, 1965; Allen *et al.*, 1998):

If $SMD_t \leq SMD_c$

$$ET_a = ET_0$$

If $SMD_t > SMD_c$

$$ET_a = ET_0 \cdot \frac{SMD_{max} - SMD_{t-1}}{SMD_{max} - SMD_c}$$

Aslyng (1965) found SMD_c and SMD_{max} to equal 30 mm and 120 mm, respectively, for the Danish reference soil. Similar values have been used in other studies (e.g. Brereton and Hope-Cawdery, 1988; Brereton *et al.*, 1996; Keane, 2001; Holden and Brereton, 2002), the latter authors varying SMD_c with topsoil depth to simulate the water buffering capacity of different soils. In the current model, both SMD_c and SMD_{max} are calibrated as site-specific input parameters.

The potential evapotranspiration, ET_0 is ideally calculated according to the FAO Penman–Monteith Equation (Allen *et al.*, 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T + 273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET_0 is the potential evapotranspiration (mm/day), R_n is the net radiation at the crop surface (MJ/m^2/day), G is the ground heat flux density (MJ/m^2/day), T is the air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m/s), e_s and e_a are the saturation vapour pressure and the actual vapour pressure, respectively (kPa), Δ is the slope of the vapour pressure curve (kPa/°C), and γ is the psychrometric constant (kPa/°C). Where values for these inputs are not available ET_0 can be calculated using the simpler Priestley/Taylor method:

$$ET_0 = a\frac{\Delta}{\Delta + \gamma}E_r \quad \text{where} \quad E_r = \frac{R_n}{l_v \rho_w}$$

where a is a constant (=1.26), l_v is the latent heat of vaporisation (J/kg) and ρ_w is the density of water (kg/m^3). The Priestley/Taylor method was implemented in *Dairy_sim* as there was little basis for deriving wind speed data for future climates and such data are rarely available on a site-specific basis.

The amount of water lost from the topsoil through either percolation or overland flow is assumed to be dependent on site-specific characteristics of the soil, and is referred to collectively as drainage. In this model, drainage is characterised by two parameters, the minimum soil moisture deficit, SMD_{min} (mm), and the maximum drainage rate, $Drain_{max}$ (mm/day). Based on extensive investigations of soil water regimes by Diamond and Sills (1998, 2001) and Diamond and Shanley (2003), the model used in this work defines three soil drainage classes, i.e. poorly drained, moderately drained, and well-drained soils. Differences between the hydrological properties of these classes are quantified by calibrating class-specific values for $Drain_{max}$, SMD_{min}, SMD_c, and SMD_{max}.

It is assumed that drainage by means of percolation or overland flow only occurs when the soil moisture content exceeds field capacity, i.e. when SMD < 0. However, it seems unrealistic that drainage can be described satisfactorily by a switch function, i.e. that drainage commences at its maximum rate as soon as SMD drops below 0 mm. Therefore, it is assumed that the actual drainage rate increases with accumulating soil moisture surpluses, i.e. from no drainage when the soil is at field capacity, to maximum drainage when the soil is saturated. Since the precise relationship between the actual drainage rate and SMD is difficult to quantify, the drainage rate *Drain* (mm) is described by a simple linear function of SMD:

If SMD > 0:

$$Drain = 0$$

If $SMD \leq 0$:

If $Drain_{max} \leq -SMD_{min}$

$$Drain = Drain_{max} \cdot \frac{SMD_{t-1}}{SMD_{min}}$$

If $Drain_{max} > -SMD_{min}$

$$Drain = -SMD_{t-1}$$

The model was calibrated and tested using multi-annual data from Ballintemple Nursery, Coillte, Co. Carlow (Brown Earth, somewhat excessively drained, sandy loam), Clonroche Research Station, Co. Wexford (Brown Earth, well drained, loam), and Johnstown Castle Research Centre, Co. Wexford (Gley, poorly drained, loam). The model was found to work well and could be used for three defined drainage classes:

1. Well-drained soils remain at field capacity on wet winter days, even during rainstorm events, and are never saturated

2. Moderately drained soils carry water surpluses on wet winter days, and can reach saturation during rainstorm events, but will return to field capacity on the first subsequent dry day; and

3. Poorly drained soils carry water surpluses on wet winter days, and reach saturation during rainstorm events, and remain below field capacity for a number of days, even when no further precipitation occurs.

Generalised parameter values for using the model were defined (Table 4.5).

4.5.3 *Impact of soil type within* Dairy_sim*: sensitivity to climate scenario and influence of soil type on duration of growth limitation and trafficability*

The soil component of *Dairy_sim* was evaluated, independently of the production element of the system simulation, using daily weather data generated for Birr during baseline, 2020 and 2050 climate periods. Data from each climate model for each scenario, and scenario-weighted means and an ensemble mean were all tested using poorly drained, moderately drained and well-drained soil parameters.

4.5.3.1 *Effect of soil type on grass growth*

The results presented in this section are derived from using the climate ensemble data. Two types of growth limitation were identified: due to water stress and due to excess water availability (Table 4.6). The well- and moderately drained soil parameterisation never suffered growth limitations due to excess water. This is inherent in the parameterisation (Table 4.5), which is formulated to simulate either no possible water excess (well-drained soil) or rapid return to field capacity (moderately drained soil). The poorly drained soil did, however, suffer periods of excess water limiting grass growth, but it was observed that the duration of this limit was predicted to decrease with climate change.

In terms of water stress, the well-drained soil suffered more water stress than the moderate and poorly drained soils. This reflects a parameterisation that represents a smaller water-holding capacity. The moderately and poorly drained soils were parameterised to behave in a similar manner under dry conditions (Table 4.5). With climate change the duration of water stress is predicted to increase for all

Table 4.5. Generalised parameter values for well-drained, moderately drained and poorly drained soils in the hybrid model (Schulte *et al.*, 2006).

Parameter	Well drained	Moderately	Poorly drained
SMD_{max}	110	110	110
SMD_{c}	0	0	10
SMD_{min}	0	–10	–10
$Drain_{max}$	N/A	>10	0.5

Table 4.6. Soil limitation (in days per year) due to water stress, water excess and total on grass growth (80th percentile value shown).

Drainage	Baseline			2020			2050		
	Stress	Excess	Total	Stress	Excess	Total	Stress	Excess	Total
Well	97	0	97	100	0	100	123	0	123
Moderate	68	0	68	82	0	82	116	0	116
Poor	68	221	289	118	208	290	116	196	312

soil types progressively through the century (Table 4.6).

The overall limit to growth imposed by the soil model was least for the moderately drained soil (Table 4.6) because there was no excess water limitation and the least likelihood of a water stress limitation. The well-drained soil had the next greatest limitation to growth entirely due to the occurrence of summer water stress. The poorly drained soil had the greatest simulated limit to growth because of both excess water and water stress. It should be noted that the limit by excess water is not as important as it may seem because it occurs in the winter months when grazing is not the main source of nutrition for the animals.

4.5.3.2 Effect of soil type on trafficability

Trafficability limitations were defined for grazing access and machinery access. These relate to the likely soil damage that might occur as a result of accessing fields where the soils are too wet. The limit to grazing access was defined for this analysis as 0 mm SMD and the limit for machine access was set as 10 mm SMD. In each case the earliest day of the year when field access might be possible was estimated and the duration of access after that date was also estimated (Table 4.7). It should be noted that these SMD limits have not been calibrated and therefore the exact day of year when limits are predicted to be imposed may not be quite correct for a given site, but the relative changes between climate periods should be correct.

There were no limitations to grazing access predicted based on the parameterisation for the well and moderately well drained soils during any climate period. Limits to machinery access were predicted because the soil has to be drier to resist damage by wheels. In this case it was predicted that the date of field access would become earlier in the year, moving forward from late May to early May and that the duration of access would increase from 109 to 149 days. This change reflects an increased seasonality of rainfall and transpiration. For the poorly drained soil it is predicted that grazing access is limited until mid-May and that with climate change access will occur earlier and can continue for longer. The same pattern is

Table 4.7. Day of year and days of available field access for grazing and machine access (80th percentile value shown).

Drainage	Baseline		2020		2050	
	Day	Duration	Day	Duration	Day	Duration
			Field access for grazing			
Well	1	365	1	365	1	365
Moderate	1	365	1	365	1	365
Poor	134	142	130	154	123	164
			Field access for machinery			
Well	148	109	140	133	130	149
Moderate	148	109	140	133	130	149
Poor	156	112	143	135	137	147

observed for machinery access. In all cases, the limit to access reflects the parameterisation of the wet end of the soil water model, hence the similarity between the well and moderately well drained soils. Further physical interpretation of the soil water model results were not isolated for this report, but the parameterisation of the model will influence predictions of available time periods for various farm management tasks such as slurry spreading, silage cutting and paddock topping.

4.5.3.3 Uncertainty associated with climate scenario data

The uncertainty associated with driving the production aspects of *Dairy_sim* will be considered in Section 4.6. From the results presented in this section it was judged that the soil model was going to have a significant influence on the management systems derived using the simulation model. It was important therefore to examine the sensitivity of the results to climate scenario input data. The data in Tables 4.6 and 4.7 were derived from the ensemble mean data. If a different climate model were used to generate the results, would the same conclusions be reached? An examination of the results in terms of the distribution of values found using the nine available data sets (three models, two emission scenarios, scenario averages and an ensemble mean) suggests that there is quite a degree of uncertainty (Table 4.8).

The results of the uncertainty analysis indicate that the soil model is not very sensitive to scenario when simulating situations around field capacity but is much more sensitive when simulating drier conditions (Table 4.8). In general, around 20% variation in predicted days with water stress limiting growth is predicted, but growth limitation with water excess is much less variable with the exception of moderately drained soils. In this case, there is a large co-efficient of variation because there were only a few days with a growth limitation but the range predicted is the same magnitude as for the water stress growth limitation periods. There is, in general, around 10% variation in grazing access with more sensitivity for the poorly drained soils but the variation for machine access (occurring when the soil becomes drier) increases to around 25%.

Examining the difference between using the mean of the nine climate scenarios and the ensemble mean reveals that there are some systematic shifts as the

Table 4.8. Uncertainty for growth limitation due to water stress and water excess and field access for grazing and machinery due to climate scenario and model data used (results based on data for 80th percentiles). SD, standard deviation; CV, co-efficient of variation.

	Water stress (days)			Water excess (days)			Grazing access (days)			Machine access (days)		
	Mean	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
Well-drained soil												
Baseline	119	42	36	0	0	0	330	22	7	95	22	24
2020	114	16	14	0	0	0	333	25	8	110	17	15
2050	111	17	15	0	0	0	333	25	8	104	35	33
Moderately drained soil												
Baseline	90	20	23	8	17	199	332	25	7	95	22	24
2020	97	18	19	18	25	138	332	24	7	116	19	17
2050	101	19	19	8	15	198	333	25	8	106	34	32
Poorly drained soil												
Baseline	88	17	19	226	15	7	130	19	15	100	22	22
2020	94	18	19	216	11	5	141	12	8	117	19	17
2050	100	19	19	221	20	9	134	25	18	108	30	28

Table 4.9. Difference between ensemble mean and mean value derived from nine climate scenarios.

Well-drained soil	Water stress (days)			Water excess (days)			Grazing access (days)			Machine access (days)		
	Well	Moderate	Poor	Well	Moderate	Poor	Well	Moderate	Poor	Well	Moderate	Poor
Baseline	–22	–22	–20	0	–8	–5	35	35	12	14	14	12
2020	–14	–15	–12	0	–18	–8	32	32	13	23	17	18
2050	12	15	18	0	–8	–25	32	32	30	45	43	9

predictions move further into the future (Table 4.9). For growth limitation due to water stress the ensemble mean is generally smaller than the mean of scenarios for the baseline and 2020 but is greater for 2050. Growth limitation due to water excess appears to be slightly underestimated by the ensemble mean as the prediction goes further into the future, but in general it is more stable than for the water stress situation. In terms of field access for grazing and machinery, the ensemble mean is consistently larger than the mean of the scenarios. This may have some significant implications for how nutrients and grass are managed in the system and should be recognised when interpreting the results of the complete system simulation.

4.5.4 *Calibration of the poorly drained soil system simulation*

The production aspect of *Dairy_sim* was tested for well-drained soils (Section 4.4.4), but after including a soil component in the system simulation to account for poorly drained soils it was necessary to calibrate this component in terms of the whole system. The parameter values presented in Table 4.5 were derived by calibration against soil water content/tension data rather than against the biological response of the grass crop. In order to evaluate the soil component of the model in a production context, a similar approach was taken to that of Section 4.4.4. Data for a production system implemented on a poorly drained soil and with high rainfall were published by Shalloo *et al.* (2004) and could be used to calibrate *Dairy_sim*. The soils at Kilmaley Research Farm are relatively poorly drained, but with some field drains installed, because they are fine textured with a tendency towards a compact subsoil. The soils can retain water for long periods but have low infiltration rates due to poor soil structure. A typical production system for the site was described by Shalloo *et al.* (2004) (Table 4.10).

Dairy_sim was parameterised with the Shalloo *et al.* (2004) data and an optimisation was performed with the aim of getting a workable feed balance for the farm assuming both a wet and a dry soil. The dry soil was used to identify whether *Dairy_sim* had captured the right trends compared with a poorly drained soil, even if the calibration could not entirely capture the poorly drained soil production system. The parameters of the poorly drained soil model (Table 4.5) and a parameter describing growth limitation due to waterlogging were also adjusted during the optimisation. The results are presented in Table 4.11.

Overall there are very few differences between the optimised *Dairy_sim*-wet system and the Shalloo *et al.* (2004) system. In order to achieve this result the $Drain_{max}$ parameter for the soil had to be set to 7, which reflects some soil management to improve

Table 4.10. Strategic system management for low-cost dairy production at Kilmaley based on poorly drained soil.

Stocking rate	38
Milk per cow (l)	5,781
N application rate (kg/ha)	240
Close for first cut	1 April
Close for second cut	21 May
Close for third cut	14 July
First-cut date	21 May
Second-cut date	14 July
Third-cut date	14 September
First-cut paddocks (number)	10
Second-cut paddocks (number)	7
Third-cut paddock (number)	2

Table 4.11. Comparison between the Shalloo *et al.* (2004) data and the optimum systems produced for poorly drained (wet) and well-drained (dry) soils at the same site.

	Dairy_sim-wet	Shalloo *et al.* (2004)	*Dairy_sim*-dry
Stocking rate (cows/ha)	1.90	1.89	2.25
N application rate (kg/ha)	236	238	236
Total DM (kg/ha)	9,438	9,932	12,303
Main silage DM (kg/ha)	4,821	4,009	5,349
Baled silage DM (kg/ha)	913	–	560
Days grazing	177	149	194
Grazed intake DM (kg/cow)	1,949	2,121	2,842
Silage intake DM (kg/cow)	2,355	2,375	1,903
Meals intake DM (kg/cow)	455	759	463
Grazed intake fraction	0.41	0.40	0.55
Silage intake fraction	0.49	0.45	0.37
Meals intake fraction	0.10	0.13	0.09

drainage compared with the central concept of a poorly drained soil as defined by Schulte *et al.* (2006), and the growth restriction due to waterlogging was set to 0.25 of the full growth rate. The major differences are days grazing and intake from supplementary meals. The grazing days difference is caused by the winter forcing not being enforced so that occasional grazing days occur at each end of the winter period. It is not possible to automate the management of these days but, when accounted for, the difference between the simulated and the field systems is much smaller. The difference in meal intake can be attributed to the feeding of supplements late in the season at Kilmaley which was not simulated in *Dairy_sim*. Overall it was concluded that the wet soil component of *Dairy_sim* could be used reliably with the calibration established at Kilmaley.

4.6 Uncertainty Associated with Climate Scenario Data Driving the System Simulation

Having tested the system simulation model in terms of its baseline reliability, it was necessary to evaluate the uncertainty that would arise from the climate scenario data used to drive the model. It was important to know how sensitive *Dairy_sim* was to the climate change data being used to drive the predictions. Nine different data sets were used, derived from:

- Hadley CM3 with emissions Scenarios A and B (HADA and HADB)
- Canadian Climate Change Model with emissions Scenarios A and B (CCCMA and CCCMB)
- CSIRO model with emissions Scenarios A and B (CSIROA and CSIROB)
- The weighted mean of the Scenario A (EnsA)
- The weighted mean of Scenario B (EnsB), and
- An overall weighted ensemble mean (EnsM).

Using the basic version of *Dairy_sim* (well-drained soil, CO_2 response), four locations were chosen at random to evaluate the data (Malin Head, Valentia, Birr and Kilkenny) and results were analysed for baseline and 2050 climate periods only. Using the soil-enabled version of *Dairy_sim*, the uncertainty associated with interaction of climate change with well- and poorly drained soils was also evaluated.

To find the optimum system, the following rules were applied. The system had to produce a near-neutral silage balance (±5 t/ha) and had to achieve <110 days of animal housing. Winter forcing was imposed to ensure a continuous housing period in the winter months. Nitrogen rate was always left unchanged (an alternative strategy is considered in Section 4.7) but stocking rate and silage strategy were adjusted. A third silage cut was always avoided if possible. Trafficability limitations were accounted for with the poorly drained soil. In the final analysis of adaptation and impact of climate change on dairy production (Section 4.7), the approach taken was slightly different in that stocking rate was maintained or decreased and N rate was minimised.

4.6.1 System differences as a result of climate model input for baseline period (no soil effect)

The range of stocking rates found for each site with the nine different climate data sets encompassed differences of seven or eight cows per hectare (Table 4.12). At Malin Head and Valentia (coastal) the HADA and HADB scenarios resulted in markedly lower stocking rates but at Birr and Kilkenny the EnsA, EnsB and EnsM scenarios produced markedly higher stocking rates. In general, the mean was skewed towards the higher stocking rates and there were relatively small standard deviations.

Climate scenario data had almost no effect on the number of paddocks required for silage (Table 4.12) and there was no systematic trend associated with scenario source that could be observed. No baled silage was cut in any of the scenarios and there was relatively little difference between the scenarios in terms of the main silage cut. As with stocking rate, lower values for main silage were found for HADA and HADB at Birr and Kilkenny. With few exceptions the target of a near-neutral silage balance was achieved for all data sets and sites. In general a range of 10–12 t/farm difference was found across the scenarios which is very small compared with the amount of silage and total DM produced each year.

Table 4.12. The minimum, maximum, mean and standard deviation (SD) for system characteristics derived by optimisation based on the nine different climate data sets.

	Stocking rate (cows/farm)	1st-cut paddocks	2nd-cut paddocks	Total DM (t/farm)	Grazed DM (t/farm)	Main silage DM (t/farm)	Baled silage DM (t/farm)	Housing days (per farm)	Silage excess DM (t/farm)
Malin Head									
Minimum	58	9	7	284	180	99	0	100	–3
Maximum	65	9	9	327	207	122	0	107	5
Mean	64	9	8	314	199	115	0	105	1
SD	3	0	1	16	10	7	0	2	3
Birr									
Minimum	55	9	9	259	157	100	0	103	–6
Maximum	60	9	9	299	179	121	0	110	6
Mean	58	9	9	279	168	111	0	106	0
SD	2	0	0	15	8	8	0	2	5
Valentia									
Minimum	62	9	7	315	196	111	0	98	–2
Maximum	70	10	9	354	220	133	0	108	12
Mean	68	9	9	333	208	125	0	104	4
SD	3	0	1	15	9	8	0	3	6
Kilkenny									
Minimum	52	9	6	254	156	90	0	97	–5
Maximum	60	9	9	288	171	117	0	108	5
Mean	55	9	8	268	165	104	0	101	1
SD	4	0	1	13	5	11	0	5	3

In general, the housing days were very stable across the scenarios (Table 4.12). The only marked exception was found with the EnsA, EnsB and EnsM scenarios for Kilkenny that caused much greater housing days than the other scenarios. Overall, the stability of the system with the different scenario data is reflected in the consistent total DM production predicted across the scenarios. A coefficient of variation of 5% for each site was found.

The trends in stocking rate reflect those found previously using *Dairy_sim* (Fitzgerald *et al.*, 2005) and there was no clear spatial trend associated with the degree of uncertainty caused by using the different climate scenarios.

4.6.2 Uncertainty associated with system differences predicted to occur by 2050 (no soil effect)

The stocking rate increases for all locations with the climate change data (Table 4.13). In general, a 15-cow per farm increase is predicted when N application remains the same and this is matched to a very small change in silage paddocks. There is relatively little difference between scenarios (up to a maximum of seven cows per farm) and the trend is consistently for an increase in stocking rate. It should be noted that this is not a prediction of what will happen with climate change (see Section 4.7) but is an evaluation of the magnitude of uncertainty associated with using the various climate data sets available.

Table 4.13. Differences in system properties between baseline and 2050 climate periods reported by location as minimum, maximum, mean and standard deviation (SD) of difference after optimisation for each of the nine climate data sets.

	Stocking rate (cows/farm)	1st-cut paddocks	2nd-cut paddocks	Total DM (t/farm)	Grazed DM (t/farm)	Main silage DM (t/farm)	Baled silage DM (t/farm)	Housing days (per farm)	Silage excess DM (t/farm)
Malin Head									
Minimum	10	0	–2	63	37	13	0	–16	–2
Maximum	17	1	2	88	64	50	3	20	9
Mean	13	0	0	75	47	28	1	2	5
SD	2	0	1	8	7	11	1	9	4
Birr									
Minimum	13	0	–2	58	38	4	0	–1	–12
Maximum	18	1	0	91	55	39	6	3	7
Mean	15	0	–1	69	49	18	2	1	–2
SD	2	0	1	11	5	12	2	2	7
Valentia									
Minimum	11	–1	–3	61	39	6	1	–15	–9
Maximum	18	1	2	76	59	29	12	11	9
Mean	15	0	0	70	47	17	6	–2	1
SD	2	1	2	4	8	7	4	9	7
Kilkenny									
Minimum	13	0	–2	59	35	12	0	–8	–6
Maximum	16	1	1	75	58	25	10	9	5
Mean	15	0	–1	68	47	18	3	4	–3
SD	1	1	1	6	7	5	3	6	3

Little change is predicted for the strategic silage management (Table 4.13). If anything, there is a trend to a smaller area being used for second-cut silage, but overall the silage management is not greatly affected by the climate scenarios and has few input data uncertainty associated with it. There is a relatively large range of predicted changes in main silage but this is still small compared with the total DM production on the farms.

For the coastal sites (Malin Head and Valentia) there is quite a large uncertainty in the change in number of housing days with climate change (up to 36 days difference for Malin Head). For the inland sites the uncertainty is much smaller. The summary data presented (Table 4.13) mask the detail of most of the scenarios. For Malin Head the housing days data cluster around a zero difference, but HADA and CSIROB were very much different from all the others. For Valentia, the housing days data are represented by extreme values generated by CCCMA, CCCMB and EnsM. While the housing days results are the most variable in terms of the scenario data used, the results cluster near a zero difference and therefore the uncertainty need not be a major worry when interpreting the results for *Dairy_sim*.

At every site except Kilkenny, the minimum silage excess was predicted using the EnsM data. This was somewhat unexpected, as it had been assumed that these data would drive a system that was close to the average. In general, there is no detectable spatial trend in the uncertainty results and there is relatively little uncertainty caused by the climate input data used with the system simulation model.

It had been planned that the EnsM data would be used to examine detail of the impact of climate change and necessary system adaptations for dairy production in Ireland. To examine the magnitude of uncertainty associated with using just this one set of data, the results for EnsM were compared with all other data sets in terms of the major system properties found after optimisation. Overall, there was a distinct bias in the EnsM-derived data compared with all other data sets. The amounts of total DM, grazed DM and main silage DM were all greater for the EnsM scenario than for any of the others. Likewise, the baled silage DM and housing days were all less for the EnsM data than for any of the other scenarios. The reason for this situation arising is the process of using a weighted mean of the HADA, HADB, CCCMA, CCCMB, CSIROA and CSIROB data sets. The EnsM data set effectively smoothes out the extremes from the source data which means that temporal extremes are not effecting the farm system model to the same extent that they are for the non-processed data sources. As there are less extreme wet and dry events in the EnsM data set the grass growth is greater which means that the system properties take on extreme values compared with the other scenario data. It was decided that further work in dairy system simulation would use EnsM in order to be consistent with other work presented in this report, but that when necessary (e.g. soil model testing and testing of the system under poorly drained conditions) the full range of available data would be evaluated in order to assess uncertainty associated with focusing on EnsM-data-derived results.

4.6.3 Uncertainty associated with system differences linked to the soil effect

Birr was chosen as the site to evaluate the uncertainty of the system model, with soil component outputs to the climate scenario data used as inputs in order to follow on from the evaluation of the stand-alone soil component. It should be noted that there are slight differences between the optimised systems for well-drained soils between the data in Tables 4.12 and 4.13 and those presented in Table 4.14. These differences reflect the fact that there is not a single ideal system, but an ‘optimum region’ in which to operate. The differences are very small.

For baseline conditions the simulated impact of poorly drained soil on the production system (Table 4.14) was to enforce a reduction in stocking rate due to a reduction in the total DM on the farm and the need for more housing days due to lack of field access at the end of autumn and in early spring. This means that the grazed DM on the farm is less with poorly drained soil, so the farm output is less and the cost per unit output is also increased making the system less profitable. This is the same conclusion drawn by Shalloo *et al.* (2004). With the predicted change in climate for the 2050 period, the impact of poorly drained soil is reduced. Both poorly and well-drained soils are

Table 4.14. System properties for baseline and difference for 2050 climate reported by soil drainage as minimum, maximum, mean and standard deviation (SD) of difference after optimisation for each of the nine climate data sets.

	Stocking rate (cows/farm)	1st-cut paddocks	2nd-cut paddocks	Total DM (t/farm)	Grazed DM (t/farm)	Main silage DM (t/farm)	Baled silage DM (t/farm)	Housing days (per farm)	Silage excess DM (t/farm)
Baseline – poorly drained									
Minimum	47	9	9	232	115	116	1	145	–4.07
Maximum	53	9	9	276	133	142	4	156	3.10
Mean	50	9	9	256	125	130	2	151	0.47
SD	3	0	0	15	7	9	1	5	2.10
Baseline – well drained									
Minimum	56	9	9	261	158	100	0	102	–3.03
Maximum	63	9	9	303	183	120	0	107	0.77
Mean	59	9	9	282	171	112	0	104	–0.30
SD	3	0	0	15	9	7	0	2	1.27
2050 difference – poorly drained									
Minimum	13	1	0	62	35	16	–2	–4	–2.60
Maximum	20	3	1	97	60	45	6	0	4.10
Mean	16	2	0	81	51	28	2	–1	0.60
SD	2	1	1	8	8	8	–3	2	2.10
2050 difference – well drained									
Minimum	12	0	0	58	31	15	0	–1	–0.47
Maximum	15	0	0	79	48	30	8	5	2.13
Mean	13	0	0	66	41	22	3	2	0.83
SD	1	0	0	7	6	5	3	2	1.00

predicted to lead to systems with higher stocking rates as a result of increases in available DM for grazing and silage. The system on the poorly drained soil improves more relative to the system on the well-drained soil. The overall result is that the simulation suggests that dairying in poorly drained soil will benefit more from climate change than dairying on well-drained soil, but the system will still be less efficient and less profitable. The degree of uncertainty associated with the nine scenario data sets is very similar for both the well- and poorly drained soils, which suggests that there is no amplification of uncertainty within the system simulation as a result of including the soil effect in *Dairy_sim*. The EnsM data generally lead to a system optimisation that had greater output due to greater available DM than for other scenarios, as discussed in Section 4.6.2.

4.7 Adaptation of Strategic and Tactical Management of Dairy Systems in Response to Climate Change

4.7.1 Background

An earlier study (Holden and Brereton, 2003b) of the effects of climate change in Ireland on annual grass production indicated that over the coming century grass production may be expected to increase significantly and that the scale of the increase would vary geographically. It was suggested that the increases in the eastern half of Ireland would be tempered by significant increases in soil water deficits. That study did not take account of the effects of CO_2

enrichment and therefore the estimated effects of climate change may be assumed to be underestimates. Furthermore, the previous study did not attempt to estimate the effects of changes in grass production and its seasonal distribution on farm system output and management or the potential effects of climate change on the environmental impacts of farming. In the present study, the approach has been considerably broadened. A detailed dairy farm simulation, including consideration of elevated CO_2 and soil effects, was used to examine changes in dairy system management, due to climate change, with respect to stocking rate, irrigation, land and slurry. The focus has been put on dairying because it is currently the most economically viable system of farming in Ireland.

It has been predicted that the number of dairy farms in Ireland will reduce to 15,000 by 2015 (Pitts, 2005). If the current EU-regulated milk output is to remain the same for Ireland then more milk will have to be produced per area of land (increased intensification) and therefore stocking rates and/or output per cow will have to increase. This scenario gives rise to the question: can low-cost grass-based milk production adapt to climate change in order to meet the intensification requirement? An alternative scenario is possible. Given a future scenario where farmers are restricted by legislation as to how much N they can use (and other inputs probably), the drugs permissible for reproduction control, and they are used by society as keepers of the environment, then a significant number of farmers will be needed to maintain national milk production at low output per unit area (extensification) with minimum inputs. In this case, the question is: can low-cost grass-based milk production adapt to climate change in order to meet an extensification requirement? In this study, climate change effects have been examined in the context of both of these scenarios.

4.7.2 System basics – strategic and tactical management

The spring-calving system of dairying that is simulated is practically a closed system. Apart from about 450 kg/cow of purchased meals, all the feed is produced within the system. The purchased meals are fed in the period after calving, at the start of lactation, to compensate for the reduced appetite of cows at this time. The principal objectives of management are to maintain a sufficient supply of grass for as long a grazing season as possible and to produce only as much silage as is required for the winter housing period. The supply of grass for grazing across the season is principally determined by weather conditions, which are beyond the control of management. Within the constraints imposed by weather, management uses a variety of controls to reconcile grass supply and herd demand. The principal control is stocking rate, which adjusts the overall balance between total supply and total demand. Total demand includes the demand for silage fed indoors during winter. The primary objective of the silage programme is to provide sufficient silage for the winter period but adjustments in the farm area allocated to silage production during April/May (first cut), June/July (second cut) and July/September (third cut) are used to control the area available across the season for grazing in order to maintain a constant supply of grass for grazing. The dates of the start and end of the grazing season may also be varied in response to the seasonal pattern of grass growth. Finally, N fertiliser has a significant effect on grass production and it can be used to control both the total grass production and (by varying the seasonal pattern of N fertiliser application) its seasonal distribution. As a closed system, an optimal system may be defined as a system where there is neither a surplus nor a deficit of silage produced.

However, total grass production and its seasonal distribution varies between years. An average grass yield of 1,000 kg/ha DM in the grazed area of the farm represents an adequate supply of grass, but the system strategy may not be able to maintain the supply at all times in all years and tactical management responses become necessary. When the average yield falls below 600 kg/ha, supplementation of grazed grass with silage and/or meals is necessary, or it may be necessary to house the herd and feed silage temporarily. At the other extreme, if average yield exceeds 1,500 kg/ha, it becomes difficult to graze efficiently and it is necessary to remove 'surplus' grass as baled silage. The simulator is 'intelligent' in that it applies these tactical responses to temporary fluctuations in grass availability. In the present work, the simulator was used to define the system for each of four periods between 1961 and 2099. The periods were 1961–1990, 2010–2039, 2040–2069 and 2070–2099. In each case the simulator was run for 30 consecutive years of each period and the system defined as proper to each period is one that represents a 30-year average and where the 30-year accumulated silage deficit/excess is minimal. In all simulations a 20-ha farm in 20 equal-area paddocks is assumed.

System simulations were generated for the locations of 11 synoptic weather stations (Belmullet, Birr, Casement Airport, Claremorris, Clones, Kilkenny, Malin Head, Mullingar, Roche's Point, Rosslare and Valentia). Daily weather data for each station for the period 1961–2099 were made available by NUI Maynooth and, given previous analysis, attention was focused on using the EnsM data. At each location the farm system simulations were repeated for a well-drained and a poorly drained soil. For selected sites the simulations were repeated with and without irrigation.

4.7.3 *Response to climate change by intensification or extensification*

Two approaches were used to examine the potential effects of climate change. In the first, the objective was to examine how the system would respond to climate change when the current baseline milk output (number of cows) was held constant. For four locations selected to represent the East, the Midlands and the West (Kilkenny, Mullingar, Claremorris and Valentia) a baseline system (1961–1990) was defined for an annual N input of 360 kg/ha. In the following three periods of climate change, ending 2099, cow number was held constant but a reduction in farm area, a reduction in annual N, and changes in its seasonal distribution were allowed. Changes in total silage area and its seasonal distribution and changes in the dates of the start and end of the grazing season were allowed. The incorporation of the effect of progressive CO_2 enrichment during the period 1961–2099 was not possible (Section 4.5.1) and the data for all four periods are all presented with and without CO_2 doubling (relative to baseline).

In the second approach, the objective was to determine if the basic grass-based system would continue to function when herd size was allowed to increase in response to the increases in grass production with climate change. In this case, the annual N strategy was held constant at the baseline level. The silage programme and the housing period were allowed to vary. The results indicated that the 11 sites may be conveniently grouped and presented as Western locations (Belmullet, Claremorris, Clones and Malin Head), Midland locations (Birr and Mullingar) and Eastern locations (Casement Airport, Kilkenny, Roche's Point and Rosslare). Valentia data are presented separately as this site did not consistently align with the other western sites. Carbon dioxide doubling is assumed for all three periods after baseline. In the first approach, the standard practice was followed of defining a winter housing period, appropriate to each location and climate, during which no grazing was allowed, but in the second approach no housing period was defined and housing was triggered only by the tactical criteria built into the simulator (herbage supply less than set criteria – see Section 4.4.2). Consequently, intermittent grazing could occur during winter, silage demand would be reduced and stocking rate would be slightly greater than it would be with a forced housing period. The most common current practise is to define and force a winter housing period, but it is not the universally accepted practise. The decision not to force a winter housing period is justified in the context that the objective was to explore the limits to intensification with climate.

4.7.4 *Maintaining baseline production (herd size) on well-drained soil*

On a well-drained soil the basic low-cost grass-based system continued to function with predicted climate change. Almost all the effects brought about by climate change were economically positive. It was possible to reduce farm area by approximately 10% with a corresponding increase in effective stocking rate on the remaining area (Table 4.15). The comparison between baseline and doubled CO_2 in the baseline period indicates that the effect was mainly due to CO_2 enrichment. Total N used was significantly reduced by climate change (Table 4.16) and there was a significant shift from early to late season applications. The reduction in total N was less in the drier east and midland locations where the shift to late season

Table 4.15. The effect of climate change at baseline CO_2 (COB) and CO_2 enriched (CO_2) on farm area and stocking rate. Well-drained soil.

Period	Location	Farm area (ha)		Stocking rate (cows/ha)	
		COB	CO_2	COB	CO_2
Baseline	Kilkenny	20	18	2.8	3.1
	Mullingar	20	18	3.0	3.3
	Claremorris	20	19	3.1	3.3
	Valentia	20	20	3.6	3.6
2020	Kilkenny	20	18	2.8	3.1
	Mullingar	20	17	3.0	3.5
	Claremorris	20	18	3.1	3.4
	Valentia	20	20	3.6	3.6
2080	Kilkenny	20	18	2.8	3.1
	Mullingar	20	17	3.0	3.5
	Claremorris	20	17	3.1	3.6
	Valentia	20	19	3.6	3.8

Table 4.16. Effects of climate change at baseline CO_2 (COB) and CO_2 enriched (CO_2) on N use. Well-drained soil.

Period	Location	COB				CO_2			
		Spring N (kg/ha)	Summer N (kg/ha)	Autumn N (kg/ha)	Total N (kg/ha)	Spring N (kg/ha)	Summer N (kg/ha)	Autumn N (kg/ha)	Total N (kg/ha)
1975	Kilkenny	135	180	45	360	0	90	0	90
	Mullingar	135	180	45	360	110	90	45	245
	Claremorris	135	180	45	360	120	90	0	210
	Valentia	135	180	45	360	65	70	30	165
2020	Kilkenny	112	164	85	361	0	60	120	180
	Mullingar	135	180	45	360	110	70	45	225
	Claremorris	135	180	45	360	120	45	45	210
	Valentia	112	164	85	361	55	60	30	145
2080	Kilkenny	112	142	105	359	0	120	120	240
	Mullingar	135	180	45	360	0	120	60	180
	Claremorris	115	175	55	345	90	45	60	195
	Valentia	110	130	120	360	55	60	60	175

applications was most marked. The pattern of response reflects the increase in summer drought in eastern areas with climate change.

The total area of silage cut was reduced by about 33%, from 17 to 12 paddock cuts, between baseline and 2080 (CO_2 doubled). First and second cuts were affected equally. The reduction in the silage programme was partly due to an increase in the mean yield per hectare cut, but was mainly due to a reduction in the amount used. The winter feeding period was reduced by about 1 month, mainly a result of an advance in the date of the start of grazing. Associated with the decrease in the silage programme was an increase in the fraction of grazed grass in the diet, from 0.61– 0.65 to 0.66–0.70. The one negative impact of climate change was that, as the silage area was reduced, there was less ground available for slurry spreading. The mean annual slurry surplus ranged 29–101 m^3 in baseline and increased to 35–142 m^3 with climate change. The increase was relatively small considering the large reduction in the silage land and the increase in stocking rate as these effects were offset significantly by the reduction in the winter housing period.

In general, the pattern of differences between locations was not affected by climate change. Between the four locations, Valentia and Kilkenny represent the two extremes of production. The stocking rate at Valentia was greatest in baseline climate and after climate change (Table 4.15). The greater productivity of the Valentia location is also reflected in that the reduction in N use with climate change was greater than at the other locations and was least at Kilkenny (Table 4.16). Similarly climate change had no effect on the relative values for grazing season duration, fraction of grazed grass in annual diet and total silage fed (all greatest at Valentia and least at Kilkenny).

4.7.5 Holding baseline production (herd size) on poorly drained soil

As in the case of the well-drained soil, the basic system functioned well on the poorly drained soil after climate change despite herbage production being limited by waterlogging and land access being restricted. The responses to climate change for poorly drained soils were qualitatively similar (with similar economic significance) to the responses on well-drained soils. In the poorly drained soil, farm area was only slightly reduced with climate change. However, the reduction in N use was greater than in the well-drained soil (Table 4.17).

Nitrogen use was completely eliminated at Claremorris and Valentia. At Kilkenny, N use was less reduced but, as in the case of the well-drained soil, its use was restricted to the summer and autumn. In the baseline period, the winter housing duration varied between 5.5 and 7 months, compared to 3–4 months in a well-drained soil. With climate change the winter housing period on poorly drained soil was reduced, but only to 5–6 months. The greater duration of the winter indoor

Table 4.17. Effects of climate change at baseline CO_2 (COB) and CO_2 enriched (CO_2) on N use. Poorly drained soil.

Period	Location	COB				CO_2			
		Spring N (kg/ha)	Summer N (kg/ha)	Autumn N (kg/ha)	Total N (kg/ha)	Spring N (kg/ha)	Summer N (kg/ha)	Autumn N (kg/ha)	Total N (kg/ha)
1975	Kilkenny	135	180	45	360	0	0	0	0
	Mullingar	135	180	45	360	0	0	0	0
	Claremorris	135	180	45	360	0	0	0	0
	Valentia	75	235	25	335	0	0	0	0
2020	Kilkenny	135	180	45	360	0	50	50	100
	Mullingar	135	180	45	360	0	0	0	0
	Claremorris	135	125	30	290	0	0	0	0
	Valentia	75	165	120	360	0	0	0	0
2080	Kilkenny	50	200	110	360	0	100	100	200
	Mullingar	75	190	95	360	0	60	0	60
	Claremorris	30	120	35	185	0	0	0	0
	Valentia	10	320	30	360	0	0	0	0

period on the poorly drained soils generated a significantly greater silage requirement compared to well-drained soils, but silage requirement was reduced with climate change. Under baseline climate between 18 (Kilkenny) and 32 (Valentia) silage paddock cuts were needed. With climate change the number of paddock cuts was predicted to be reduced to between 19 and 26. As silage became more important on the poorly drained soils the fraction of grazed grass in the diet of the cows was less than that needed on well-drained soil. In baseline climate, the fraction in poorly drained soil was 0.38 (Valentia) to 0.54 (Kilkenny), compared to 0.61 (Kilkenny) to 0.65 (Valentia) in a well-drained soil. With climate change this increased to 0.44 (Valentia) to 0.60 (Kilkenny), compared to 0.66 (Kilkenny) to 0.70 (Valentia).

The greater duration of the winter housing period and the reduction in the silage area on the poorly drained soil meant that slurry management becomes more problematic. Climate change aggravated the slurry disposal problem because surplus slurry was predicted to be approximately doubled from *c.* 100 m^3 to 220 m^3. The pattern of difference between locations was generally the same as in the case of the well-drained soil but was less distinct.

4.7.6 *System intensification with climate change on well-drained soil*

The trends in total grass production (Table 4.18) between locations show the effect of differences in rainfall between the east coast and western areas and between climate periods. In the first climate period, total grass production differed by about 10% between the east and west locations. All locations responded to irrigation but the response was greatest in the east and least in the west. With irrigation, differences between locations were relatively small. By 2080, production in the west without irrigation was predicted to be 20% greater than in the east but with irrigation there was no difference across the country.

Table 4.19. Effect of climate change on irrigation water demand (m^3/ha).

	Casement	Claremorris	Valentia
Baseline	1,614	361	507
2080	2,724	866	1,202

The volumes of water required for irrigation (Table 4.19) reflected the scale of the production responses. Full irrigation of the whole farm was assumed in all cases. Water demand per hectare increased between the baseline climate period and 2080 from 1,614 to 2,724 m^3 (equivalent to 161–272 mm rainfall) in the east, from 507 to 1,202 m^3 at Valentia and from 361 to 866 m^3 in the west. In the east, the demand per hectare of 2,724 m^3 by 2080 is equivalent to 54,480 m^3 on a 20-ha farm and this implies a water reservoir of 2 m depth covering almost 3 ha.

In the baseline climate period (non-irrigated), stocking rates varied between 3.1 cows/ha in the east and midlands to 3.2 and 3.5 in the west and Valentia, respectively. By 2080 (non-irrigated), stocking rates increased to between 3.9 cows/ha in the east and 4.6 cows/ha at Valentia. In the baseline period, irrigation gave relatively moderate increases in stocking rate, to 3.4 and 3.7 cows/ha in the east and at Valentia, respectively, but by 2080 the responses were much greater, to approximately 5 cows/ha.

In the simulations, a winter housing period was not defined and housing was triggered only when grass availability was insufficient. As a result some intermittent grazing occurred during winter and differences in housing days then provide some indication of differences in winter growth. Relative to baseline, the housing period decreased with climate change by about 1 week in the east and midlands and less in the west and Valentia. With irrigation, which did not affect winter growth, the housing period was

Table 4.18. Effects of climate change on total grass production (DM t/ha) for well-drained soil.

	Rain fed				Irrigated		
Period	**East**	**Midlands**	**West**	**Valentia**	**East**	**West**	**Valentia**
Baseline	14	15	16	17	16	16	18
2080	17	19	21	21	24	22	24

Table 4.20. Effect of climate change and irrigation on slurry surplus (m^3) for a well-drained soil.

	Rain fed				Irrigated		
	East	Midlands	West	Valentia	East	West	Valentia
Baseline	0	0	5	0	63	23	6
2080	0	3	60	3	251	196	144

greater by about 1 week in the west and about 2 weeks in the east due to increases in stocking rate. The changes in the duration of housing and in stocking rate affected the slurry surplus (Table 4.20). Without irrigation, surpluses of slurry only occurred in the west and Valentia after climate change. However, the significant increases in stocking rates with irrigation generated significant slurry surpluses at all locations and in all periods. The problem was least in the baseline period and was greatest in the east where surpluses reached 251 m^3 by 2080.

4.7.7 System intensification with climate change on poorly drained soil

The pattern of response in total grass production was broadly the same on poorly drained soils as for well-drained soils (Table 4.21). Total grass yield was about 10% less on the poorly drained soil and the climate change effect on production was slightly less than on the well-drained soil. Greatest predicted production was at Valentia and lowest production was predicted to be in the east. Total grass yield declined between 2010 and 2099 at all locations. Baseline climate stocking rates were 2.6–2.7 cows/ha, but with climate change stocking rates were predicted to increase to between 3.3 and 3.5 cows/ha for an intensification scenario. Lower production in the east compared with the west and a decline in production at all locations by 2080 (the same patterns as in the well-drained soil) indicate that summer drought might become a factor affecting production on poorly drained soils at all locations.

Irrigation was not applied in the simulations for the poorly drained soil.

The housing period was greater on the poorly drained soil at all locations (about 140 days in the east and about 200 days in the west and Valentia compared to 65 and 70 days in the east and west on well-drained soil) and associated with this was an increase in the problem of slurry surplus. The surplus slurry increased with climate change due to the increase in stocking rate (Table 4.22) with values up 400–500 m^3 in the west and Valentia being predicted. The east was affected to a lesser extent.

Table 4.22. Effect of climate change on slurry surplus (m^3/ha) on a poorly drained soil.

	East	Midlands	West	Valentia
Baseline	50	101	173	269
2080	98	206	438	478

4.7.8 Climate change and the seasonal distribution of grass supply for grazing

Apart from its effect on farm total annual grass production, climate change also significantly altered the pattern of grass supply for grazing during the grazing season. In baseline climate, grass supply was above the 500 kg DM/ha critical limit for tactical supplementation (or housing) from mid-March until early October at the midland, western and Valentia locations and until early September at the east location (Fig. 4.10). The earlier fall to the critical level in the east reflected late-summer drought. The peak in seasonal

Table 4.21. Effect of climate change on grass production (DM t/ha) and herd size on a 20-ha farm on poorly drained soil.

	Total DM				Cows			
	East	Midlands	West	Valentia	East	Midlands	West	Valentia
Baseline	13	14	14	15	52	52	51	55
2080	16	18	19	19	64	71	69	70

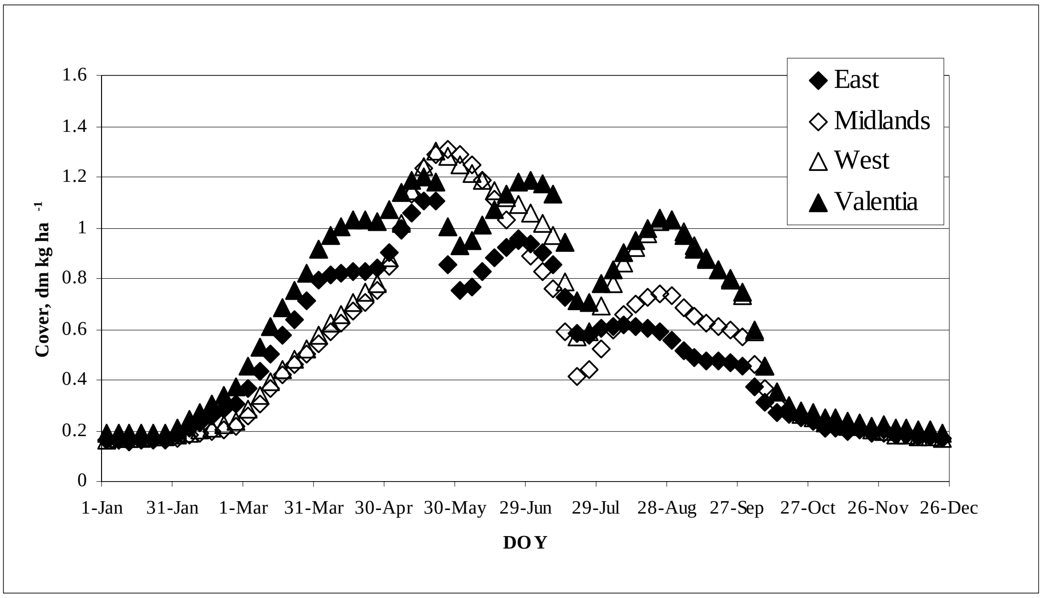


Figure 4.10. Seasonal distribution of grass available for grazing (Cover). Baseline climate – well-drained soil.

grass availability at all locations occurred about the end of May.

After climate change, by 2080, the season was brought forward (Fig. 4.11). The seasonal peak occurred earlier, in early April. Grass supply was above the critical limit from early March until end September in the west and at Valentia. In the east and midlands, the supply was low from mid-July on. The curves presented represent 30-year averages and at an average supply of less than 700 kg/ha from mid-July critical conditions would occur in late summer in a high

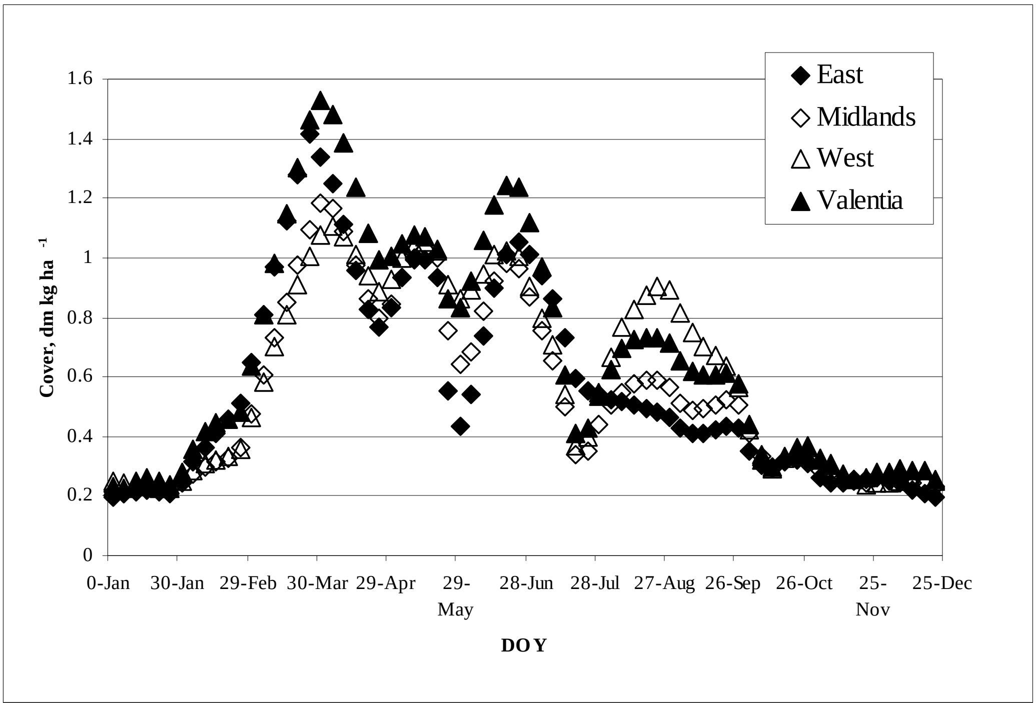


Figure 4.11. Seasonal distribution of grass available for grazing (Cover). 2080 climate – well-drained soil.

fraction of years at Valentia also. The persistence of critically low grass supply from mid-August in the east, midlands and probably Valentia as well suggests that, in these locations, a period of housing in mid-season would make it possible to allow grass supply to recover for a late season grazing period (this is the common practice in the Galicia region of north-west Spain currently). This possibility was not simulated.

4.7.9 Replacement of conserved grass forage with maize forage

Typical management of Irish dairy units is based on a low-cost spring-calving strategy with 90% of annual feed derived from grass grown on the farm. Almost 70% of feed is of grazed grass managed by rotational grazing, the remainder is conserved forage and concentrates. The objectives of the work presented here were to examine how the management system has to be modified when part of the dairy unit land is allocated to maize silage instead of grass silage production, and to examine how climate change might impact on grass and maize management within the production system.

Dairy_sim (well-drained soil without irrigation) was used to simulate the operation of a hypothetical farm for maximum production at three locations under baseline climate and under the climate conditions predicted for the climate period 2050 (2041–2070), and at 0, 10 and 20% allocation of dairy unit area to maize. Unit 1 was located in the warm, dry south-east (Wexford). Unit 2 was located in the cool, humid north (Leitrim) and Unit 3 in the warm, humid south (Cork) (Holden and Brereton, 2004). In each unit/climate/ maize scenario, the system was simulated for 30 successive years using weather data generated from monthly means by stochastic weather generation (Richardson, 1985; Geng *et al.*, 1986) from the data for Sweeney and Fealy (2003). The same weather data were used to simulate the production of a generic short-season maize type using the CERES-Maize Model (Jones *et al.*, 1984). The grassland management simulated was the same as the NDP described by O’Donovan (2000).

Under baseline climate the stocking rate at 0% maize area was 2.4 cows/ha for Units 1 and 2 and 2.7 for Unit 3. In the 2050 scenario, the rates were 2.6 for Unit 1 and 3.1 for Units 2 and 3. In all unit/climate scenarios stocking rate was reduced as the maize area increased. At 20% maize area, stocking rate was reduced by about 10% in all cases. The number of grass silage paddocks was reduced but the reduction did not compensate fully for the allocation of land to maize. Similarly, the reduction in land area for grazing also created a feed deficit at turnout and late in the season.

The conversion of part of a grassland unit to maize silage production would result in a stocking rate reduction over the range of production environments existing or predicted for Ireland. However in all cases, the stocking rate on the grass area of the unit increased, by more than 10% in most cases, as the maize area increased. This suggests that the acquisition of maize silage from outside the unit would enable significant increases in stocking rate within the unit, but the potential increases (to *c.* 3 cows/ha) are environmentally challenging. An alternative interpretation of the results is that the outsourcing of maize silage would allow a dairy unit to maintain an environmentally acceptable stocking rate using less N fertiliser.

4.8 Environmental Issues

This section will examine the close relationship between grass production, herd size and slurry surpluses.

4.8.1 Productivity and animal manures

The volume of manure generated daily during housing by cows of the type used in the simulations is approximately 107 l or 0.1 m^3 (at 6% DM and diluted by rain water, washing water and urine). The total volume of manure accumulated during housing is the product of this volume, herd size and housing days. In the system simulations it was assumed that slurry spreading was restricted to the first- and second-cut silage paddocks at 50 and 33 m^3/ha, respectively, as this ensures that all grazing land has grass of maximum palatability to the cows. As a result of these assumptions, the slurry surpluses calculated by *Dairy_sim* and reported in preceding sections are possibly overestimates because slurry may be applied more widely on the farm area (e.g. on the grazing area) if necessary. It is also theoretically possible to spread slurry in winter months, but this practice will be restricted by law and should not be considered by a responsible farmer.

The slurry surplus data (Tables 4.20 and 4.22) have been presented as an indication of the likely trends that may be expected with climate change. The total volume of manure produced during housing on the well-drained soil is predicted to vary between about 400 and 750 m^3. Volumes were lower in the east and Valentia compared to the midland and west locations (Table 4.23). On the poorly drained soil the volumes were greater by a factor of about two (700–1,400 m^3) than in the well-drained soil, but were still lower in the east. Climate change decreased the volumes in the management system that maintained baseline stocking rates (extensive) but increased the volumes in the system where the potential to increase stocking rate was exploited (intensive). The preceding sections have shown that the primary effect of climate change is to increase grass production.

4.8.2 Grass production and herd size

Total farm grass production is the primary determinant of farm output (or stocking rate). This was shown in the analysis of the sensitivity of stocking rate to the range of parameters that may vary within the simulated system (see Section 4.4.3). The close relationship between grass production and herd size was evident from the system simulations (Fig. 4.12).

However, there was a consistent difference between the geographical regions (east, midlands and west) which suggests that the number of cows supported per unit of grass production is approximately 8% greater in the east than in the west. The midlands are intermediate. It is significant that the different 'efficiencies' appear to be characteristic of the three regions because they are maintained with climate change. The relationships plotted in Fig. 4.12 assemble the data for all climate periods for each location. The different 'efficiencies' may be explained by differences in the proportion of total farm production

Table 4.23. The effect of climate change, management and location on manure production for a 20-ha dairy unit.

Soil	Management	Location	Manure total	
			Baseline	2080
Well drained	Extensive	East	678	476
		Midlands	756	606
		West	775	610
		Valentia	727	612
	Intensive	East	434	491
		Midland	533	664
		West	552	756
		Valentia	497	616
Well drained	Intensive	East	586	931
Irrigated		West	616	883
		Valentia	540	775
Poorly drained	Extensive	East	805	705
		Midlands	941	913
		West	1,022	931
		Valentia	1,198	1,098
	Intensive	East	749	902
		Midland	827	1,115
		West	1,051	1,297
		Valentia	1,182	1,365

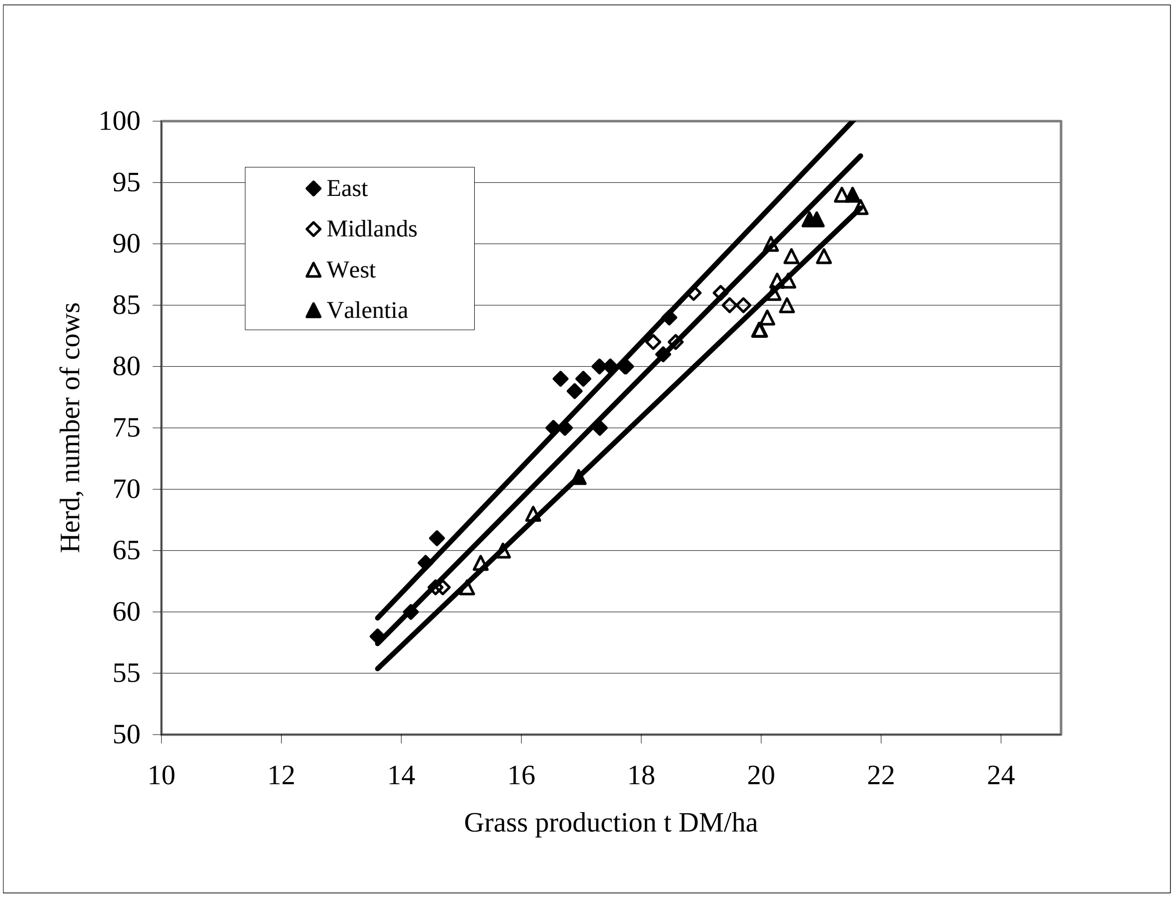


Figure 4.12. The relationship between grass production (t DM/ha) and herd size. DM, dry matter.

that is harvested as silage. Grazed grass is harvested and consumed directly by the animal with 100% efficiency. In contrast, at most 80% of the standing crop before harvest of silage is consumed by the animal. Up to 25% of the standing silage crop mass is lost during harvest, ensiling and feeding. In eastern locations, silage represented a smaller element in the total feed budget and consequently effective utilisation of total grass produced was greater. In the context of climate change, it is notable that the greater efficiency of the eastern locations is unaffected by climate change.

4.8.3 Grass production vs herd size vs silage balance vs slurry surplus

Despite the increase in summer water deficit, the principal effect of climate change is to increase total grass production in all locations, with or without irrigation and irrespective of soil type. As grass production increases stocking rate increases and the closed system, in terms of grass supply and demand, is maintained with climate change. The total 20-ha farm silage surplus accumulated over 30 years was usually between +50 and –50 t DM (in terms of the system, an insignificant amount – over 30 years it represents less than 2 t annually and less than 40 kg per animal per annum). It has, however, become increasingly important to recognise that animal slurry is also a significant product of the system and, like silage, the production and use of slurry needs to be balanced. The results of this study show that on a well-drained soil there is no surplus slurry until the system production of grass exceeds about 16.5 t/ha DM (Fig. 4.13), which represents a stocking rate of about 4 cows/ha in the west or 4.5 cows/ha in the east (Fig. 4.12). As system productivity increased beyond these limits slurry surpluses increased. In poorly drained soils the critical level of system productivity was significantly lower (Fig. 4.13), about 12.5 t/ha DM or 3.0 cows/ha. The critical levels of system productivity

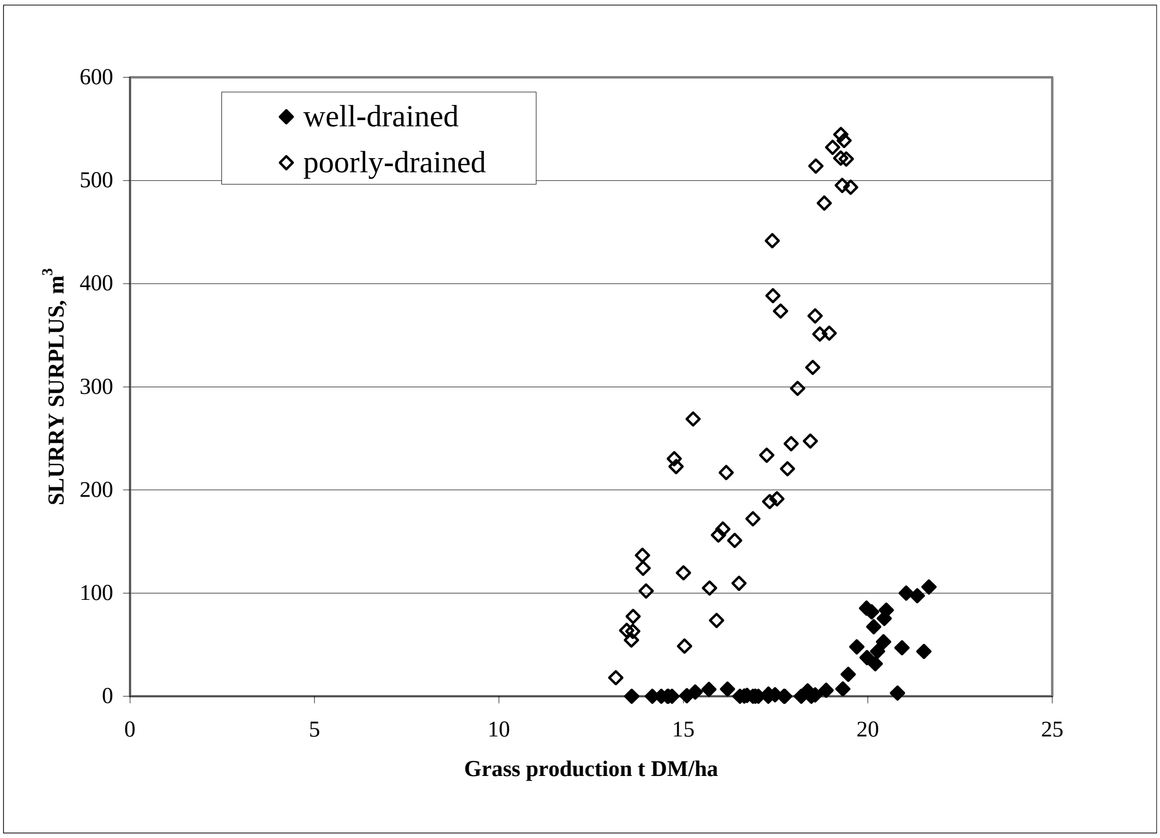


Figure 4.13. The relationship between slurry surplus (m^3) and system productivity (t DM/ha) on well- and poorly drained soils. DM, dry matter.

in both well-drained and poorly drained soils could be exceeded with climate change with an intensification scenario, so that it appears that the exploitation of the potential of climate change will be limited unless land outside the dairy unit is used for slurry disposal. An extensification scenario should, however, be workable.

4.8.4 Water deficit and water surplus

The main effects of climate on the system were the limits on growth through water deficit in summer and, in poorly drained soils, of waterlogging/trafficability in winter. As indicated by the irrigation tests the incidence of drought in the west was relatively low both in baseline climate and by 2080. Some drought tended to occur in July–August. Although the average number of days per year with water deficit greater than zero was more than 100, the frequency of that deficit in that period was less than 5 years in 10. The average number of days with a deficit that reduced growth by 25% was less and the frequency was much reduced. More severe droughts occurred by 2080 but these were rare. At the Valentia and midland locations, moderate drought (growth more than 25% restricted) was predicted to become more common with climate change; although severe drought (growth more than 50% restricted) increased in frequency with climate change it was still relatively uncommon by 2080. In the east, moderate drought was common in baseline climate and became more common with climate change. The drought tended to occur earlier with climate change. The frequency of moderate drought increased to over 8 years in 10 by 2080, and the frequency of severe drought increased to almost 7 years in 10. There were only slight differences in drought incidence and severity between well-drained and poorly drained soils.

In the poorly drained soils the number of days per year when the soil was usually un-trafficable (in more than 8 years in 10) was about 170 in the west but was less in the midland and east locations (about 120 and 100 days, respectively). The number of trafficable days was little affected by climate change. The number of days when growth was reduced by waterlogging was very close to the number of un-trafficable days at each location.

4.8.5 Estimates of potential changes in animal disease prevalence

Liver fluke infestation is the most economically important parasite in cattle and sheep in Ireland (Murphy *et al*., 2004). In order to identify some issues that may arise with regard to climate change and animal disease, it was decided to evaluate the potential for liver fluke infestation using the Ollerenshaw Index:

$$M_t = \left(\frac{P - ET_P}{25.4} + 5\right)N$$

where M_t is the monthly value of the index, P (mm) is the monthly precipitation, ET_p (mm) is the potential evapotranspiration and N is the number of rain days (>0.2 mm rain). When M_t exceeds 100 it is set to 100 except in May and October when the maximum value is halved (Murphy *et al*., 2004). The constant 5 is used to ensure that a positive value is always calculated and the constant 25.4 arises because the index was originally formulated when observations were made in inches (Mercer *et al*., 2001). When summed for the period May to October, the summer index is formed. When summed over October to May the winter index is formed. Summer index values in excess of 480 and winter index values in excess of 380 (Mercer *et al*., 2001) indicate potential for epidemic situations to arise.

Figure 4.14 shows the expected change in the Ollerenshaw Index based on the predicted climate, grass growth and soil conditions for the baseline and 2080 periods for systems optimised for intensification and extensification.

The baseline climate period data are very similar to those presented by Mercer *et al.* (2001), which suggests that the calculation of ET_p using the soil model in *Dairy_sim* was reasonably reliable. It can be

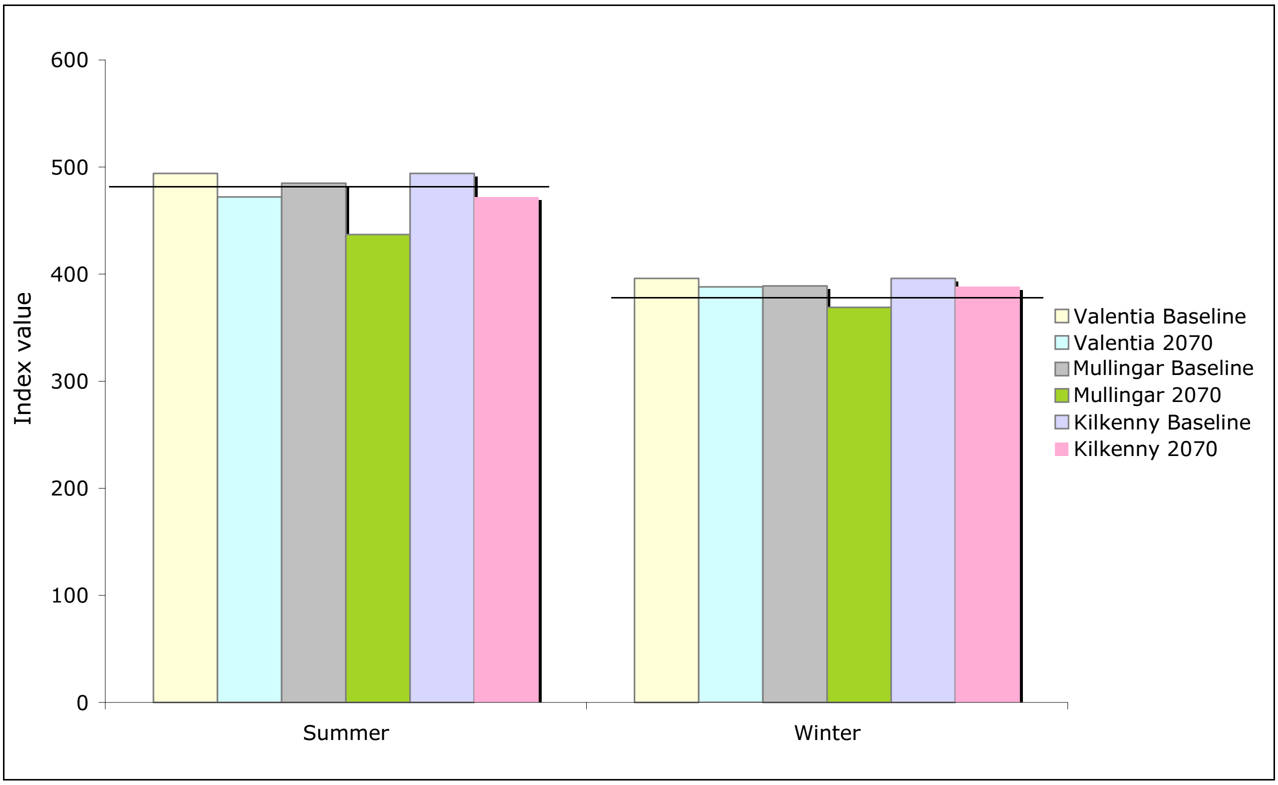


Figure 4.14. Predicted Ollerenshaw Index for summer and winter for the baseline and 2080 climate periods for well-drained soils. The horizontal lines represent critical thresholds for infection.

seen from Fig. 4.13 that, although there is a reduction in both indices with climate change, there is little change in the likelihood of epidemic conditions occurring.

4.8.6 *Some observations on changes in thermal stress to animals*

The criteria used to estimate the changes in days of cold stress and heat stress were based on the review by MacCarthy and Lynch (1986). The critical daily maximum temperature for heat stress used was 25°C. The minimum critical temperature for cold stress was varied according to rainfall and radiation levels of the day (Table 4.24).

The number of days of cold stress decreased with climate change (Table 4.25). The baseline cold stress tended to be greatest in the west but the decrease to 2080 was greater in the west locations (Malin Head, Belmullet) than at the other locations. In all periods cold stress days were least at Valentia and Rosslare. Heat stress days were very low in all periods at all locations but there was a small increase with climate change at the inland locations, Birr, Mullingar and Kilkenny. With climate change the reduction in the period of cold stress was due to the changes in spring and autumn. At Rosslare and Valentia, the end of the cold-stress period shifted from early in April to late March and the start of cold stress was shifted from mid-October to early in November. At the other locations the end of the period shifted from late to early April and the start of the period from late in September to mid-October.

Table 4.24. Critical minimum temperatures (°C) in relation to rainfall and radiation.

Radiation MJ/m^2/day	Precipitation (mm/day)	
	<1.0	**>1.0**
<8.0	–25	8
8.0–16.0	–35	5
>16.0	–40	0

4.9 Concluding Observations

4.9.1 *Spatial issues for system adaptation*

The range of results between the intensification and extensification scenarios, both of which can be optimised to permit a balanced system in terms of low-cost grass production, means that there is ample scope within dairy production systems to successfully adapt to climate change. The seven agro-climatic regions defined in Section 4.1.3 were used to generalise the results.

1. **East Ulster, East Leinster.** Warm (*c.* 9.5°C) and relatively dry (75 mm) causing water stress in grass, barley and potato, and to a lesser extent in maize.

   For dairying this is principally characterised by a high summer water deficit that restricts grass output and stocking rates. Water deficits will increase significantly with climate change but nevertheless increases in stocking rate or, alternatively, moderate reductions in fertiliser use will be possible. Reduced fertiliser N will be

Table 4.25. Predicted change of the effects of climate on thermal stress.

	Cold stress (days)				Heat stress (days)			
	Baseline	**2020**	**2050**	**2080**	**Baseline**	**2020**	**2050**	**2080**
Rosslare	135	135	121	110	0	0	0	0
Kilkenny	168	170	160	150	1	0	3	8
Birr	163	167	159	135	0	0	1	3
Mullingar	179	180	172	159	0	0	0	2
Malin	168	159	149	139	0	0	0	0
Belmullet	171	162	149	136	0	0	0	0
Valentia	154	145	126	107	0	0	0	0

concentrated in the second half of the season to counteract the increasing effects of water deficit. The N strategy will not fully counteract the feed deficit and there will be supplementation of grazed pasture. This may result in the introduction of a mid-season housing period. Irrigation would bring production in this area to the same level as other regions but the use of irrigation is unlikely because the volumes of water required are large. The effects of climate change are predicted to be similar in poorly drained soils, though output would be less, compared to the well-drained soils. The changes indicated should also apply to eastern and coastal parts of Region 6.

2. **Central Connaught.** Moderate temperatures (8.5–9.0°C) and average rainfall (86 mm), resulting in moderate to good yields of grass, barley, maize, potato and soybean. Average conditions with few extremes, moderate water stress and few growing season length limitations.

   The features of the system and climate change effects are expected to be similar to those in Regions 2, 3 and 4. Summer water deficit is expected to increase with climate change but not to the extent expected in Region 1. Otherwise the responses to climate change will be similar. Increases in stocking rate or, alternatively, decreases in N use will be greater. A similar shift in N use to summer and autumn is expected. The late-summer feed deficit will be less acute so that no major changes to the system are expected in this region and farmers should easily adapt to climate change. On poorly drained soils, production will still be possible, and may improve relative to baseline, but may not be competitive relative to well-drained soils. The scope for reducing nitrogen use will be greater on the poorly drained soils.

3. **Intermixed with Cluster 4 in Central Ulster.** Moderate temperatures (8.5–9.0°C) and dry to average rainfall conditions (82 mm) lead to moderate to good barley yield but poor to moderate grass, maize and potato yield. Some water stress limitations.

   For dairying, climate change effects will be similar to those described for Region 2. No major changes to the system are required in this region. There is scope for increasing output or minimising inputs and farmers should easily adapt to climate change. On poorly drained soils production will still be possible, and may improve relative to baseline, but may not be competitive relative to well-drained soils.

4. **Intermixed with Cluster 3 in Central Ulster.** Cool (<8.5°C) and average to wet (92 mm) (cooler and wetter phase of the intermixture of Clusters 3 and 4) conditions result in relatively poor grass, maize and soybean yield, but good barley yield and moderate potato yield. There are some growing season length limitations.

   For dairying, climate change effects will be similar to those described for Region 2. No major changes to the system are required in this region. There is scope for increasing output or minimising inputs and farmers should easily adapt to climate change. On poorly drained soils production will still be possible, and may improve relative to baseline, but may not be competitive relative to well-drained soils.

5. **West Ulster.** Cool temperature (<8.5°C) and relatively wet (105 mm) conditions lead to poor grass, maize and soybean yields but good barley and potato yields. There are some growing season length limitations.

   The dairying system and the expected effects of climate change in Clusters 5 and 7 are similar. No major changes to the system are required in this region. Production in these regions is greater than in Regions 1 to 4 (non-irrigated) and the difference will be maintained with climate change. There is little or no effect of water deficit in these regions at baseline and although the incidence of summer drought will increase with climate change, the effect will still be relatively unimportant. There is scope for increasing output or minimising N inputs but N will continue to be concentrated in the first half of the season. On poorly drained soils, it will be possible to maintain current stocking rates with little or no N. Production will improve relative to baseline, but still be lower relative to well-drained soils

6. **South and south-west Munster.** Warm temperatures (9.5–10.0°C) and relatively wet conditions (106 mm) lead to good grass, barley and maize yields and provide conditions with potential for crops such as soybean. Potato yield is limited.

   Region 6 is currently the area with greatest dairy output and this advantage will be maintained with climate change. No major changes to the system are required in this region. As in all the other regions there will be scope for increasing output or minimising nitrogen inputs. Summer drought will become more common than at present. The effect will be greater than in Regions 5 and 7, but will not affect the basic operation of the system. As in Regions 5 and 7 there is scope to eliminate nitrogen use in poorly drained soils without reducing production below its current level. The eastern parts of the region will tend to share the more extreme drought conditions of Region 1.

7. **North-west Connaught.** Moderate temperatures (*c.* 9.0°C) and wet conditions (107 mm) permit moderate yields of grass, maize and soybean but good yields of barley and potato. There is a possible temperature/season length limitation.

   The responses expected in this region will be similar to those described for Region 5. No major changes to the system are required. There is scope for maximising output or minimising inputs which will permit farmers to readily adapt to climate change. On poorly drained soils production will still be possible, and will improve relative to baseline, but will still be low relative to well-drained soils

4.9.2 Nitrogen and water balance for crops

- It can be concluded that there will be no major changes to system management necessary in order to maintain spring barley production with similar spatial distribution as currently found. Where rainfall remains adequate by the 2050 climate period, it is probably going to be possible to reduce the N application rates.

- For the potato crop, the simulations result in the conclusion that irrigation is going to be essential in most areas where potatoes are currently grown. For most places where potatoes are currently grown, between 150 and 300 mm of irrigation water will be required every year, but this will mean that the N application rates can probably be halved.

4.9.3 Dairy_sim *as a system simulation tool for evaluating climate change impacts and adaptations*

- *Dairy_sim* in its basic form is a useful tool for evaluating climate change impacts on dairy production systems.

- More field/laboratory work is required to permit a better formulated and tested model of CO_2 response for grass to be integrated into the system simulation. There is sufficient evidence to support implementing a fractional response to change in CO_2 based on other stresses on the grass plant.

- Integration of a simple soil model (based on water balance and grass growth) permits an evaluation of soil limitation to grass growth (excess and stress) and field access. These have implications for grazing days and slurry management.

- *Dairy_sim* in both its basic form (well-drained soil and CO_2 response) and with a soil component is not overly sensitive to uncertainty associated with the climate scenario data. Using EnsM data derived from multiple models and scenarios does, however, tend to lead to the prediction of more efficient systems compared to relying on data from specific models and scenarios. This is because the EnsM tends to smooth out seasonal extremes in the data set which means that the grazing system tends not to become as stressed as it does with the other data sets.

- There is no spatial trend associated with uncertainty propagated through the system simulation from the climate scenario data; therefore, it is acceptable to use the EnsM data for most impact/adaptation assessment purposes.

4.9.4 Climate change impact on dairy production and system adaptations

- On poorly drained soil, the stocking rate has to be reduced because there is less DM available on the farm and longer housing periods are required. With climate change, the relative improvement in the system is greater for poorly drained soils but they still lag behind well-drained soils in terms of the potential profit that could be extracted from the system (assuming target is maximum output).
- The conversion of part of a grassland unit to maize silage production would result in a system stocking rate reduction over the range of production environments existing or predicted for Ireland.
- There will be scope to increase production (intensification) while maintaining a balanced low-cost grazing system if policy and economic conditions merit such an approach to farming.
- There will be scope to maintain baseline output while reducing nutrient inputs (extensification) which is in line with current national and European environmental policy.
- There is a broad range of strategic and tactical management options available which means that dairy production in Ireland should be able to conformably adapt to potential climate change (within the range of uncertainty that exists) and remain viable in terms of output, relatively unchanged production system and potential for profit.

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5 The Impact of Climate Change on Semi-Natural Ecosystems in Ireland

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5.1 Introduction

It is clear from Chapter 2 that Irish climate in the 21st century is likely to be warmer, with drier summers, wetter winters and more variable patterns of rainfall and temperature. There is also evidence that the Irish climate is changing, in particular, through increasing air temperatures and changing patterns of rainfall (Sweeney and Fealy, 2002). A major cause of this is now recognised as due to the increasing concentration of carbon dioxide (CO_2) and other greenhouse gases (GHGs) in the atmosphere. Before the Industrial Revolution, the atmospheric CO_2 concentration was about 270 ppm but it has now risen by about 30% to 375 ppm. Unless severe controls are placed on GHG emissions it is predicted that CO_2 concentrations will rise to 530 ppm by 2050 and could exceed 700 ppm by 2100 (IPCC, 2007). Clearly, assessing the long-term impacts of future climate change at both the plant species and the ecosystem levels presents major challenges because of the complex and interacting changes in the environment which will take place over space and time.

Evidence of the impact of global warming in the last half of the 20th century on the phenology of plants has been widely reported (Walther *et al.,* 2002), while long-term records of the timing of phenological stages of plants have been successfully used in Ireland to indicate changes in climate, in particular spring warming. In Ireland, the leafing of some trees species is now occurring 30 days earlier than 30 years ago (Sweeney *et al.,* 2002; Donnelly *et al.,* 2004, 2006) and it is anticipated that these changes will continue to occur into the future as a consequence of increasing temperature.

There is a great deal of evidence that climate determines the large-scale distribution of many temperate plant species (Woodward, 1987) and changes in climate have a profound influence on species range and expansion (Walther *et al.,* 2002; Walmsley *et al.,* 2007). Climate envelope models (also known as ecological niche models) (Pearson and Dawson, 2003) provide valuable insight into the extent and location of a species' potential distribution under predicted climate scenarios. The climate envelope simply represents the full spectrum of climates encountered within the distribution of a species.

There have been a number of recent criticisms of the climate envelope approach, including the view that they are too simplistic (Hampe, 2004) and that they fail to recognise that the species distributions that we observe today may not be in equilibrium with the current climate (Woodward and Beerling, 1997). Furthermore, the effects on species distributions of biotic interactions, physical barriers to dispersal and human management mean that the realised niche does not represent the absolute limits to the species range. Consequently, correlating current climate with the observed species distribution may not therefore identify the full potential climate range of the species (Pearson and Dawson, 2003). Despite these deficiencies Huntley *et al.* (2004) have recently demonstrated that the distribution of species from diverse taxonomic groups and representing different life forms and trophic levels can be modelled successfully using a limited number of bioclimatic variables. Furthermore, projections made using species-climate envelope models have been used widely to support estimates of species extinction risks under climate change for a large number of taxa (Huntley *et al.,* 1995).

As a result of future climate change in Ireland, we expect to see changes in species behaviour and ecosystem distribution across Ireland. In order to predict these changes, we examine first the timing of life cycle events (phenology) such as leafing of trees, which are influenced primarily by temperature. In particular, we describe how changing spring temperature can influence phenology of tree species and how modelling of this can help predict the timing of these events in future. Secondly, we assess the influence of changing temperature and rainfall patterns on vulnerable ecosystems and in particular focus on wetlands.

5.2 Impact of Climate Change on Phenology

Phenology is the study of periodic biological events, such as the onset of spring plant growth and flowering, migration of birds or insect appearance dates, all of which are triggered by environmental signals (Schwartz, 1999, 2003) and can be used as indicators of elements of global change. Because there is a predictable relationship between phenology and climate, long-term phenological observations on trees, such as the dates of bud burst, flowering, leaf discoloration and leaf fall, provide historical records showing how climatic conditions have changed at the local level.

There has been interest for many years in the recording of phenological events by natural historians, particularly across Europe. For example, the Royal Meteorological Society in the UK established a phenology network in 1875 (Sparks *et al.,* 2000a) and Finnish phenological records go as far back as 1748 (van Vliet and de Groot, 2001). Despite changes in recording methods since the initiation of these programmes, the importance of these historic records as indicators of environmental and climate change is now well established (Sparks *et al.,* 2000a) and examination of long-term phenological data sets has provided measures of biological responses to climatic variation (Sparks and Carey, 1995). However, interpretation of these data records, in terms of identifying the exact causal relationship between climate and development and extrapolation to larger geographic regions, presents a challenging problem for environmental modellers (Schwartz, 1999).

In this section, we provide an inventory of phenological data sets available in Ireland, examine trends in historical records of tree phenology and investigate environmental triggers of bud burst in *Betula pubescens*.

5.2.1 Inventory of phenological data sets in Ireland

The systematic collection of phenological data on trees in Ireland started in 1966 with the establishment of four gardens in the International Phenological Garden (IPG) network (Chmielewski and Rötzer, 2001). In spring of 2004, an additional IPG was established at Armagh Observatory, in Northern Ireland. The IPG network was established in 1959 to collect phenological data from sites across Europe. Vegetatively propagated clones of trees and shrubs were planted at each site in order to standardise the experimental material and avoid varietal differences in response to climate. There are 63 IPGs throughout Europe, recording data from 24 tree species (http://www.agrar.hu-berlin.de/pflanzenbau/agrarmet/ipg.html). The data collected at each site in Ireland have been collated by Met Éireann (the Irish Meteorological Service), before being sent to the co-ordinator of the IPG at Humboldt Universitat in Berlin. A preliminary analysis of these data revealed that spring phenophases of some trees could be used as an indicator of climate change in Ireland (Sweeney *et al.,* 2002).

Other sources of phenological data on plants collected in Ireland include agro-phenological data for the development of models that determine the appropriate timing of fungicide application. Accumulated thermal time drives the phenological models for fungicide application to winter wheat developed at Teagasc, Oak Park. In addition, as part of various European collaborative projects investigating the effect of climate change and air pollutants on agricultural crops (spring wheat and potato), phenological data were collected to determine the impacts of increasing atmospheric concentrations of carbon dioxide and ozone on certain developmental stages of these crops (Donnelly *et al.,* 2000; Finnan *et al.,* 2002). Finally, the relationship between disease incidence and phenological development for winter and spring cereals and potato has been investigated by the Department of Agriculture and Rural Development in Northern Ireland.

Another important source of phenological data in Ireland can be derived from the Irish East Coast Bird Reports which are produced by BirdWatch Ireland (formerly Irish Wildbird Conservancy). These annual reports monitor bird behaviour along the east coast of Ireland and provide more than 20 years of data on arrival times of migratory birds as well as sightings of rare species in the area. An examination of the timing of arrival dates of long-distance migrant species to Ireland is currently under way and preliminary results would suggest that many of the bird species are arriving earlier over the 20-year period from 1980 to 2000 and that this is influenced by increasing spring temperature.

In addition, phenological observations on butterfly appearance dates at different locations in Ireland (http://www.butterflyireland.com/phenology.htm) have been recorded by Dublin Naturalists' Field Club (supported by the Heritage Council Wildlife Grant Scheme). The database covers the years 2004 and 2005 and divides the butterflies into indigenous and migrant species. The information provided includes common name, scientific name and dates of first and last sightings. Finally, a limited amount of data (1997–2003) of frog spawning dates are available from the Irish Frog Survey (http://www.ipcc.ie/hopline.html) by the Irish Peatlands Conservation Council.

Our survey has revealed that currently there are more phenological data available for plant species than for animals or insects in Ireland but, undoubtedly, there are other sources of phenological data still to be found. Unfortunately, there has been little co-ordination of these data to date although with the establishment of Nature's Calendar – Ireland (http://www.biology.ie) in February 2004 this situation is being addressed by establishing a phenology network for the whole of Ireland. However, the scheme is voluntary and clearly requires a greater level of support.

5.2.1.1 Summary of the current status of phenological data collection and use in Ireland

- Spring phenophases of tree species used as an indicator of climate change
- Investigation of the environmental triggers of spring phenological phases of tree species
- Development of mechanistic models for bud burst of tree species
- Recording of arrival dates of long-distance migrant bird species to the east coast of Ireland as an indicator of climate change
- Phenological models for fungicide application to winter wheat by Teagasc
- Investigations of the relationship between disease incidence and phenological development for winter and spring cereals and potato by the Department of Agriculture and Rural Development Northern Ireland (DARDNI).

5.2.2 Analysis of long-term phenological records

The need for more in-depth analysis of the Irish phenological data as indicators of climate change was highlighted during a previous EPA-funded project entitled *Climate Change Indicators for Ireland* (Sweeney *et al.,* 2002). As part of that project, the timing of spring phenological phases from a suite of tree species was identified as being a useful indicator of increasing spring temperatures. Preliminary analysis of the data suggested that the beginning of the growing season (defined as the date of leaf unfolding) showed the greatest sensitivity to climate differences. There was less evidence to suggest that the end of the growing season (the date of leaf fall) occurred later. Data from the four phenological gardens in Ireland, that are members of the IPG network, were used. These gardens are located at Valentia, Co. Kerry, John F. Kennedy Arboretum (JFK), Co. Wexford, Johnstown Castle (JC), Co. Wexford and the National Botanic Gardens (NBG) in Dublin. However, the data have been subjected to a more rigorous and sophisticated statistical approach (described below) than in the previous report.

In Europe, warming has been detected in the form of an increased mean annual air temperature of between 0.3°C and 0.6°C since 1900, with further increases of as much as 2°C above the 1990 levels being predicted by 2100 using climate models (European Environment Agency, 1998). There is now little doubt that climate is warming on a global scale but change at a local level may be more variable and subtle and therefore more difficult to detect (IPCC, 2007). One approach to assessing effects of climate change at a local level is through establishing the relationships between developmental processes in living organisms (phenology) and seasonal climatic conditions and using these relationships as indicators of ambient climate.

In mid-latitudes, bud burst, leaf emergence and flowering of many species are dependent on spring air temperatures (Sparks *et al.*, 2000b; Chmielewski and Rötzer, 2001). Numerous studies, particularly in Europe and North America (Ahas, 1999; Beaubien and Freeland, 2000; Menzel, 2000; Sparks *et al.*, 2000a; Defila and Clot, 2001; Chmielewski and Rötzer, 2001; Badeck *et al.,* 2004) have shown that the timing of spring events has become earlier, particularly since the 1970s and the earlier onset of spring growth in plants in temperate climates (Schwartz, 1999) has been used as an indicator of climate change. On the other hand, the timing of autumn events such as leaf discolouring and leaf fall has shown less change (Chmielewski and Rötzer, 2000; Menzel, 2000; Defila and Clot, 2001) over the same time period. This suggests that the length of the growing season (LGS) is increasing mainly due to the earlier onset of spring and that factors other than temperature, such as photoperiod and increasing atmospheric CO_2 concentration, may have a stronger influence than temperature on the timing of events at the end of the growing season.

5.2.3 Methodology

For the purpose of this study, data from nine tree cultivars (see Table 5.1) common to most of the Irish sites were analysed. Statistical analysis was performed on data collected between 1970 and 2000. The phenological stages recorded for each cultivar included beginning of unfolding of leaf (i.e. beginning of the growing season) (BGS) and leaf fall (i.e. end of the growing season) (EGS). The LGS was calculated from the number of days between BGS and EGS. Beginning of leaf unfolding is recorded when the first regular surfaces of leaves become visible in several places (about three to four) on the observed plant. Leaf fall is recorded when half of the leaves of the observed plant have fallen.

In order to test the relationships between phenological stages and climate, average monthly air temperature data from each site, provided by Met Éireann, were correlated with phenological stages.

The Pearson correlation statistic was used to test the sensitivity of the phenological stages to temperature. Linear regression was used to test the relationships between BGS and spring temperature and LGS and annual average temperature. A structural time series model was used to analyse the trends in phenological stages and spring temperatures at each site (Brockwell and Davis, 1996). This method uses a local linear trend model assuming a time-varying local slope. This stochastic trend will not generally show a monotonic increase or decrease over time. However, a test of significance of the slope may be carried out by looking at the *t*-statistic of the local slope estimator and treating it as asymptotically normal (de Jong, 1989; Harvey, 1989). This approach can handle missing data and is therefore particularly useful for phenological data, where missing or unreliable records can arise.

5.2.4 Results

5.2.4.1 Timing of the beginning and the end of the growing season

According to the results of the structural time series analysis, BGS at all sites has become significantly earlier since recording began for some, but not all, species/cultivars (Table 5.1; Fig. 5.1). At Valentia, all species/cultivars, except *Betula pubescens* (P = 0.0753) (Fig. 5.1a_i), are now leafing earlier than in the 1970s. At the other three sites, advancement of BGS has been much less marked with only three species/cultivars at the JFK and the NBG and two species/cultivars at JC showing significantly earlier leaf unfolding. At the NBG, data collected for both *Prunus* cultivars prior to 1983 have been omitted from statistical analysis because of an anomalous and sudden 50-day delay in BGS (Fig. 5.1) as a result of which the data were considered to be unreliable.

Fewer data were available for EGS than for BGS (Fig. 5.1). Insufficient data for *Prunus avium* at the JFK (Fig. 5.1f_{ii} and 5.1g_{ii}) and *Populus tremula* at the NBG (Fig. 5.1e_{iii}) have prevented effective statistical analysis. Also, very few consecutive data were available for *Populus* at the JFK (Fig. 5.1d_{ii} and 5.1e_{ii}) so that

Table 5.1. (a) P value of the temporal contrast test statistics for the beginning, the end and the length of the growing season at four phenological gardens in Ireland. NA, data not available; NV, statistical test not valid due to lack of data. Significant temporal contrast ($P \leq 0.05$) in bold. (b) Number of species showing change in a particular direction for each of the phenological stages. Valentia is Valentia Observatory, JFK is the John F. Kennedy Arboretum, NBG is the National Botanic Gardens in Dublin and JC is Johnstown Castle. No change refers to those changes that are not statistically significant, while Earlier or Later represents whether the smoothed curve (after structural time series analysis) was increasing or decreasing.

(a) Species/cultivar	Beginning of growing season				End of growing season				Length of growing season			
	Valentia	JFK	NBG	JC	Valentia	JFK	NBG	JC	Valentia	JFK	NBG	JC
Betula pubescens	0.0753	**0.0392**	0.1132	0.4254	0.1330	**0.0126**	0.8840	0.1880	0.9864	**0.0262**	0.5816	0.2882
***Fagus sylvatica* 'Har'**	**0.0017**	0.0635	NA	0.0587	**0.0000**	0.1006	NA	0.9235	**0.0016**	0.0593	NA	0.4399
***Fagus sylvatica* 'Tri'**	**0.0012**	0.5223	NA	NA	**0.0344**	0.4891	NA	NA	**0.0001**	0.5122	NA	NA
Populus canescens	**0.0004**	0.0640	0.8880	**0.0032**	**0.0443**	0.3273	**0.0231**	**0.0049**	**0.0021**	0.1556	**0.0149**	**0.0007**
Populus tremula	**0.0002**	0.0772	0.1709	0.1573	0.3964	**0.0189**	NV	0.1396	**0.0012**	0.4946	NV	0.4731
***Prunus avium* 'Bov'**	**0.0291**	**0.0383**	**0.0444**	0.1368	**0.0003**	NV	**0.0019**	0.1460	**0.0011**	NV	**0.0283**	0.0886
***Prunus avium* 'Lut'**	**0.0408**	0.2893	**0.0426**	**0.0023**	**0.0023**	NV	**0.0231**	0.2029	**0.0013**	NV	**0.0385**	0.0872
Sorbus aucuparia	**0.0032**	0.5917	NA	NA	**0.0031**	**0.0019**	NA	NA	**0.0029**	**0.0027**	NA	NA
Tilia cordata	**0.0016**	**0.0272**	**0.0016**	0.5044	**0.0032**	0.6771	0.6554	0.0746	**0.0081**	**0.0262**	0.0660	**0.0235**

(b) Species showing change	Earlier	Later	No change	Earlier	Later	No change	Longer	Shorter	No change
Valentia	8	0	1	0	7	2	8	0	1
JFK	3	0	6	1	2	4	1	2	4
NBG	3	0	3	1	2	2	0	1	4
JC	2	0	5	0	1	6	1	1	5

Figure 5.1. Day of year on which leaf unfolding (end of dark grey bars) and leaf fall (beginning of light grey bars) occurred, from 1970 to 2000, for each of the tree species at all sites. The length of the growing season is represented by the number of days between leaf unfolding and leaf fall (white area on graphs).

statistical analysis was less reliable than for the other data sets. At Valentia, seven of the nine species/cultivars observed showed a later EGS (Table 5.1; Fig. 5.1). At sites other than Valentia, although the majority of species showed no change in the date on which leaf fall occurred over the observation period, some showed a trend towards earlier EGS. For example, leaf fall is now occurring later than in the 1970s for *Betula pubescens* at the JFK (Fig. $5.1a_{ii}$) and *Populus canescens* at the NBG (Fig. $5.1d_{iii}$).

5.2.4.2 *Correlation of the beginning of the growing season with temperature*

There were significant negative correlations between the average spring air temperature (February to April inclusive) and BGS at most sites over the period from 1970 to 2000 (Table 5.2). At Valentia and the JFK, an increase of 1°C in average spring temperature resulted in an advance of BGS by approximately 7 days and 4 days, respectively, and at both locations *Populus* showed a greater advancement than the other species/cultivars (Table 5.2). For most cultivars at JC, an increase in spring temperature of 1°C resulted in BGS advancing by 7 days but at the NBG only one species (*Prunus avium*) showed such a trend.

5.2.4.3 *Changes in the length of growing season*

At Valentia, the LGS, as indicated by the number of days between BGS and EGS, increased for all trees except *Betula* over the 31 years from 1970 to 2000 (Table 5.1; Fig. 5.1). In contrast to this, only a small number of the trees at the other sites showed any increase in the length of the growing season. Consequently, at Valentia there was a significant correlation between LGS and average annual air temperature but there was no relationship at the other sites (Table 5.2). At Valentia, an increase of 1°C in annual temperature resulted in an increase in LGS of between 9 days for *Sorbus aucuparia* and 29 days for *Fagus sylvatica* 'Tri' (Table 5.2).

5.2.4.4 *Consequences of changing temperature on phenological development of tree species*

Here structural time series analysis was used to model the trends in tree phenophases over time. In the past,

Table 5.2. Pearson correlation between the average spring (February to April) air temperature and the beginning of the growing season (BGS) and the average annual temperature and the length of the growing season (LGS). Correlations significantly different from 0 (P ≤ 0.05) in bold. Valentia is Valentia Observatory; JFK is the John F. Kennedy Arboretum, NBG is the National Botanic Gardens in Dublin and JC is Johnstown Castle. NA, data not available; NV, statistical test not valid due to lack of data. Number of days refers to the number of days increase or decrease in response to a 1°C increase in temperature.

Species	Spring temperature *vs* BGS				Annual temperature *vs* LGS			
	Valentia	JFK	NBG	JC	Valentia	JFK	NBG	JC
Betula pubescens	**–0.54**	**–0.42**	0.02	**–0.70**	**–0.43**	–0.16	–0.12	0.30
Number of days	–7	–5	0	–9	15	5	1	8
***Fagus sylvatica* 'Har'**	**–0.49**	**–0.48**	NA	0.12	**–0.35**	–0.02	NA	–0.16
Number of days	–6	–4	NA	1	16	4	NA	–3
***Fagus sylvatica* 'Tri'**	**–0.46**	**–0.55**		NA	**–0.51**	–0.04		NA
Number of days	–6	–4			29	1		
Populus canescens	**–0.72**	**–0.62**	0.22	**–0.37**	**–0.46**	–0.11	–0.62	–0.27
Number of days	–10	–7	1	–6	10	–3	–15	–1
Populus tremula	**–0.61**	**–0.60**	0.26	0.36	**0.37**	0.22	NV	0.03
Number of days	–12	–7	1	2	11	6		3
Prunus avium 'Bov'	**–0.60**	**–0.33**	**–0.84**	**–0.49**	**–0.40**	NV	0.67	–0.09
Number of days	–7	–4	–8	–6	15	NV	14	–2
***Prunus avium* 'Lut'**	**–0.69**	**–0.34**	**–0.76**	**–0.57**	**–0.34**		0.72	0.18
Number of days	–7	–4	–6	–7	12		11	5
Sorbus aucuparia	**–0.51**	**–0.23**	NA	NA	**–0.25**	0.53	NA	NA
Number of days	–7	–2			9	–2		
Tilia cordata	**–0.62**	**–0.41**	–0.34	**–0.42**	**–0.47**	–0.49	0.59	–0.05
Number of days	–8	–3	–2	–6	23	8	5	–1

linear regression has been the most widely used model for describing trends in these types of data but this approach has been found to be unsatisfactory in dealing with stochastic variation in climate data (Chmielewski and Rötzer, 2001). The natural stochastic variation of temperature through the years introduces a level of noise that can remove meaningful estimation of change by linear regression. Indeed, the proportion of variance explained by linear regression in our study was extremely small (i.e. R^2 ranged between 0.002 and 0.50 for BGS). In contrast, the structural time series analysis used here takes seasonal and yearly stochastic variations into account. It is capable of isolating the effect of climate change from the noise, and allows a much better characterisation and testing of the trend in the current data (Brockwell and Davis, 1996).

As the unfolding of leaves is primarily a response to ambient temperatures prior to and during the process (Chmielewski and Rötzer, 2001), BGS correlated with spring (February–April) air temperatures, at least for some species, at all phenological gardens in Ireland. Overall, the phenological responses over the period 1970–2000 clearly showed advances in BGS. According to these data, an increase of 1°C in average spring temperature leads to an averaged advance in leafing of approximately 1 week. This is in agreement with Sparks *et al.* (2000a) and Chmielewski and Rötzer (2001), who also reported that BGS of trees across Europe advanced by approximately 1 week as a result of a 1°C increase in spring air temperature. However, this averaged spring advancement has been shown to vary depending on location and species. Likewise, in Ireland, at the south-western site (Valentia) *Populus* showed the greatest advancement in BGS.

When analysing phenological data on leaf unfolding for the period 1969–1998 for a group of four species (*Betula pubescens, Prunus avium, Sorbus aucuparia* and *Ribes alpinum*) across Europe, Rötzer and Chmielewski (2000) and Chmielewski and Rötzer (2001) found a 6-day per decade advancement for the British Isles/Channel Coast region which included Ireland. The average advancement for the whole of Europe was 3 days per decade according to Chmielewski and Rötzer (2001), while a 2-day per decade advancement was reported by Menzel (2000) based on 751 observations from the IPGs across Europe between 1951 and 1996. A possible reason for the different values reported by these authors is because different species were used in each study. According to Chmielewski and Rötzer (2001), BGS for the whole of Europe is expected to advance by 7 days with an increase of 1°C in spring temperature.

In this analysis, we have adopted a simplistic model where leaf unfolding is assumed to be directly proportional to average spring temperature. An alternative approach is to hypothesise that leaf unfolding is controlled by accumulated temperature above a threshold. Furthermore, there may also be additional environmental drivers such as winter chilling temperatures and photoperiod. The danger of attributing advancing BGS simply to average spring temperature is illustrated by a comparison of the data obtained from the NBG and Valentia. Even though the recorded spring air temperatures at the NBG increased at a faster rate than at Valentia this was not reflected in an earlier start to leafing for some species/cultivars. The answer to this anomaly may lie in the fact that the average spring temperature was higher at Valentia and, possibly more significantly, the minimum temperature was also higher. If phenological models of leaf development assume that temperate trees require a threshold temperature of between 0 and 5°C before there is a proportional response to increasing temperature (Rötzer *et al.,* 2004) our data show that a threshold temperature will not have been reached as often at the NBG as at Valentia, with the result that all species have shown earlier leafing at Valentia.

At all Irish sites, some, but not all, of the species have shown a progressively later EGS over the observation period. As was the case for spring events, the strongest signal came from the south-west of the country at Valentia. However, an **earlier** onset to EGS was found for some species (e.g. *Betula pubescens* at the JFK) and similar results have been reported in both the UK (Chmielewski and Rötzer 2001) and Germany (Menzel *et al.*, 2001). Menzel *et al.* (2001) also observed both later and earlier autumn events for many species across Germany but they stressed that autumn events were less sensitive to a change in climate than spring events due to the influence of other environmental triggers such as day length. In other work, autumn phenophases have been advanced, delayed or failed to change in the same cultivar/ species across large geographical areas, indicating a possible site-specific nature of the phenological responses (Sparks and Carey, 1995). Consequently, great care must be exercised in attempting to extrapolate phenological responses across large areas.

For many species the LGS increased due to both an earlier start to the growing season and a delay in the date on which leaf fall occurred. The greatest increase in LGS was observed in the south-west of the country at Valentia. At other European locations where LGS has increased it has also been due primarily or exclusively to an earlier start to spring (Rötzer and Chmielewski, 2000; Chmielewski and Rötzer, 2001; Menzel *et al.,* 2001). At Valentia, for those species that responded, an increase of 1°C in annual average temperature resulted in an average 2-week extension to LGS, whereas the average increase at the other Irish sites was 5 days. Chmielewski and Rötzer (2001) also reported a 5-day lengthening of the growing season for Europe as a whole, while White *et al.* (1999) found a similar extension for the eastern USA, with an increase of 1°C in annual average temperature.

The results of this study have shown that in Ireland, along with an increase in mean spring and mean annual temperature, the timing of phenological events has advanced in the case of BGS and delayed in the case of EGS over the last 30 years, particularly in the south-west of the country. However, the spring phenological response could not be explained simply by average spring temperature, indicating an influence of other environmental factors on phenology. Consequently, average spring temperature in Ireland may not be a reliable predictor of BGS. The challenge is now to isolate the precise temperature variables and other environmental conditions that are influencing BGS. As with all environmental indicators, care must be taken in defining both the indicator, in this case phenophase, and the parameter being indicated, in this case average spring temperature. While it is widely accepted that temperature is a driver of phenology, the temperature influence on spring phenophases appears to be far more subtle and complex than average spring temperature.

5.3 Identifying Environmental Triggers of Tree Phenophases

While we can demonstrate that there is a relationship between the timing of spring phenophases and temperature, the effect of other environmental factors has not been fully considered in models of spring phenology. Most studies simply establish a linear relationship between the timing of the observation and accumulated thermal time. In addition, while this approach provides some information on how spring phenology responds to spring temperature (i.e. during the phase of quiescence, or ecodormancy), it does not take into account the earlier stages of dormancy (endodormancy), during which low temperatures are the dominant driver. Endodormancy is broken by ‘chilling fulfilment’, which is usually defined as the accumulation of a certain number of hours (or days) at temperatures below about 10°C (Sarvas, 1974; Battey, 2000). With global warming, we face the threat of warmer winters during which the chilling requirement of trees might not be fulfilled.

Understanding the impacts of climate on plant phenology will improve only if all environmental drivers are incorporated into mechanistic phenology models, taking into account the biological processes underlying plant development. For this reason, more experimental studies that explore the response of plant phenophases to their environmental triggers during all the phases of winter rest (dormancy induction, endodormancy and ecodormancy) are necessary. The aim of this study was to test experimentally the effect of different environmental drivers on bud burst, so that a better mechanistic understanding of the processes leading to growth onset and more comprehensive models of plant phenology can be developed (Chuine, 2000).

5.3.1 Methodology

Five tree species from the Irish IPG sites were sampled and vegetatively propagated during the spring and summer of 2003. The selected species were *Betula pubescens*, *Fagus sylvatica*, *Salix aurita*, *Salix smithiana* and *Tilia cordata*. The choice was based on the results of a previous study (Sweeney *et al.,* 2002), which suggested *Betula pubescens*, *Fagus sylvatica* and *Tilia cordata* as the most responsive IPG species to variations in spring temperature. The two *Salix* species were selected because of their ease of propagation.

Eight experiments in controlled environmental conditions were performed on the clonal material, which was either in the form of potted trees or bud sticks between 2003 and 2005. The tested environmental factors included temperature, photoperiod, light intensity and nutrient availability (see Table 5.3 for a more detailed description of the treatments and Table 5.4 for a list of the species tested in each experiment). The experiments were designed to investigate their main effects and interactions during the different phases of winter rest on the timing and percentage of bud burst, as follows:

1a Main effects and interaction of chilling duration and spring photoperiod

1b Effect of forcing temperature on fully chilled bud sticks

1c Effect of light intensity on fully chilled bud sticks

Table 5.3. Treatments received by the clones of *Betula pubescens*, *Fagus sylvatica*, *Salix smithiana*, *Salix aurita* and *Tilia cordata* in each of the experiments performed during the study. 'Daily records' refers to non-controlled temperature (received outdoors or in the glasshouse) which was nonetheless recorded daily or obtained from a nearby weather station.

	Dormancy induction			Chilling			Forcing		Additional factors tested
	Temperature (°C)	Photoperiod (h)	Duration (days)	Temperature (°C)	Photoperiod (h)	Duration (days)	Temperature (°C)	Photoperiod (h)	
1a	Daily records	Natural	Until 10 Nov	3	0	0, 11, 29, 55, 105	18	8, 16	NA
1b	Daily records	Natural	NA	Daily records	Natural	NA	0, 6, 12, 18, 24, 32	16	NA
1c	Daily records	Natural	NA	Daily records	Natural	NA	22	16	High and Low light intensity (during forcing)
2a	Daily records	Natural	NA	Daily records	Natural	0, 30, 55, 95	22	10,12,14,16	NA
2b	Daily records	Natural	Until 20 Nov	2, 4, 6, 10	0	30, 55, 95, 122	22	16	NA
2c	Daily records	Natural	NA	Daily records	Natural	NA	Daily records	Natural	Low K, Low N
3a	Daily records, 18	Natural, 8	60	10, 18	8, 16	50	Constant 20, cycles 10–20, 15	16,12, 9 increasing to 16	NA
3b	10, 18	8	30, 60	10	0, 8	0, 50	20	16	NA

Table 5.4. List of species used in the experiments.

Experiments	Species
1a	*Betula pubescens, Fagus sylvatica, Salix smithiana, Salix aurita, Tilia cordata*
1b	*Betula pubescens, Fagus sylvatica, Salix smithiana*
1c	*Betula pubescens, Fagus sylvatica, Salix smithiana, Tilia cordata*
2a	*Betula pubescens, Fagus sylvatica*
2b	*Betula pubescens, Fagus sylvatica, Salix smithiana, Tilia cordata*
2c	*Betula pubescens, Salix smithiana, Tilia cordata*
3a	*Betula pubescens*
3b	*Betula pubescens*

2a Main effects and interaction of chilling duration and spring photoperiod

2b Main effects and interaction of chilling temperature and chilling duration

2c Effect of nutrient deficiency

3a Main effects and interactions of duration and temperature of dormancy induction, and temperature and photoperiod of chilling

3b Main effects and interactions of dormancy induction photoperiod, and chilling temperature and photoperiod, and forcing temperature regime.

5.3.2 Results

5.3.2.1 Effect of photoperiod on bud burst

Short days and long nights have long been known to be the main trigger inducing autumn dormancy (Wareing, 1956). This was confirmed by the results of Experiment 3b: plants that underwent dormancy induction for 60 days at a photoperiod of 8 h were fully dormant at the start of the chilling treatment, as shown by the high rates of bud burst after the chilling treatment. On the other hand, plants that during the same period underwent dormancy induction at a naturally decreasing photoperiod (from 15.7 h on 20 July to 12.2 h on 19 September) were less responsive to the chilling treatment and showed a delay in the time to bud burst after chilling (Fig. 5.2). This may be a consequence of a delay in attaining dormancy due to the longer photoperiod prior to chilling.

The results from Experiments 3a and 3b suggest that photoperiod does not play an important role in dormancy release during chilling accumulation. The timing of bud burst of plants subjected to chilling at a 16-h photoperiod did not differ significantly from that of plants that received chilling at an 8-h photoperiod. On the other hand, when dormancy was partially broken, a long photoperiod appeared to increase the percentage and rate of bud burst. When plants were subjected to different chilling durations and transferred into forcing treatment at either 8- or 16-h photoperiods, the latter treatment enhanced bud burst in partially chilled plants (11, 29 and 55 days of chilling). After 105 days of chilling, plants responded to forcing temperature in a similar way regardless of photoperiod (Fig. 5.3). This response has also been reported in other studies (Cannell and Smith, 1983; Myking and Heide, 1995), and was more pronounced in *Fagus sylvatica* and *Betula pubescens* than in *Tilia cordata* and the two *Salix* species. Given the future predictions for milder winters where trees might only partially meet their

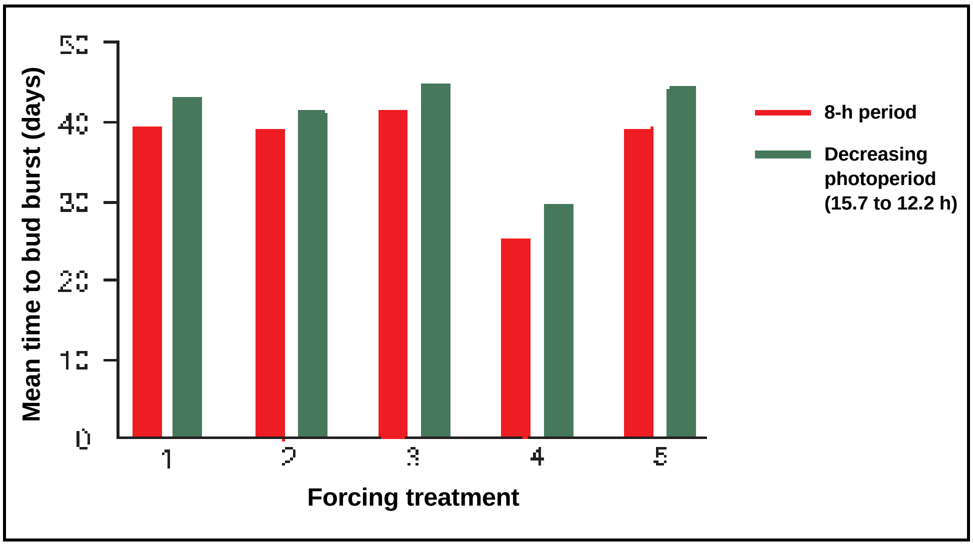

Figure 5.2. Effect of photoperiod during dormancy induction on IPG clones of *Betula pubescens*. Forcing treatments: (1) alternate 8-day long warm (20°C) and cold (10°C), (2) alternate 8-day long cold (10°C) and warm (20°C), (3) alternate 4-day long warm (20°C) and cold (10°C), (4) constant temperature (15°C) at constant photoperiod (12 h), and (5) constant temperature (20°C) at constant photoperiod (16 h).

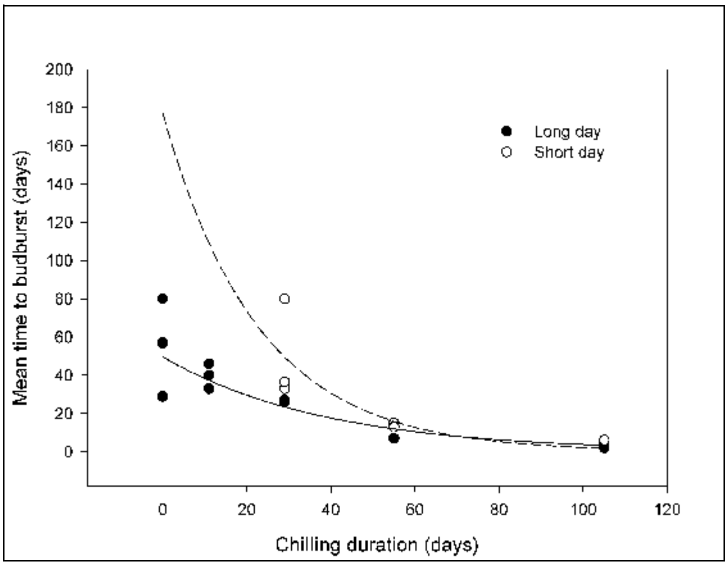

Figure 5.3. Time to bud burst (days) in either an 8-h (short day) or 24-h (long day) photoperiod in *Betula pubescens* clones after exposure to different chilling durations at 3°C (Caffarra *et al.,* submitted).

chilling requirements, it is important that this factor be included in phenological models.

5.3.2.2 Effect of temperature on bud burst

Temperature affects the progress of dormancy in all of its phases. The findings from these experiments indicate that low temperature increases the rate of dormancy induction in *Betula pubescens*. For example, while plants that received a 30-day dormancy induction period at 10°C were fully dormant (virtually no bud burst was observed after transfer into forcing conditions), plants that were subjected to 18°C during the same period responded to forcing conditions by resuming growth, i.e. 55% bud burst. It might be concluded that low autumn temperatures hasten the attainment of endodormancy. This finding corroborates the study of Håbjørg (1972), who concluded that low temperatures (8°C) lead to faster growth cessation and apical dormancy than higher temperatures (18°C).

Low temperatures are necessary for dormancy release (Cannell, 1989). In all species tested in this study, days to bud burst decreased with increasing duration of chilling, irrespective of chilling temperature and photoperiod. This has also been found by other studies (Murray *et al.,* 1989; Myking and Heide, 1995). While increasing chilling enhances the rate of bud burst, the results in the present work indicate that chilling requirements vary widely between species. For example, *Betula pubescens* and *Fagus sylvatica* resumed growth after transfer into forcing conditions with only 20 days of chilling, while *Tilia cordata*, *Salix aurita* and *Salix smithiana* needed at least 50 days of chilling to show the same type of response.

For *Betula pubescens* and *Salix smithiana* the effect of chilling temperatures was most evident in the initial stages of dormancy (after 30 days of chilling for *Salix smithiana* and 95 days of chilling for *Betula pubescens*). At this stage, chilling at 10°C was less effective than chilling at 2, 4 or 6°C. No statistically significant difference was observed between the effects of the different chilling temperatures. While incubation at 10°C delayed dormancy release for *Betula pubescens*, in the longer term (105 days), it advanced bud burst. This might be due to the accumulation of post-chilling thermal time during incubation. Similar findings have been made by Myking and Heide (1995). On the other hand, the rate of bud burst in *Tilia cordata* did not appear to be influenced by any of the chilling temperatures tested in this study (Fig. 5.4). For this species, the response of dormancy release to chilling temperature might be abrupt, and the range of active chilling temperatures wider than that tested.

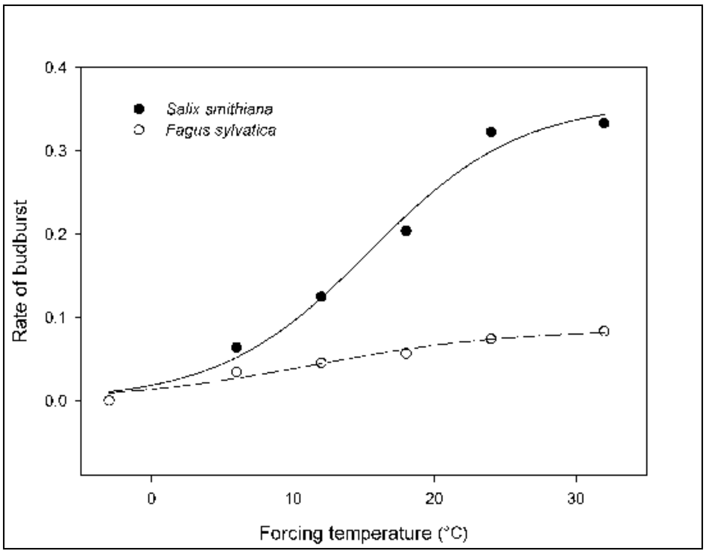

Figure 5.4. Effect of forcing temperature on the rate of bud burst (1/days to bud burst after transfer into forcing conditions) of fully chilled bud sticks of *Fagus sylvatica* and *Salix smithiana.*

While low temperatures are necessary for dormancy release, high temperatures are needed in the later stages of winter rest for meristematic cell division and leaf primordia development leading to bud burst (Battey, 2000). The results from this investigation confirm that increasing temperature advances bud burst in fully chilled plants. The rate of bud burst shows a sigmoidal response to increasing temperature, reaching the optimum between 24 and 32°C. The species tested differ in the slopes and rates of response, suggesting that thermal time to bud burst and forcing rate is species-specific. In Fig. 5.5 the responses of the rate of bud burst to forcing temperature are compared in *Salix smithiana* and *Fagus sylvatica*.

5.3.2.3 Effect of light intensity on bud burst

In all species but *Salix smithiana*, a statistically significant difference in the time to bud burst was found between plants that had received different light intensities after transfer into forcing conditions. *Betula pubescens, Fagus sylvatica* and *Tilia cordata* bud sticks that received high light intensities showed a tendency to earlier bud burst by about 1–3 days, compared with the shaded treatment. However, when plants were subjected to different light regimes during chilling, no effect was detected. It might be concluded that weather conditions conducive to bud burst affect bud burst rate only after chilling requirements have been fulfilled, and that the effect is small if compared to the effects of other factors, such as temperature and chilling duration.

5.3.2.4 Effect of nutrient availability on bud burst

Nutrient deficiency is known to delay the phenological phases of agricultural crops. In this study, nutrient-deficient regimes (low N and low K) were confirmed to delay bud burst in *Betula pubescens, Tilia cordata* and *Salix smithiana*. The lack of both nutrients significantly delayed the phenology of *Tilia cordata* and *Salix smithiana* (from 2 to 4 days), while for *Betula pubescens*, only low nitrogen appeared to have an effect, resulting in a bud burst delay of about 2 days.

In conclusion, the factors that most appeared to affect the timing of spring phenology during the course of this study were temperature and photoperiod. The effect of temperature on the progress of **dormancy** depended on the plant’s developmental stage. While high temperature delayed development during endodormancy, it promoted growth resumption after the plant’s minimal chilling requirement had been met. Photoperiod had a positive effect on bud burst, but it was found to be critical only when chilling was insufficient. In general, photoperiod affected species with a more northerly distribution (*Fagus sylvatica* and *Betula pubescens*). Light intensity and nutrient availability also positively affected timing of bud burst,

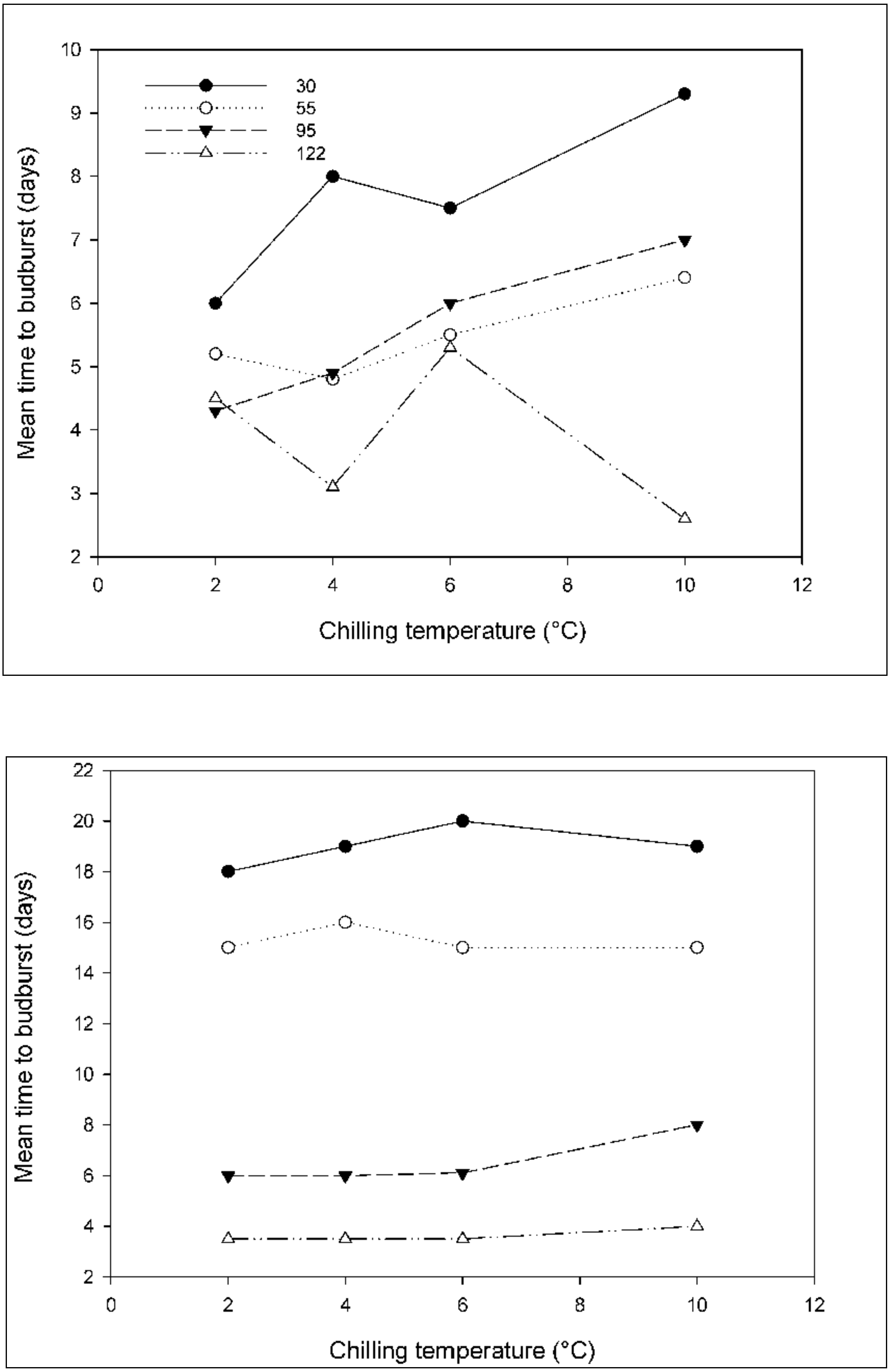

Figure 5.5. Time (days) to bud burst in (a) *Betula pubescens* and (b) *Tilia cordata* after exposure to different chilling durations (days) and temperatures.

although their effect was small, if compared with that of temperature and photoperiod. The varied response exhibited by the different species and the interactions found between the factors tested in this study call for the development of models of tree phenology that are species-specific and based on realistic assumptions regarding the processes occurring during dormancy.

5.4 Impact of Climate Change on Semi-Natural Habitats

5.4.1 Introduction

Habitats are the basic building blocks of the environment and consist of living organisms and their physical environment (Hossell *et al*., 2001). The most up to date and comprehensive description of Irish habitats can be found in Fossitt (2000). Climate change is predicted to alter habitats in several ways, by for example, increasing the length of the growing season, by changing the range for particular species or by giving competitive advantage to some species (e.g. drought tolerant) over others. In other cases, the area occupied by a particular habitat may change. For example, due to sea level rise a restriction in the area available for coastal habitats, such as salt marshes and sand-dune complexes, may occur or habitats may shift. Responses of habitats to climate change may vary because habitats are more or less restricted by factors other than climate such as rock type and soil type (Hossell *et al*., 2001).

It is expected that initial responses to climate change will be rather subtle changes in plant responses, such as increases in primary production and changes in species composition. The longer-term movement of habitats will be very dependent on the human influence on land use, as, for example, migration of species will be dependent on the availability of suitable migration routes. A comprehensive review by Byrne *et al.* (2003) of the potential impacts of climate change on habitats in Ireland identified several habitat types as having a medium–high or high vulnerability ranking to projected increases in temperature and changes in rainfall patterns. The most vulnerable habitats included sand dunes, lowland calcareous and calaminarian grasslands, montane heath, active raised bog, degraded raised bog, calcareous fens and petrified springs, alkaline fen, bog woodland, turloughs and upland oligotrophic lakes. Here we focus primarily on peatlands and turloughs.

5.4.2 Impact on peatlands and turloughs

The growth of peat is determined by the climate, the nature of the terrain and the rate of peat accumulation (Foss *et al.,* 2001). Peat accumulates at a rate of approximately 1 mm/year. In Ireland, we can divide our peatlands into three main groups:

1. Blanket bogs
2. Raised bogs
3. Fens.

The main differences between the three peatland types are shown in Table 5.5.

Blanket bogs are further subdivided into two categories:

1. 'Atlantic blanket bogs' which are confined to coastal plains and inter-mountain valleys, at low altitude (<200 m) in high rainfall areas along the western seaboard, and
2. 'Mountain blanket bogs' which occur on relatively flat terrain in the higher Irish mountains above 200 m and are more widely distributed around Ireland.

Table 5.5. Characteristics of Irish peatlands (O'Connell, 1987).

	Fen	Raised bog	Blanket bog
Formed	Lowland lake basins	Lowland lake basins	Upland mineral soils
Peat depth	Up to 2 m	Up to 12 m	Up to 7 m
Annual rainfall	800–900 mm	800–900 mm	>1,250 mm
pH	Alkaline/Neutral/Acidic	Acidic	Acidic
Rain days per year		150–175	>200
Source of nutrients	Groundwater	Atmosphere/rain	Atmosphere/rain

Atlantic blanket bog formation requires an annual rainfall >1,200 mm (Crushell, 2000). However, the absolute amount of rainfall is probably less important than the distribution throughout the year (Charman, 2002). Lindsay *et al.* (1998) suggest that the following conditions are necessary for blanket bog formation:

- Minimum of 160 wet days (>1 mm rain/day).
- Mean temperature of <15°C for the warmest month.
- Minor seasonal fluctuation in temperature.

Raised bogs occur on land below 150 m in the midlands of Ireland. They require a rainfall of between 800 and 900 mm per year and, similar to blanket bogs, they obtain their nutrient supply from rainfall (Crushell, 2000). Raised bogs develop in lake basins or hollows in the landscape and eventually form dome-shaped mounds of peat up to 12 m thick. Fens, which are widely distributed throughout the country, most commonly in the west and midlands of Ireland (Hammond, 1984; Crushell 2000), are a wetland system with a permanently high water level on alkaline to slightly acidic peat soil. Fens principally develop by infilling of shallow lake basins and, similar to raised bogs, they occur in locations where the annual amount of rainfall is between 800 and 900 mm. Fens in this context exclude those that form on slopes where there is an outflow of base-rich groundwater or in river flood plains. Finally, turloughs are topographic depressions in karst areas which are intermittently inundated on an annual basis, mainly from groundwater, and which have a substrate and/or ecological communities characteristic of wetland. They occur across central and western Ireland and are controlled by a combination of factors that encompasses geology, hydrology, climate and soil depth. A change in any of these factors would result in a habitat that is intrinsically different to that of the turlough habitat.

Climate change is expected to promote an increased decomposition of peatlands. Longer drier summers will promote the drying and cracking of some peat surfaces in raised bogs and this may result in increased decomposition due to a greater vulnerability to erosion from higher winter precipitation. Schouten *et al. (*1990) have shown that even a slight lowering of the water table may decrease the differentiation of the bog vegetation pattern which increases the percentage of dwarf shrubs and graminae species and reduces the peat-forming mosses.

In a recent report on the implications of climate change for Northern Ireland, Montgomery (2002) highlighted the uniqueness of Irish peatlands and their vulnerability to changing climatic conditions. The extent to which peatlands are affected by climate change depends largely on the temporal characteristics of the change. For example, changes in winter precipitation or temperature are unlikely to have a significant effect, whereas even small changes in the summer water balance may be enough to alter conditions for plant growth and peat decay such that climate change becomes a threat to their survival. Furthermore, the rate of addition of plant debris to form new peat will decrease, causing a gradual shift toward a drier dwarf-shrub or grass-dominated heath. Such deterioration of peatlands would release additional carbon dioxide to the atmosphere and is potentially one of the most serious impacts of climate change in Ireland (Kerr and Allen, 2001). According to Berry *et al.* (2001), future changes in effective rainfall will influence the seasonal response of turloughs while the rapid fissure and conduit flow associated with karst landscape may also be sensitive to changes in rainfall patterns in future.

Evidence from the fossil record (Woodward, 1987; Huntley, 2001) and from recently observed trends (for reviews see Hughes, 2000; Walther *et al.*, 2002) shows that changing climate has a profound influence on species' range expansion and contraction. It is therefore expected that predicted future climate change (IPCC, 2007) will have a significant impact on the distribution of species. Peatlands originally covered more than 16% of the land surface of Ireland. The importance of conserving Irish peatlands has been recognised by the international community through the European Parliament (Resolution 1983), the International Mire Conservation Group (Resolution 1990) and the Council of Europe (Recommendation No. R (81)11, 1981). More recently, the Habitats Directive, the Birds Directive and the Convention of Biological Diversity have strengthened the conservation of Irish peatlands.

Here we describe climate change impacts at the ecosystem level using the climate envelope concept to identify impacts on vulnerable habitats in Ireland with emphasis on the extent of peatlands and turloughs. No attempt is made to consider the effects of climate change on the future condition of these ecosystems.

5.4.3 Methodology

5.4.3.1 Reference data and statistical analysis

Gridded data for peatland distribution were provided by the Irish Peatlands Conservation Council. The data set included four categories of peatlands:

1. Mountain bogs
2. Atlantic blanket bogs
3. Raised bogs
4. Fens.

Gridded reference data for the turloughs were provided by the National Parks and Wildlife Service. The descriptive statistic parameters were calculated using Microsoft Excel© and SPSS© (version 12). Principal Component Analysis was performed with PC-ORD© (version 4.01) and maps were produced using GIS software ArcGIS 9© and its extensions, Spatial Analysis and Geostatistic.

5.4.3.2 Climate data

The climate data used were provided by the Irish Climate Analysis and Research Unit (National University of Ireland, Maynooth) to construct climate envelopes for peatland and turlough systems and to assess the movement of these climate envelopes in response to climate change during this century. The future climate data were extrapolated from a downscaling of a global circulation model (GCM), the Hadley Climate Model (HadCM3). Details of the statistical downscaling and the resulting data sets can be found in Sweeney and Fealy (2002) and Holden et *al.* (2003). In brief, the resulting downscaling provided 852 10 × 10 km grid cells for the whole of Ireland. For each of these cells monthly climate data (maximum and minimum temperatures, radiation and precipitation) for the baseline period (1961–1990) 2001, (2041–2070) 2055 and (2061–2090) 2075 climate scenarios were defined.

5.4.3.3 Selection of climatic and bioclimatic variables

A number of climatic and bioclimatic variables that are known to have an influence on the distribution of natural peatlands were derived from these data to develop a climate envelope model of Irish peatlands (Table 5.6). It is important to note that non-climatic features such as rock substrate and slope are excluded from this analysis.

Principal component analysis (PCA) was then used to identify the most important climate variables. PCA provides a means of creating new 'variables' which capture the maximum amount of variability within the existing data set. This is achieved by the creation of new axes within the existing data space, with the first positioned to capture the greatest spread within the data. The second axis is then defined orthogonally in relation to the first and the values for the second principal component for each 10 km × 10 km grid square are assessed from this axis. Further axes are defined within the data space until the variation within the data set explained by an axis drops below a predefined threshold as measured by the axis eigenvalue. For this analysis a standard threshold value of 0.7 was adopted. The PCA resulted in the creation of two principal components, which together explained more than 98% of the variation within the nine variables in the 2001 scenario. Analysis of the factor score (Table 5.7) then provides an indicator of the bioclimatic variables that contribute to each factor.

Figure 5.6 shows the factor scores (analysis of the factor scores provides an indication of the bioclimatic variables that contribute to each factor) for each of the first two axes plotted across Ireland using the spatial interpolation method of kriging. The contribution of the rainfall data to the first axis is apparent from the east–west gradient of the scores as expected. Likewise the effects of temperature produced a north–south gradient in the second axis. To determine the likely total percentage of suitable climatic area (SCA) loss for both peatlands and turloughs in Ireland, the integrated factor determined by the PCA in which each bioclimatic variable influenced the overall climate was determined. To establish the current SCA from the 2001 climate data, the presence/absence of each peatland type and turlough for each grid cell was determined and the range of each bioclimatic variable in those grid cells

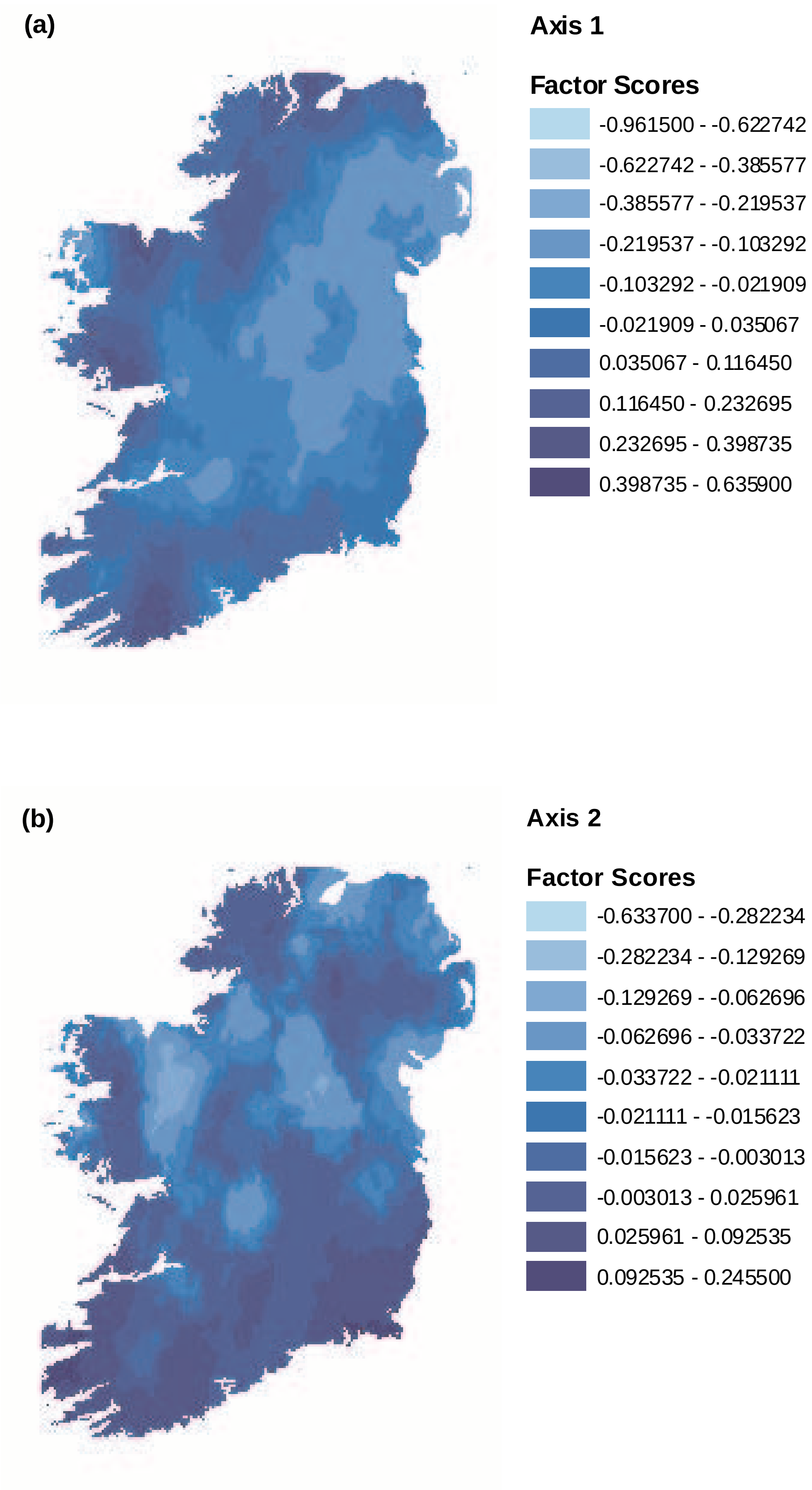

Figure 5.6. Factor scores for the first two principal components plotted across Ireland for 2001 using spatial interpolation and showing the spatial pattern of the two most important variables which contribute to most of the variation within the data set: (a) Axis 1 relates to rainfall variables, and (b) Axis 2 relates to temperature variables.

Table 5.6. Climatic and bioclimatic variables included within the classification which are known to have an influence on the distribution of peatlands.

Variable	Unit
T – Yearly average temperature	°C
Tmin – Average temperature of the coldest month	°C
Tmax – Average temperature of the warmest month	°C
P – Total annual average precipitation	mm
Ps – Summer precipitation (total average precipitations of June, July and August)	mm
Pw – Winter precipitation (total average precipitations of December, January and February)	mm
Eto – Annual average potential evapotranspiration (after Thornthwaite)	mm
Pn – Annual average net precipitation (P-Eto)	mm
Hu – Annual average humidity index	mm
Ic – Continentality Index (range between the average temperatures of the warmest and coldest months of the year)	

Table 5.7. Relationship between the principal component factor axes and the original climatic and bioclimatic variable data set. Variables are listed in order of the factor scores that explain a significant amount of their variance.

PCA 2001	
Axis 1	**Axis 2**
Net precipitation (Pn)	Average temperature of coldest month (Tmin)
Yearly average precipitation (P)	Yearly average temperature (T)
Yearly average humidity index (Hu)	Average temperature of warmest month (Tmax)
Winter precipitation (Pw)	Continentality Index (Ic)

where peatlands or turloughs were found was obtained. Subsequently, by projecting the present SCA of each bioclimatic variable to the 2055 and 2075 scenarios, we could determine the SCA loss for each habitat type in future. By combining the integrated factor from the PCA of each bioclimatic variable to the SCA loss by 2055 and 2075, the total SCA loss was established.

5.4.4 Future distribution of peatlands and turloughs in Ireland

5.4.4.1 Atlantic blanket bog distribution

Table 5.8 shows that at present Atlantic blanket bog locations are found in areas receiving between 75 and 1,406 mm Pn and that 95% of this habitat type are located in areas where Pw is below 652 mm. Quantitative parameters of the probability distribution of Atlantic blanket bogs are negatively skewed for all bioclimatic variables pertaining to the first component of the PCA, where mean P is 1,343 mm and 68% of these bogs are located in areas receiving above 1,200 mm rainfall. This agrees with Crushell (2000) who reported that blanket bog formation requires an annual rainfall of >1,200 mm.

Box plots (Fig. 5.7) show the distribution of Atlantic blanket bogs observed in each grid cell related to some bioclimatic variables. According to the analysis, taking yearly average temperature into account, 80% of the SCA for blanket bog will be lost by 2055 and 75% by 2075. The opposite trend is shown for precipitation variables. The SCA for blanket bogs will decrease by 33% by 2055 and 25% by 2075 in relation to yearly average precipitation and, as regards summer precipitation, 32% of the SCA will be lost by 2055, with no further increase by 2075. Finally, as regards net precipitation, 25% and 27% of the SCA will be lost by 2055 and 2075, respectively, for Atlantic blanket bogs in Ireland.

Table 5.8. Atlantic blanket bogs in 2001 baseline. Temperature (T), average temperature of the coldest month (Tmin), average temperature of the warmest month (Tmax), precipitation (P), summer precipitation (Ps), winter precipitation (Pw), potential evapotraspiration (Eto) and net precipitation (Pn).

	T (°C)	Tmin (°C)	Tmax (°C)	P (mm)	Ps (mm)	Pw (mm)	Eto (mm)	Pn (mm)
N	75	75	75	75	75	75	75	75
Mean	8.74	4.19	12.48	1,342.65	243.11	437.02	612.07	730.57
Standard deviation	0.70	0.83	0.71	359.23	48.58	135.48	15.80	366.60
Minimum	6.89	1.90	10.77	704.54	149.50	208.48	568.81	70.83
Maximum	10.31	6.06	13.75	2,001.21	340.96	679.40	644.07	1,405.65

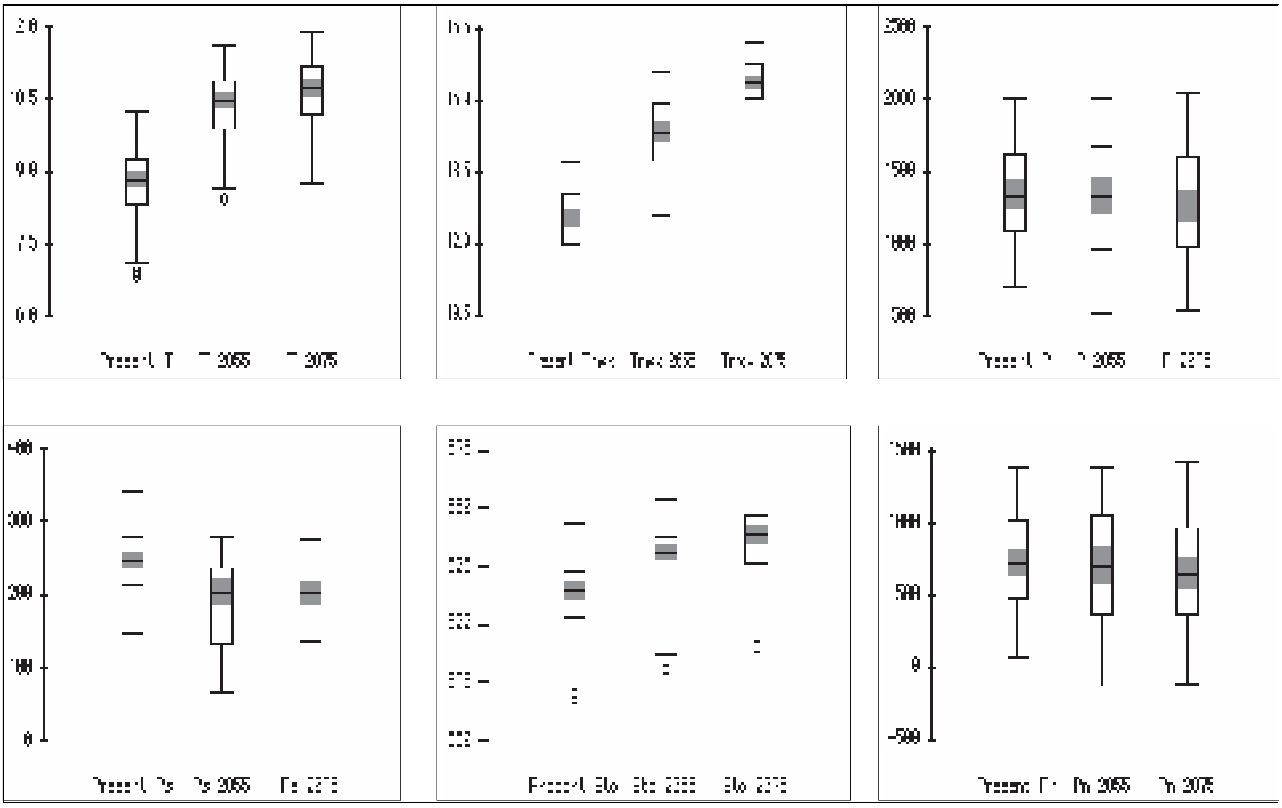

Figure 5.7. Box plots of the temperature (T), average temperature of the warmest month (Tmax), precipitation (P), summer precipitation (Ps), potential evapotranspiration (Eto) and net precipitation (Pn) for grid cells detected that are suitable for Atlantic blanket bogs under current and future predictions. The lower boundary shows the 25th percentile, the upper boundary the 75th percentile. The whiskers show the highest and lowest values excluding outliers.

5.4.4.2 Mountain blanket bog distribution

Mountain blanket bog (Table 5.9) occurs where current Pn has a range between 138 and 1,285 mm rainfall and 95% of these bogs are located in areas where mean P is approximately 1,330 mm.

Predictions for 2055, as regards yearly average temperature, suggest that mountain blanket bog will loose 74% of its SCA increasing to 84% by 2075 (Fig. 5.8). In relation to precipitation variables, the SCA will decrease by 35% by 2055 and 36% by 2075. In addition, as regards yearly average precipitation and summer precipitation, the SCA loss for mountain blanket bogs will be 52% for both 2055 and 2075. Finally, in relation to net precipitation, the SCA loss is predicted to be approximately 36% by 2055 and 2075.

Table 5.9. Mountain blanket bog in 2001 baseline. Temperature (T), average temperature of the coldest month (Tmin), average temperature of the warmest month (Tmax), precipitation (P), summer precipitation (Ps), winter precipitation (Pw), potential evapotranspiration (Eto) and net precipitation (Pn).

	T (°C)	Tmin (°C)	Tmax (°C)	P (mm)	Ps (mm)	Pw (mm)	Eto (mm)	Pn (mm)
N	76	76	76	76	76	76	76	76
Mean	8.66	4.00	12.42	1,329.61	243.86	428.33	609.62	719.99
Standard deviation	0.740	0.924	0.659	304.020	40.970	115.547	16.217	308.45
Minimum	7	1	11	764	167	221	559	138
Maximum	10	6	14	1,891	323	645	647	1,285

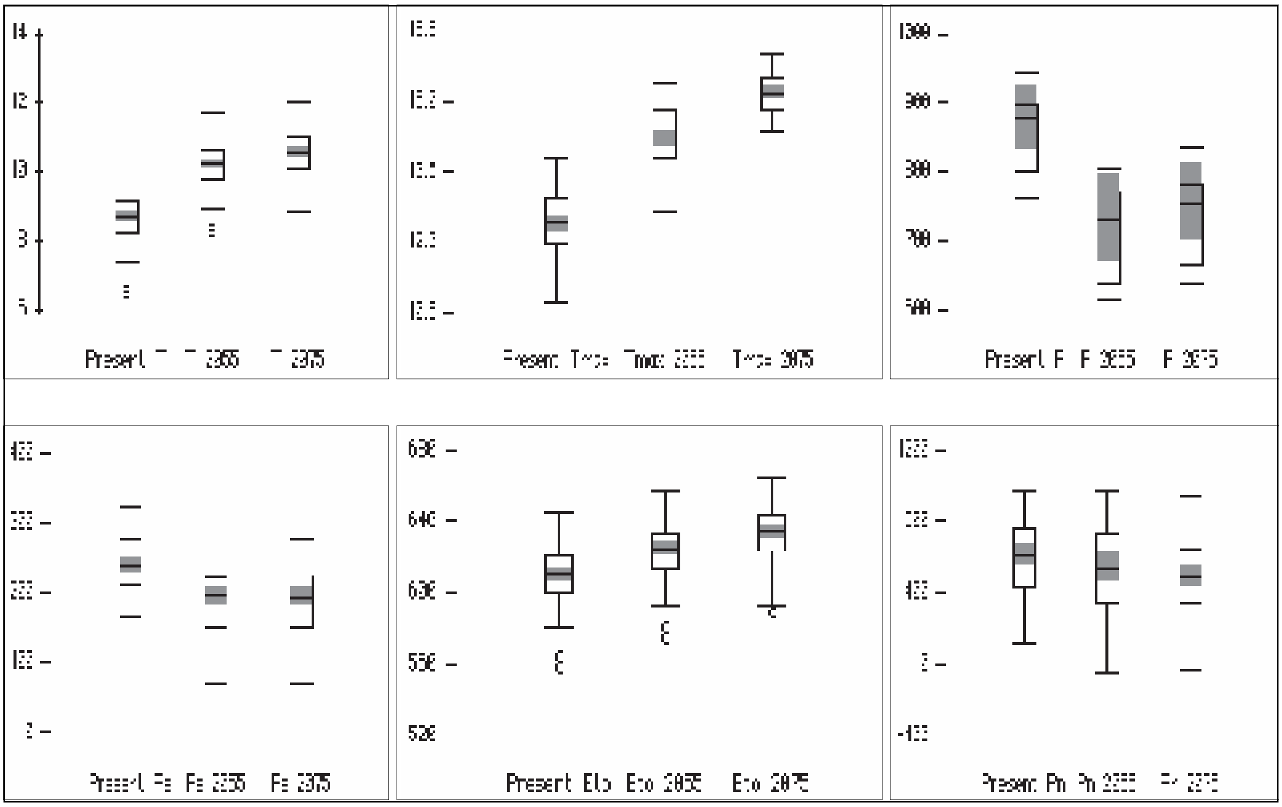

Figure 5.8. Box plots of the temperature (T), average temperature of the warmest month (Tmax), precipitation (P), summer precipitation (Ps), potential evapotranspiration (Eto) and net precipitation (Pn) for grid cells detected that are suitable for mountain blanket bogs under current and future predictions. The lower boundary shows the 25th percentile, the upper boundary the 75th percentile. The whiskers show the highest and lowest values excluding outliers.

5.4.4.3 Raised bogs distribution

Table 5.10 shows that at the present raised bog locations are found in areas receiving between 212 and 1,003 mm Pn and that 95% of the current bogs are located in areas where Pw is below 437 mm.

The projections (Fig. 5.9) suggest that, as regards temperature, raised bogs will have lost all of their SCA by 2055. Because of the importance placed on precipitation as a bioclimatic variable in the PCA, we believe that the SCA that will be lost by raised bogs is best explained by bioclimatic variables such as precipitation which by 2055 shows an SCA loss of 26% and by 2075 a loss of 28% is predicted. The summer precipitation data show more drastic results, indicating

Table 5.10. Raised bogs in 2001 baseline. Temperature (T), average temperature of the coldest month (Tmin), average temperature of the warmest month (Tmax), precipitation (P), summer precipitation (Ps), winter precipitation (Pw), potential evapotranspiration (Eto) and net precipitation (Pn).

	T (°C)	Tmin (°C)	Tmax (°C)	P (mm)	Ps (mm)	Pw (mm)	Eto (mm)	Pn (mm)
N	878	878	878	878	878	878	878	878
Mean	8.86	4.19	12.70	1,208.53	228.56	384.34	614.76	593.76
Standard deviation	0.704	0.842	0.644	259.389	36.037	97.202	14.595	265.663
Minimum	6	1	10	705	148	208	548	71
Maximum	10	6	14	2,025	342	694	647	1,426

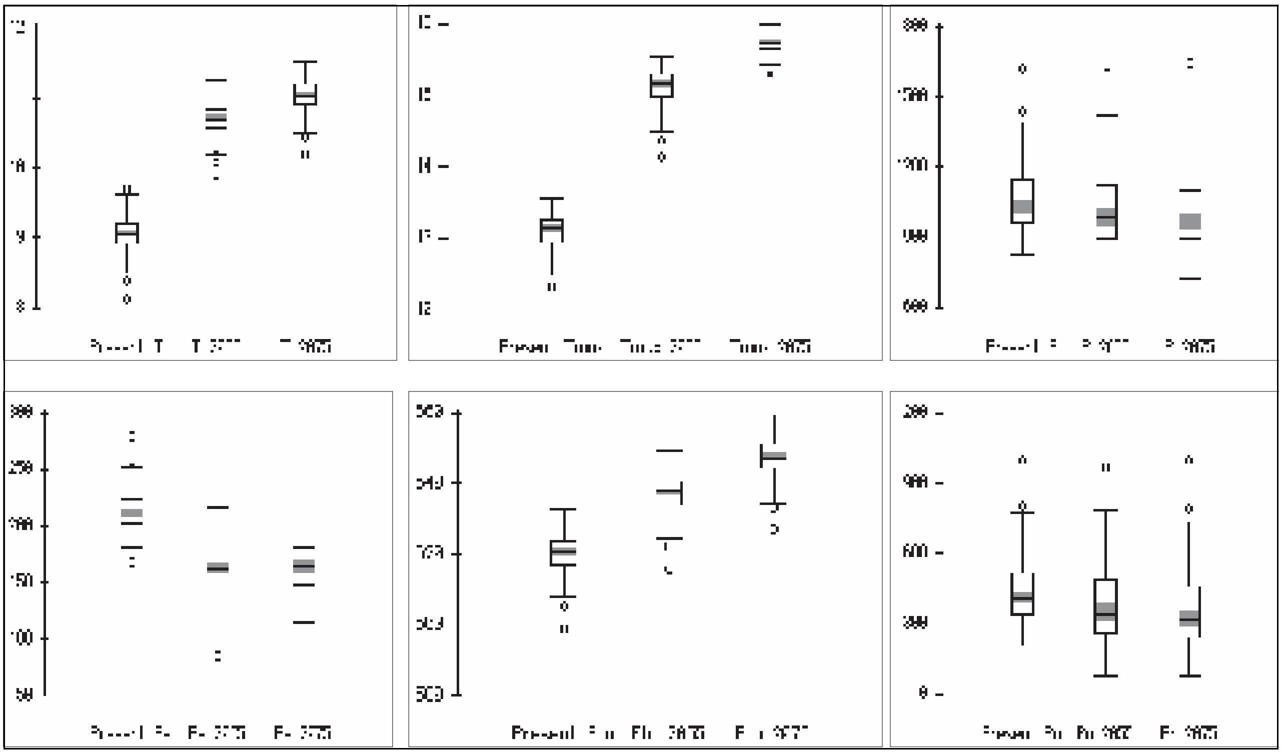

Figure 5.9. Box plots of the temperature (T), average temperature of the warmest month (Tmax), precipitation (P), summer precipitation (Ps), potential evapotranspiration (Eto) and net precipitation (Pn) for grid cells detected that are suitable for raised bogs under current and future predictions. The lower boundary shows the 25th percentile, the upper boundary the 75th percentile. The whiskers show the highest and lowest values excluding outliers.

that by 2055 89% and by 2075 87% of the SCA for this habitat will be lost. Finally, the yearly net precipitation box plot presents similar results as the yearly average precipitation results, indicating a loss of 31% and 37% SCA for raised bogs by 2055 and 2075, respectively.

5.4.4.4 Fen distribution

Table 5.11 shows the quantitative parameters of the probability distribution of fens in Ireland in the 2001 baseline year. The data of the 222 cells where fens were distributed present a positive skewness with a sharp peak (positive kurtoses) for the most representative bioclimatic variables of the first component of the PCA. This indicates that a small number of fens experience more extreme bioclimatic conditions than the majority. However, the locations of fens vary between 138 and 1,426 mm Pn and 95% of

Table 5.11. Fens in 2001 baseline. Temperature (T), average temperature of the coldest month (Tmin), average temperature of the warmest month (Tmax), precipitation (P), summer precipitation (Ps), winter precipitation (Pw), potential evapotranspiration (Eto) and net precipitation (Pn).

	T (°C)	Tmin (°C)	Tmax (°C)	P (mm)	Ps (mm)	Pw (mm)	Eto (mm)	Pn (mm)
N	222	222	222	222	222	222	222	222
Mean	8.99	4.35	12.92	1,158.55	222.45	366.85	618.20	540.43
Standard deviation	0.60	0.73	0.54	239.67	33.49	90.14	13.24	245.56
Minimum	6.50	1.37	10.73	763.57	148.77	221.04	559.09	137.89
Maximum	10.44	6.28	13.86	2,025.24	342.28	693.87	646.77	1,425.96

the fens are located in areas where the Pw is below 548 mm, where the mean P is 1,159 mm and Tmax never exceeds 14°C.

Box plots (Fig. 5.10) show the distribution of fens related to a set of bioclimatic variables. Comparison of the number of fens actually observed in each grid cell demonstrates that areas of suitable climate for fens are lost under future scenarios. Global circulation model outputs statistically downscaled suggest that, by 2055, the extreme south and south-west coast of Ireland may have average temperature increases by up to 1.5°C in winter and 2°C in summer. Considering yearly average temperature, the model projects that, by 2055, 87% of the fens will lose SCA and this value increases to 93% by 2075. For the average temperature of the warmest

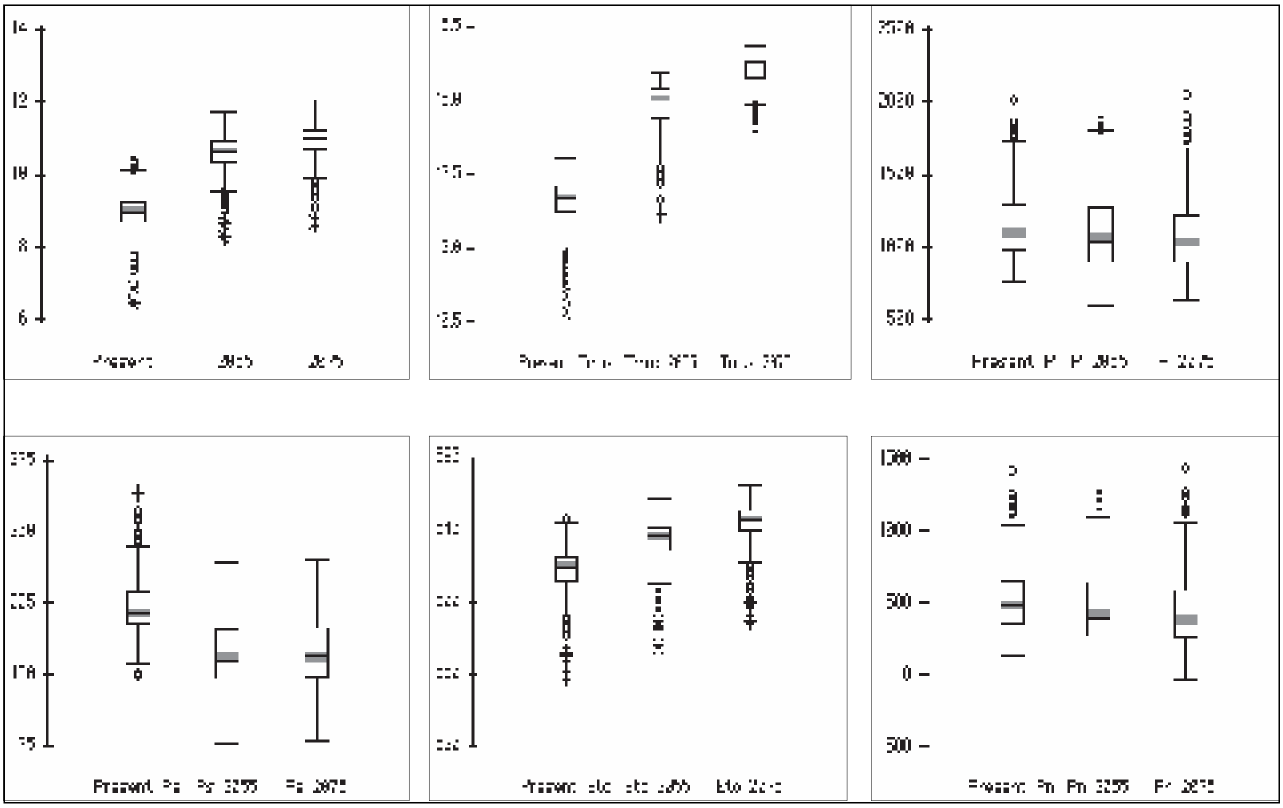

Figure 5.10. Box plots of the temperature (T), average temperature of the warmest month (Tmax), precipitation (P), summer precipitation (Ps), potential evapotranspiration (Eto) and net precipitation (Pn) for grid cells detected that are suitable for fenlands under current and future predictions. The lower boundary shows the 25th percentile, the upper boundary the 75th percentile. The whiskers show the highest and lowest values excluding outliers.

month, 96% of the SCA will be lost by 2055 and this increases to 100% by 2075. The opposite trend is shown for precipitation variables. Because predictions suggest that within the next 50 years the yearly average precipitation will increase by 10% in winter and decrease by between 10 and 40% in summer, the SCA for fens will decrease by 18% by 2055 and 14% by 2075 for yearly average precipitation but, considering summer precipitation data, 55% of SCA will be lost for fens by 2055 and 52% by 2075. Finally, considering the net precipitation, 19% of the SCA for fens in Ireland will be lost by 2055 and 2075.

5.4.4.5 Turlough distribution

Under present climatic conditions turloughs occur where Pn has a range between 184 and 800 mm and 95% of them are located in areas where the mean P is 1,379 mm. Locations where turloughs occur have a mean potential evapotranspiration rate of 622 mm with a Pn of 767 mm for 95% of cases. Finally, mean temperature is 9°C with a mean maximum temperature during summer time that never exceeds 14°C (Table 5.12).

By 2055, as regards yearly average precipitation, the SCA loss for turloughs is predicted to be 73% with a slight decrease to 71% by 2075. As regards summer precipitation, SCA loss will be 87% by 2055 and 84% by 2075. Finally, for net precipitation, SCA loss will be 72% by 2055 and 2075.

In summary, the model indicates that by 2055 41% of the fens will lose their SCA and this value increases slightly to 42% by 2075 (Table 5.13). As over the next 50 years, the annual average precipitation is predicted to increase by 10% in winter and decrease by between 10 and 40% in summer, the SCA for raised bogs will decrease by 32% by 2055 and 38% by 2075. A similar trend is found for mountain blanket bogs (Table 5.13). The SCA for turloughs is predicted to be 45% less than at present by 2055 and 39% less than at present for 2075. This analysis clearly indicates that under the climate change scenarios Irish peatlands and turloughs will progressively lose their current available climate space.

5.4.5 Implications for future distribution of peatlands and turloughs

The validity of the bioclimate envelope approach has received a number of criticisms of late (Davis, *et al.,* 1998; Pearson and Dawson, 2003; Hampe, 2004; Luoto *et al.,* 2005) which partly revolve around the assertion that many factors other than climate play an important role in determining species distributions and their dynamics over time. In addition, we are still unclear as to whether vegetation distribution is currently in equilibrium with the climate and, if it is, whether this can be maintained when the rate of change is predicted to be ten times faster than over the warming of the end of the last glaciation. There is no doubt that the great complexity of semi-natural ecosystems makes the accurate prediction of future responses to climate change very difficult to achieve (Pearson and Dawson, 2003). It is important to remember that SCA may perhaps best be regarded as representing a maximum potential future distribution that is unlikely to be fully realised due to the operation of more local factors (land use, habitat availability and host plants) and, more importantly, the need for species to disperse in order to fulfil new potential ranges. Also, the migration distance involved in

Table 5.12. Turloughs in 2001 baseline. Temperature (T), average temperature of the coldest month (Tmin), average temperature of the warmest month (Tmax), precipitation (P), summer precipitation (Ps), winter precipitation (Pw), potential evapotranspiration (Eto) and net precipitation (Pn).

	T (°C)	Tmin (°C)	Tmax (°C)	P (mm)	Ps (mm)	Pw (mm)	Eto (mm)	Pn (mm)
N	32	32	32	32	32	32	32	32
Mean	9.15	4.56	13.11	1,161.14	225.29	368.93	622.38	538.75
Standard deviation	0.28	0.32	0.28	134.81	18.87	50.32	6.28	138.29
Minimum	8.60	4.00	12.51	810.41	165.70	246.50	609.77	184.78
Maximum	9.75	5.24	13.68	1,414.86	256.34000	465.62	635.85	800.65

Table 5.13. Total loss (%) of suitable climatic area (SCA) by bioclimatic variable for 2055 and 2075 for peatland types and turloughs. T, annual average temperature; Ts, summer temperature; Tw, winter temperature; P, total annual precipitation; Pw, winter precipitation and Pn, net precipitation (=P – evapotranspiration).

	Fen	Raised bog	Atlantic blanket bog	Mountain blanket bog	Turlough
2055					
T	3	3	3	2	4
Ts	9	8	9	6	9
Tw	10	4	9	10	14
P	3	2	6	2	2
Ps	9	11	6	6	10
Pw	2	0	2	3	4
Pn	4	3	5	2	2
Total	**41**	**31**	**39**	**31**	**45**
2075					
T	3	3	3	3	4
Ts	9	9	9	9	9
Tw	13	10	11	12	14
P	3	2	5	2	1
Ps	9	10	6	6	8
Pw	1	1	2	3	2
Pn	4	4	5	2	1
Total	**42**	**38**	**40**	**37**	**39**

fulfilling the climate space may be beyond the capabilities of some species. These results therefore represent only a first step in projecting the potential impact of climate change on peatlands and turloughs in Ireland. We are also conscious that many other factors such as biotic interactions, evolutionary change and dispersal ability, play an important part in determining species distributions and the dynamics of distribution changes. However, we contend that climate is the prime factor influencing peatlands distribution and that we have been able to identify the potentially suitable climate space for wetlands as the climate changes.

By 2055, the model indicates that 41% of the fens will lose their SCA and this value increases slightly to 42% by 2075. As over the next 50 years, the annual average precipitation is predicted to increase by 10% in winter and increase by between 10 and 40% in summer, the SCA for raised bogs will decrease by 32% by 2055 and 38% by 2075. A similar trend occurs for mountain blanket bogs, while raised bogs are predicted to lose 32% of their SCA by 2055 and 38% by 2075. Because of the importance attributed by the PCA to the bioclimatic variables relating to precipitation, we believe that the SCA for raised bogs that will be lost is best explained by annual average precipitation which shows a loss in SCA of 27% by 2055 and of 28% by 2075. The results described here therefore show that under the climate change scenarios Irish peatlands will progressively lose their current available climate space.

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6 Conclusions: Key Vulnerabilities and Risks

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6.1 Introduction

Addressing the vulnerability of Ireland to future climate change has two dimensions which must constantly be borne in mind. Firstly, the scientific uncertainty of when, how much, and where vulnerability arises must be tackled using the best available techniques and expert judgement. A considerable 'uncertainty cascade' remains in this area due to a number of unknowns concerning factors affecting the future projection of climate. Among these are:

- How will global energy, population and economic activity evolve in the years ahead?
- How will the natural world respond to increased atmospheric concentrations of greenhouse gases?
- How can coarse global climate models be 'downscaled' to provide reliable information of use for policy makers and environmental managers in Ireland?
- How will various components of the Irish environment, both natural and socio-economic, respond to the climate changes projected?

This study has sought to narrow the scientific uncertainties for Ireland by developing novel downscaling techniques for combinations of global climate models and subsequently using the output to drive impact models in key sectors such as agriculture, water resources and biodiversity.

Secondly, however, it is clear that any impact analysis must be tempered by consideration of how Irish socio-economic systems will respond in terms of adaptation and mitigation to a changed climate risk environment. While reducing the scientific uncertainty provides an essential input to policy processes, decision making about how to respond to climate change threats will be influenced by a range of other agendas. It is thus appropriate to reiterate the comments of the (Intergovernmental Panel on Climate Change) IPCC in the *Synthesis Report* of the *Fourth Assessment Report* that:

"*Adaptive capacity is intimately connected to social and economic development, but is unevenly distributed across and within societies. The capacity to adapt is dynamic and is influenced by a society's productive base, including natural and man-made capital assets, social networks and entitlements, human capital and institutions, governance, national income, health and technology. It is also affected by multiple climate and non-climate stresses, as well as development policy... However, financial, technological, cognitive, behavioural, political, social, institutional and cultural constraints limit both the implementation and effectiveness of adaptation measures. Even societies with high adaptive capacity remain vulnerable to climate change, variability and extremes*" (IPCC, 2007).

6.2 Future Climate Scenarios

Mean annual temperatures in Ireland have risen by 0.7°C over the 1890–2004 period. As a mid-latitude country Ireland can expect its future temperature changes to mirror quite closely those of the globe as a whole. Estimates of global temperature change by the end of the present century are currently in the region of 1.8–4.0°C (IPCC, 2007). Using a multi-model ensemble to downscale to the Irish Synoptic Station network, this study concludes that Irish mean temperatures will rise by 1.4–1.8°C by the 2050s and by in excess of 2°C by the end of the century. Summer and autumn warm much faster than winter and spring, with a pronounced continental effect becoming apparent whereby the midlands and east warm more than coastal areas. A high degree of confidence exists in warming projections.

Ongoing precipitation changes in Ireland are currently showing increases in the west in winter and decreases in the south-east in summer (McElwain and Sweeney, 2007). Future precipitation changes are less certain to project than temperature, but constitute the most important aspect of future climate change for Ireland. Ensemble mean projections suggest that winter rainfall in Ireland by the 2050s will increase by approximately 10%. By contrast, reductions in summer of 12–17% are projected by the same time. By the 2080s, these figures are likely to have increased to 11–17% and 14–25%, respectively. The largest percentage winter increases are expected to occur in the midlands while by the 2050s summer reductions of 20–28% are projected for the southern and eastern coasts, increasing to 30–40% by the 2080s.

Analysis of likely climate extremes matches many of the suggested trends. Lengthier heatwaves, much reduced number of frost days, lengthier rainfall events in winter and more intense downpours in summer are projected. At the same time an increased summer drought propensity is indicated, especially for eastern and southern parts of Ireland.

6.3 Vulnerabilities in Water Resource Management

Hydrological impacts of projected climate change were derived for three future periods using downscaled output to drive conceptual catchment rainfall run-off models in nine representative catchments across Ireland. Significant reductions in soil moisture storage were projected, with differences between the catchments controlled largely by soil permeability considerations. Soil moisture deficits commence earlier, and extend later, in the year as the century proceeds. Of some concern is the tendency for groundwater recharge to be lower for longer, sustained periods, increasing the risk of drought when a dry summer follows a drier than average winter. Such impacts would be felt greatest in catchments more dependent on groundwater, such as the Suir, Blackwater and Barrow.

Significant changes in streamflow are likely to occur. For the 2050s, for example, increases in February of 15–18% are projected for the Suir and Barrow, while reductions of 12–22% in November are projected for the same two catchments. These trends become further enhanced as the century proceeds and clearly have implications for flood management in winter and water resource availability in summer. In the vital water supply rivers of the east, for example, streamflow reductions in excess of 70% can be expected for some autumn months by the end of the century.

As might be expected, these hydrological changes manifest themselves more clearly in changes in high and low flow frequencies. In terms of high flow events the 10-year flood reduces to a 3.4- to 7.1-year event on most catchments by the 2050s. The 50-year flood becomes a 6.5- to 34.4-year event on all but one catchment studied. In practical terms this means that the magnitude of the existing 50-year flood increases substantially. On the River Moy, for example, the magnitude of the 50-year flood almost doubles under one scenario by the 2080s. By the end of the century, the 50-year flood has reduced to a 10-year event on the majority of rivers modelled. Despite drier summer conditions, most Irish rivers show a reduction in extreme low flows through the summer months for the early decades of this century. This is largely a result of groundwater contributions. However, rivers less dominated by groundwater contributions show increasing frequency of low flow days (lowest 5 percentile values). By the 2050s, for example, the Boyne has 3–12 more low flow days per year and by 2080 the Moy has 12–13 more low flow days.

Adaptation to these changed conditions will be specific to the characteristics of the catchment concerned. Groundwater-dominated catchments will require a different treatment than surface-flow-dominated catchments. A commitment to adaptation in several areas is now required:

- Flood frequency calculations require amendment for civil engineering structures to ensure protection of people and infrastructure in the years ahead.
- Increased levels of erosion and greater suspended loads will have to be managed for all Irish rivers.
- Stormflow drainage systems will pose a greater threat to water quality and will require redesign for future conditions.
- Water supply and waste water treatment calculations clearly require amendment, especially

in large urban areas dependent on surface supplies. This is especially true of the Greater Dublin Area.

- Discharge consents will require to take account of changing low flow conditions, and higher water temperatures, if water quality and aquatic biodiversity are to be preserved. Failure to do so will compromise the successful implementation of the Water Framework Directive.
- Climate-change-related hydrological considerations will require integration into the planning process for projects, plans and programmes in an explicit manner at all scales.

6.4 Vulnerabilities in Agriculture

Irish agriculture can, if positioned appropriately, adapt successfully to the challenges of climate change. The principal challenges will come from wetter winter and drier summer soils, though increased temperatures will also play an important role. Different challenges will be posed in different regions:

- In east Ulster and east Leinster, water stress in grass, barley, potato and, to a lesser extent, maize will occur on a much increased frequency. Summer soil moisture deficits will be problematic for dairying, losses from which may be partially compensated by reductions in fertiliser inputs. Late summer feed deficits may require supplementation or the introduction of a mid-season housing period.
- In much of Connaught and central Ulster, less stresses are apparent in summer and good yields of grass, barley, maize, potato and, later in the century, soybean can be expected. Scope for reduced fertiliser inputs will be greater in areas of poorly drained soils.
- In the extreme north-west, cool temperatures and relatively wet conditions will produce lower grass, maize and soybean yields, but good barley and potato yields. Dairying will not be heavily impacted.
- In south and south-west Munster, the combination of warmer and relatively moist conditions will suit most crops and enable dairying to continue much as at present. Potato yields will be limited and summer droughts will be more common, though not as severe as further east.
- Adaptation to climate change for Irish agriculture will centre either on maximising outputs or minimising inputs. Generally, the potential for considerable reduction in nitrogen application rates will occur.
- For the key dairying sector, a range of response options exists for adapting to climate change which should mean the continuing viability and profitability of this sector.

6.5 Vulnerabilities in Natural Ecosystems

Changes in species behaviour and viability and in ecosystem distribution across Ireland will occur in conjunction with the projected climate changes. Changes in the timing of life-cycle events such as leafing, bud burst and leaf fall can be expected as preliminary responses and will be instrumental in altering biodiversity. Particularly vulnerable ecosystems can also be identified where successful adjustment to new conditions is unlikely.

- Temperature and photoperiod exert strong controls on bud burst, though different species are likely to respond to changes in these parameters in varied ways. Winter chilling requirements mean that simple responses to warming of Irish climate are complicated and require species-specific modelling to predict.
- Long-term shifts of habitats in Ireland will be dependent on human controls such as the availability of suitable migration corridors.
- The most vulnerable habitats include sand dunes, lowland calcareous and calaminarian grasslands, montane heath, raised bogs, calcareous fens, turloughs and upland lakes.
- Increased decomposition of Irish peatlands will be facilitated mainly by cracking during drier summers. Compositional changes within the peatlands will be associated with further deterioration.
- As determined by climate envelope modelling, the suitable climate area for fens may have declined

by 40% by mid-century with corresponding losses for raised and blanket bogs of over 30% and 45% for turloughs over the same period.

6.6 Bridging the Gap

This report has sought to employ new techniques for integrated climate change impact assessment to narrow the uncertainties facing policy makers seeking to make informed responses to imminent climate change. These uncertainties centre at present on the reliability of model-based projections of future climate scenarios and the nature of the response of environmental systems to climate perturbation. While considerable progress has been made in assessing how Ireland's environment will respond to climate change, further research is required into several key aspects.

Firstly, more quantitative investigation of the key vulnerable sectors is needed, with particular emphasis on the role played by changes in the frequency of extreme events. These aspects are among the most difficult to quantify but have safety implications which need elucidation. The application of the precautionary principle is a necessary background consideration.

Secondly, research is needed into thresholds at which Irish environmental systems are triggered into an unfavourable and possibly unrecoverable response. For this it is essential to possess a knowledge, which goes beyond modelling, of how complex dynamic interaction between environmental systems functions and how interactions at various scales may occur.

Thirdly, to further improve integrated assessments requires the development of more sophisticated risk assessment techniques. These require a combination of scientific probabilities of particular climate impacts as used in this study together with improved modelling of how socio-economic systems change and adapt to the multifaceted stresses imposed on them.

Fourthly, Ireland can and must adapt to the challenge of climate change. Barriers to this, both scientific and socio-economic, require to be identified and addressed in order that Ireland can be optimally positioned to thrive in a changing world.

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