Part 2: Climate change: predictions and impacts
Chapter 3. A REVIEW OF GLOBAL CLIMATE PROJECTIONS AND LIKELY SCENARIOS FOR IRELAND

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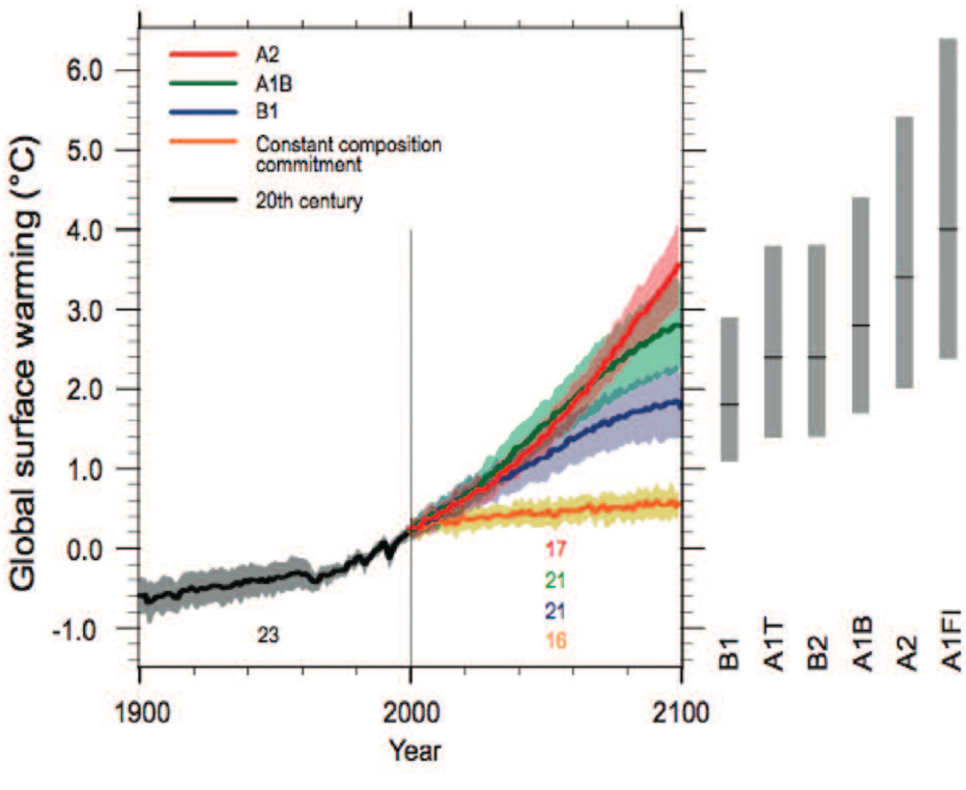
3.1 Introduction

This chapter is a review of national and regional climate scenarios for Ireland within the broader context of the likely global impacts of climate change. Projected seasonal changes in two key meteorological variables - temperature and precipitation - are outlined for three 30-year future time periods: the 2020s, 2050s and 2080s. Changes in extremes of temperature and precipitation are also discussed. This chapter provides the basis for the discussion of the physical impacts of climate change on inland waterways and the coastal environment in Chapter 4.

The latest report from the IPCC, the Fourth Assessment Report (2007a), states that warming of the climate system is now *unequivocal* and that human activities are *very likely* (>90% confidence levels) to be the cause of recent warming. Direct measurements of atmospheric levels of CO_2 since the 1950s show increasing concentrations of this important greenhouse gas (GHG), while anthropogenic methane emissions are currently more than double their pre-industrial levels. Current atmospheric concentrations of CO_2 are over 380 ppm (parts per million by volume) and represent an increase of over 35% above relatively stable pre-industrial levels of 280 ppm. These direct measurements of CO_2 are consistent with ice core data employed to assess atmospheric concentrations prior to the 1950s. Based on ice cores from Vostok Station, in Antarctica, present day concentration levels have not been exceeded in the last 400,000 years nor, most likely, in the past 20 million years (IPCC, 2001).

Even if concentrations of GHGs were maintained at the levels of 2000, warming is likely to continue at a rate of 0.1 °C to 0.2°C per decade for the next 20 years (IPCC, 2007a). Assuming a continuation of current rates of increase of global anthropogenic CO_2 emissions, a doubling of present day concentration levels is likely to occur by the end of the century. A doubling of the global warming potential (GWP) of all GHGs would occur much earlier. As a consequence, global temperatures are likely to increase by between 1.8°C to 4.0°C by 2080-2099 relative to 1980-1999 (Figure 3.1). An increase in temperatures of these magnitudes, if realised, would have a wide range of impacts.

Figure 3.1 Global surface warming for six emissions scenarios (IPCC, 2007a)



Estimates of future emissions are crucial to projecting changes in global temperatures due to increased radiative forcing arising from an increase in GHGs. However, future projections of anthropogenic climate change arising from increased concentrations of atmospheric CO_2 are subject to a high degree of uncertainty (Jones, 2000). As future human behaviour and actions are not predictable, in any deterministic sense, a set of future emissions scenarios are used to provide scenarios of future climate change.

In 1992 the IPCC published the first emissions scenarios, which were the precursor to the present Special Report on Emissions Scenarios (SRES) employed in both the Third and Fourth Assessment Reports (IPCC, 2001, 2007a). These scenarios assume varying levels of future demographic, technological, environmental, societal and economic developments that result in different emissions scenarios for the main greenhouse gases. While over 40 emissions scenarios were developed, four central 'families' (or sets) of equally probable scenarios span approximately 80% of the range of predictions contained in the SRES. Models based on these four emissions scenarios, A1, A2, B1 and B2 (Box 1), will always result in a range of future climate scenarios due to uncertainties inherent in the modelling system (Hulme & Carter, 1999).

Description of the SRES emissions scenarios (Source: IPCC, 2001)

The **A1 emissions scenario** describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.

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

The **B1 emissions scenario** describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 scenario, but with rapid changes in economic structures towards a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

The **B2 emissions scenario** describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with a continuously increasing global population at a rate lower than in A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 scenarios. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

3.2 Global climate change

Based on these SRES emissions scenarios, projections from a range of global climate models (GCMs) are employed in the Fourth Assessment Report and suggest that significant impacts on the world's climate are likely to occur over the present century. The projected increases in global temperatures are unlikely to be uniformly distributed, with increased rates of warming, nearly double that of the global average, projected for high latitudes. Regional variations in the magnitude and rate of warming will also affect the distribution and rates of change of other meteorological variables, such as precipitation.

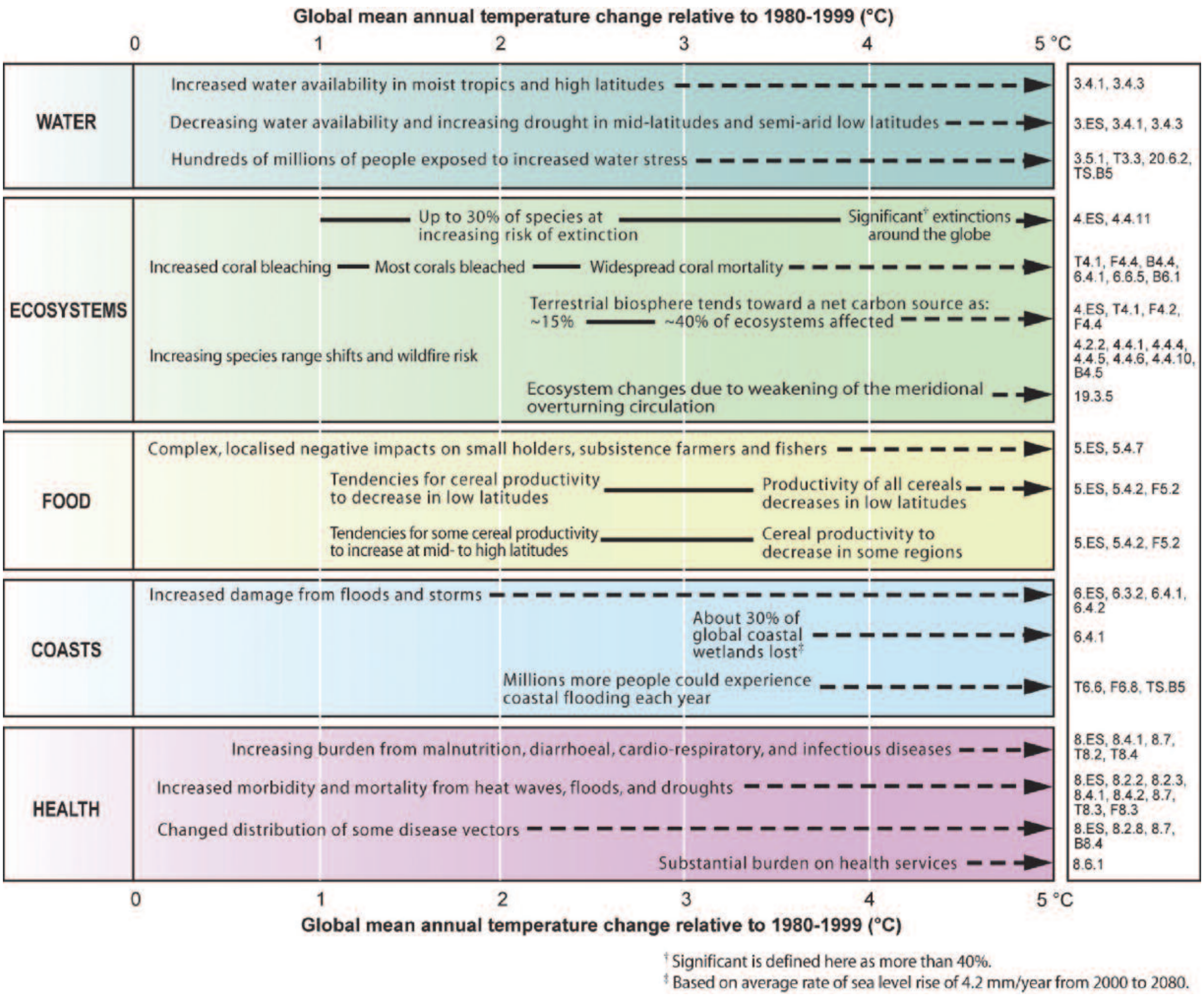
Model projections suggest that:

- Global temperatures are likely to increase by between 1.8°C to 4.0°C by 2080-2099, relative to 1980-1999
- An increase in the frequency of hot extremes, heat waves and heavy precipitation events is very likely
- Precipitation is likely to increase in mid- to high-latitudes, with reductions in the lower latitudes. Large interannual variations in precipitation are also projected
- Widespread retreat of mountain glaciers. Snow cover is projected to contract. Melting of the upper permafrost layers
- Antarctica to gain mass due to enhanced snow fall, while Greenland is likely to lose mass due to a greater relative increase in runoff (IPCC, 2001). Summer sea ice is projected to shrink in both the Arctic and Antarctic. Arctic summer sea ice to disappear towards the end of this century in some model projections

- Globally averaged sea level is projected to rise by between 0.28m and 0.43m by the end of the present century, relative to 1980-1999. (Projected ranges are likely to be conservative, as they exclude important uncertainties in the carbon-cycle feedback)
- A pole-ward shift in storm track locations is projected. While the number of tropical cyclones per year is likely to decrease, their intensity is expected to increase leading to fewer, but more intense storms
- The Atlantic meridional overturning circulation (MOC), of which the Gulf Stream is a part, is very likely to slow down during the present century, with an estimated reduction of 25%. It is, however, unlikely to undergo an abrupt transition during this period (Source: IPCC, 2007a)

Table 3.1 illustrates the projected global impacts in a range of key sectors as a consequence of temperature increases. Due to the projected increase in precipitation, water availability is likely to increase at higher latitudes whereas there will be lower water availability over much of the mid-latitudes and dry tropics (IPCC, 2007b). These changes are likely to exacerbate current pressures posed by flooding and drought in the respective regions. Where moisture availability is not a limiting factor, crop yield potential is likely to increase for global temperature increases of between 1°C and 3°C. Above this threshold, yield is likely to decrease. Large changes in ecosystem structure and function are considered likely if temperatures exceed 1.5 °C -2.5°C, with 20-30% of species at risk from extinction (IPCC, 2007b). Changes in the geographic extent of environments are also likely. Coastal ecosystems, such as salt marsh, are particularly vulnerable due to projected increases in sea level, while coasts are likely to undergo significant changes due to both an increase in sea level and the impact of more intense storms. An increased risk of flooding, due to sea level rise, will place hundreds of millions of people at risk, particularly in densely populated, low lying regions (IPCC, 2007b).

Table 3.1 Projected global impacts for key sectors for various temperature increases (IPCC, 2007a)



3.3 Regional climate scenarios

Despite the increasing sophistication of global climate models, regional climate projections are still affected by a 'cascade of uncertainty' which results from translating future socio-economic storylines into greenhouse gas emissions and subsequent climate change scenarios. Table 3.2 illustrates the global temperature response (❑T_{global}) for the UK's Hadley Centre Global Climate Model (GCM), the HadCM3, and the aforementioned sets of emissions scenarios, A1, A2, B2 and B1 for the 2080s. The regional response for the HadCM3 GCM and four marker emissions scenario is also illustrated, on a seasonal and annual basis for Ireland.

Table 3.2 *Projected global atmospheric concentrations plus global and regional temperature changes for Ireland from the HadCM3 global climate model and four emissions scenarios (data from Mitchell* et al.*, 2002).*

(summer = ❑T_{JJA}, winter = ❑T_{DJF}, annual = ❑T_{ANN})

Scenario	Concentrations(ppmv)	Label	❑T_{GLOBAL}	❑T_{JJA}	❑T_{DJF}	❑T_{ANN}
A1 (A1F1)	970	High	4.8°	3.1°	2.7°	3.0°
A2	856	Medium-high	3.9°	2.3°	2.3°	2.4°
B2	621	Medium-low	3.0°	1.5°	1.4°	1.5°
B1	550	Low	2.5°	1.5°	1.6°	1.5°

Differences arise between various research centres' models largely as a consequence of varying climate sensitivities (change in temperature due to a doubling of CO_2) and different parameterisation schemes employed by the various modelling centres. 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 (see Figure 3.1). Hulme and Carter (1999) consider this practice as 'dangerous', as crucial uncertainties remain suppressed.

While GCMs are adequate tools for assessing the likely impacts of climate change at the global scale, their spatial resolution, which is in the order of ~2.5° x 3.75° lat/long (~250km x 350km at the latitude of Ireland), is generally too coarse to inform impact analysis at the regional scale. As a consequence, a number of *downscaling* techniques have been developed in order to overcome this scale mismatch to produce detailed regional climate scenarios:

i. Regional climate models (RCMs), are 'nested' within a GCM but operate on a much smaller spatial domain, therefore available computational resources can be employed to produce climate scenarios at a much higher resolution than their parent GCM. In recent years, the use of RCMs to produce regional climate scenarios has become more widespread due to the availability of high performance computers. However, the spatial resolution of many RCMs is still in the order of tens of kilometres which is still a limiting factor for impact analyses.
ii. An alternative technique of empirical downscaling has found widespread application due to the ease of implementation in producing high resolution regional climate scenarios. It is a statistical-based technique that does not have the same computational requirements as an RCM, but produces results that are comparable to an RCM.

Research undertaken by the Community Climate Change Consortium for Ireland (C4I) located at Met Éireann, has been based on an RCM and a combination of AOGCMs (Atmosphere-Ocean Global Climate Model) for various future time periods (1950-2100; 2021-2060) (McGrath *et al.*, 2008). However, Fealy and Sweeney (2007; 2008a; 2008b) have employed the alternative technique of statistical downscaling to produce high spatial and temporal resolution climate scenarios for Ireland for the present century (1991-2100).

While spatial differences do exist between the regional climate simulations from both techniques, results are largely consistent in terms of the magnitude of change projected with respect to the key parameters of temperature and precipitation and thus we can have some degree of confidence in the projections. Climate scenarios produced from both C4I and Fealy and Sweeney (2007; 2008a; 2008b) employ a range of GCMs and so cater for some inherent uncertainties arising from differences in climate sensitivity and parameterisation schemes. However, the climate scenarios produced by Fealy and Sweeney (2007; 2008a; 2008b) employed a longer time period for all model simulations and therefore their results are described in greater detail below. Results are presented for three 30-year future time periods centred on the 2020s, 2050s and 2080s, for the ensemble or multi-model average of three GCMs, namely, HadCM3 (Gordon *et al.*, 2000), CGCM2 (Flato *et al.*, 2000) and CSIRO mkII (Watterson *et al.*, 1997), and two emissions scenarios, A2 (Medium-high) and B2 (Medium-low). The difference in temperature and precipitation are presented relative to the observations from the 30-year baseline period of 1961-1990.

Due to uncertainties that arise in climate modelling, individual GCM simulations can vary considerably both in terms of the timing and location of simulated changes. These differences are also reflected at the regional scale, again emphasising the importance of employing a number of GCMs and emission scenarios. Fealy and Sweeney (2008a) found that the greatest differences occurred in the downscaled scenarios for the 2020s period, with one model (HadCM3) projecting a very slight cooling (0.1) during the winter months for this period. Such a value is unlikely to represent a significant change however. Seasons experiencing the greatest warming were also found to differ during the 2020s (Fealy and Sweeney, 2008a). By the 2050s, a greater consistency was found between the downscaled scenarios in terms of the direction of change, however, a difference of almost 2°C was found between the 'warmest' and 'coolest' models. By the 2080s, the difference between the 'warmest' and 'coolest' models was found to be in the order of 3°C (Fealy and Sweeney, 2008a). Similar results were found for precipitation, with both direction and magnitude differences between the individual model projections for the 2020s. By the 2050s, the direction of change was found to be consistent for all seasons, but magnitudes differed between models. A fuller discussion on the downscaled inter-model ranges for both temperature and precipitation are discussed in Fealy and Sweeney (2008a). It is important to note that these model ranges do not account for how well an individual global climate model can replicate the statistics of the observed climate assessed over a common time period and thus, some measure of how 'good' an individual model is required to account for this. The Climate Prediction Index (CPI), originally derived by Murphy *et al.* (2004) and later modified by Wilby and Harris (2006) for application in impacts studies, is one such technique that can account for, or measure, the ability of individual global climate models to replicate the statistics of the observed climate.

Prior to deriving the ensemble means, Fealy and Sweeney (2008a) assessed model differences between the individual GCMs and observed upper air and surface variables based on the Climate Prediction Index (CPI). The CPI produces a weighting for each GCM based on its ability to reproduce the statistics of the observed climate when compared over the 1961 to 2000 period. Models that attain higher scores or weights therefore contribute a greater proportion to the derived ensembles. Ensemble mean changes in temperature and precipitation are quoted in the tables below (Tables 3.3-3.4) along with the unweighted model ranges derived from the downscaled values from individual global climate models. While the unweighted values display a considerable range in values, no measure of how 'good' a particular model is, is accounted for in these ranges and therefore, the value ranges need to be interpreted with great care.

NATURAL CLIMATE VARIABILITY

Ray Bates (UCD)

Globally, the phenomenon associated with the greatest natural climate variability is the El Niño-Southern Oscillation (ENSO). This consists of the quasi-periodic (3-7 year period) sloshing of warm water from the Western Pacific warm pool eastwards along the equator towards South America, causing anomalous warming of the sea surface over a large area of the equatorial Pacific. The anomaly is so large (locally in excess of 3°C at times) and covers such a large area that it exerts an appreciable influence on the global mean surface temperature. The largest positive ENSO of the twentieth century occurred in 1998 and gave a noticeable peak in the global mean temperature curve in that year. Since then, ENSO has continued to oscillate, but has not since attained anything like the large positive 1998 values. Throughout most of 2008, ENSO was in a negative phase, contributing to the observed dip in the global mean temperature in the year past.

ENSO also has an appreciable influence on the variability of climate throughout the entire Pacific region on the 3-7 year time scale, but it does not have an appreciable influence on European climate variability.

The phenomenon giving the greatest natural climate variability in northern Europe, including Ireland, is the North Atlantic Oscillation (NAO). The simplest measure of this phenomenon is the surface pressure difference between the Azores and Iceland. The NAO varies on time scales from inter-annual to multi-decadal. When the NAO is positive (large pressure difference), the north Atlantic westerlies tend to be stronger than normal, bringing anomalously moist air to northern Europe with cooler than normal temperatures in summer and milder than normal temperatures in winter; when it is negative (small pressure difference), the Atlantic westerlies are weaker than normal and warm dry summers and cold dry winters are more common. Unlike ENSO, the NAO does not influence the global mean temperature.

Scaife *et al.* (2005) have provided evidence that the observed decrease in the number of frosty nights and the change in precipitation extremes in northern European winters in the decades 1965-95 are attributable much more to a trend towards a more positive phase of the NAO than to increased greenhouse gases. It was widely felt for some time that the observed NAO trend was itself a signal of human-induced climate change, but since the 1990s the upward trend in the NAO has reversed, casting doubt on any relationship between it and increasing greenhouse gases.

Scaife *et al.* (2005) have also shown that the ability of current Global Climate Models (GCMs) to reproduce the observed low-frequency variability of the NAO is limited, even when the sea surface temperature and the greenhouse gas concentrations are prescribed. They have shown that the low skill in this area can be improved by prescribing the anomalies in the stratospheric circulation, which is also poorly simulated by the GCMs. An improved representation of the stratosphere may therefore, in time, lead to improved GCM skill in reproducing the NAO variability.

Another feature of natural variability affecting Ireland is the multi-decadal variability (MDV) in the north Atlantic sea surface temperature. Unlike the NAO, which is primarily an atmospheric phenomenon, the MDV is primarily oceanic. It has been estimated by Polyakov *et al.* (2009) that the MDV accounts for 60% of the North Atlantic warming since 1970, the remainder being due to a long term trend that is likely to be human-induced.

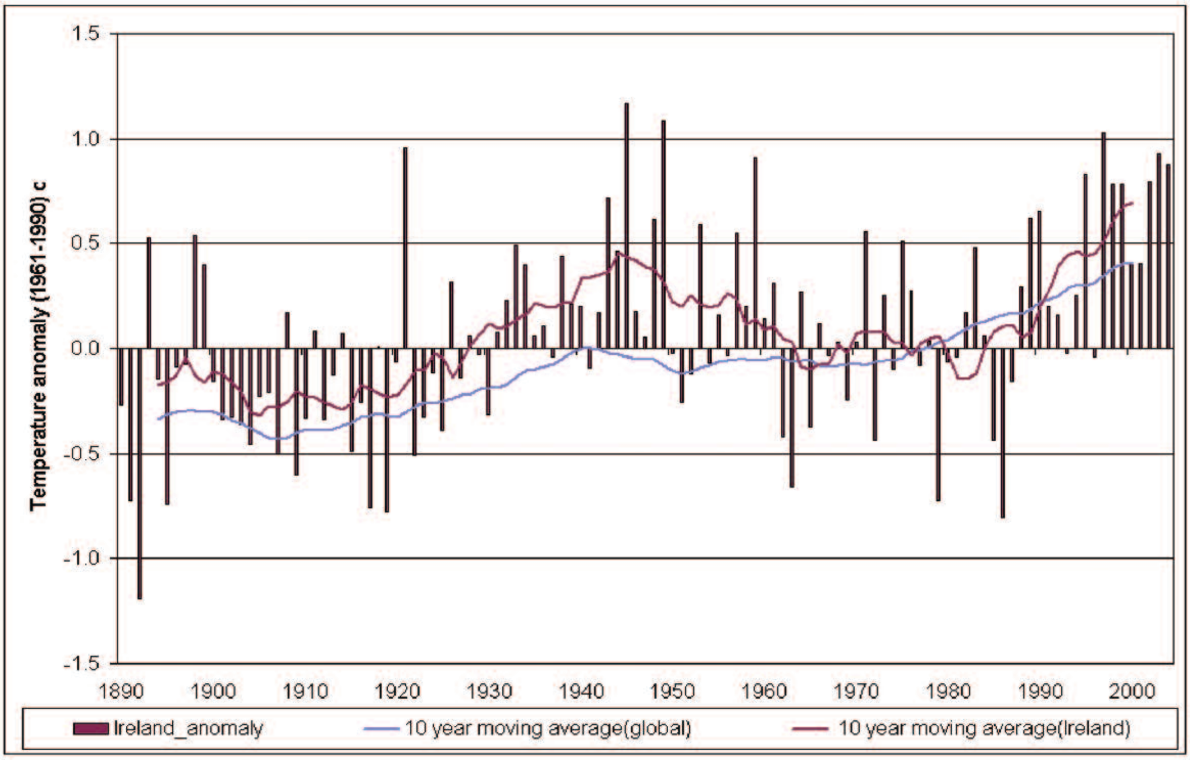
In summary, at our geographic location, large natural variability on the regional scale is superimposed on the emerging signal of human-induced climate change. There can be little doubt that the global average temperature and sea-level rise already show the emergence of the human-induced signal, but for regional climate variables at our location it will be some time before the human-induced signal clearly emerges from the noise of natural variability.

3.4 Observed and projected changes in the Irish climate

3.4.1 Temperature

In an analysis of the indicators of climate change in Ireland, McElwain and Sweeney (2007) detected a linear increase of 0.7°C in the Irish temperature records over the 1890-2004 period. Warming occurred in two periods, 1910-1949 and 1980-2004, with the rate of warming in the latter period, of 0.42°C/decade, nearly double that of the earlier period (Figure 3.2). Regional climate projections for Ireland indicate that a mean warming rate of between 0.2 °C to 0.3°C per decade is likely to continue over the course of the present century.

Figure 3.2 Global and Irish Temperature anomalies 1890-2005 (McElwain & Sweeney, 2007)



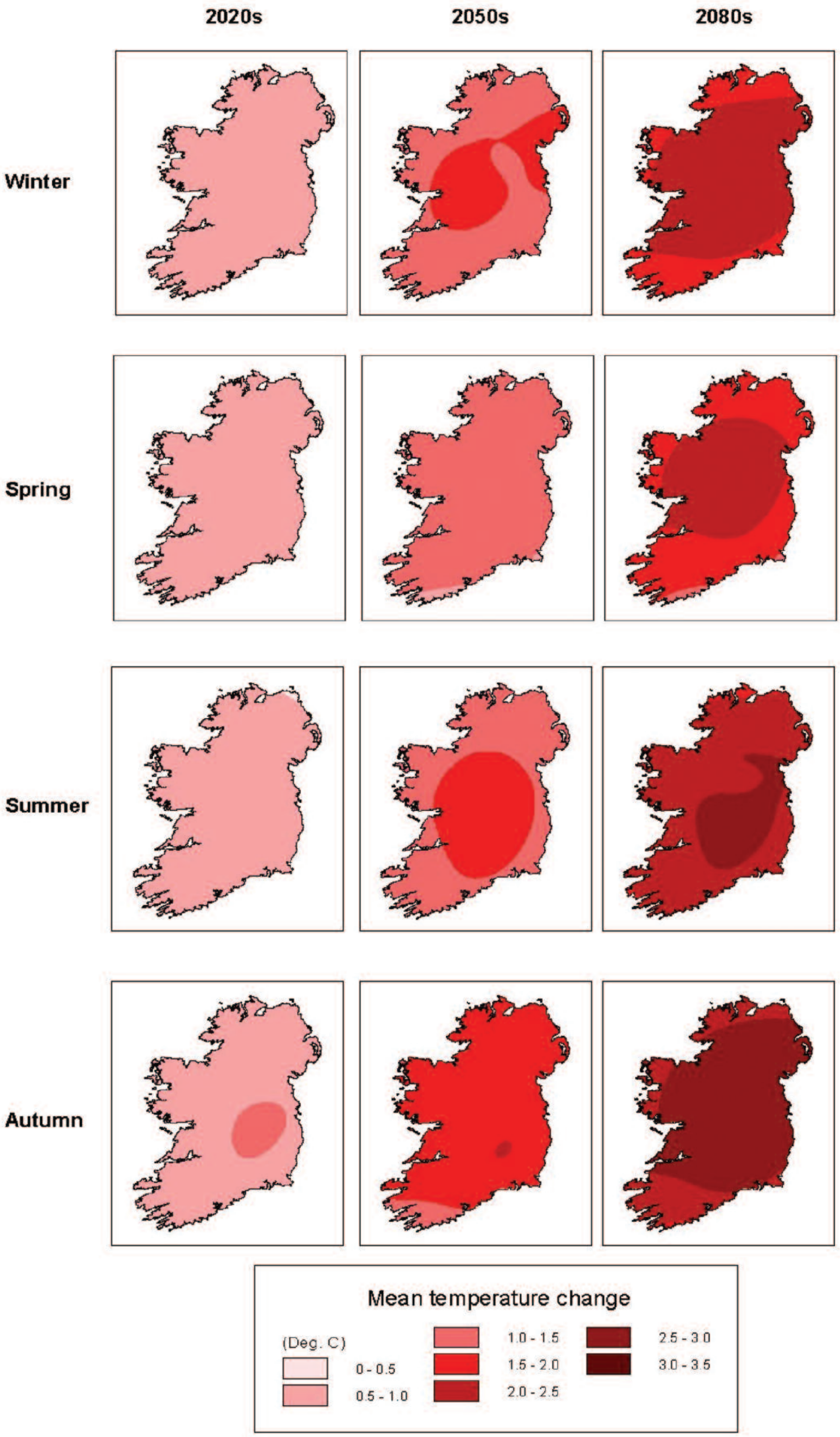
Regional projections suggest that, by the 2020s, seasonal average temperature will increase by between 0.7 °C -1.0°C relative to the 1961-1990 period (Table 3.3) (Fealy & Sweeney, 2008a; 2008b). A warming continental effect also becomes evident during the months of September, October and November, with the largest temperature increase projected to occur in the eastern portion of the Midlands.

By the 2050s, this continental effect becomes further enhanced with mean temperatures projected to increase by 1.4 °C -1.8°C, relative to the 1961-1990 period, with the largest increases occurring in the midland region (Figure 3.3). The greatest warming again occurs during the autumn months, consistent with the earlier projections. The continental effect becomes apparent during all seasons by the 2080s, with mean temperature projected to increase by between 2.1°C -2.7°C.

Table 3.3 Ensemble mean temperature increases (˚C), based on the Climate Prediction Index (CPI), for each season and time period averaged for all stations employed in the analysis of Fealy and Sweeney (2008a; 2008b). Unweighted model ranges are illustrated in brackets. (Fealy and Sweeney, 2008a; 2008b)

Season	2020	2050	2080
Winter: *Dec, Jan, Feb.*	0.7˚ (-0.1 - 1.9)	1.4˚ (0.5 - 2.6)	2.1˚ (0.8 - 3.9)
Spring: *Mar, Apr, May*	0.8˚ (0.4 - 1.2)	1.4˚ (0.7 - 2.0)	2.0˚ (1.3 - 2.5)
Summer: *June, July, Aug.*	0.7˚ (0.4 - 1.2)	1.5˚ (1.3 - 2.5)	2.4˚ (1.7 - 3.3)
Autumn: *Sept, Oct, Nov.*	1.0˚ (0.3 - 1.8)	1.8˚ (1.1 - 2.7)	2.7˚ (1.7 - 3.6)

Figure 3.3 Mean seasonal temperature increases projected for the 2020s, 2050s & 2080s



3.4.2 Precipitation

Projected changes in precipitation suggest that an increased seasonality (Table 3.4) and a change in the spatial distribution are likely (Figure 3.4) for all future time periods. By the 2020s, mean ensemble changes suggest that winter precipitation is likely to increase by approximately 3%. A similar magnitude decrease in national precipitation is projected to occur during the summer months, although a large regional decrease, of the order of 10-16%, is projected to occur along the south and east coast.

Table 3. 4 Ensemble percentage change in precipitation (%),based on the Climate Prediction Index (CPI), for each season and time period averaged for all stations employed in the analysis of Fealy and Sweeney (2007; 2008a). Unweighted model ranges are illustrated in brackets (values shown are rounded to nearest whole number). (Fealy & Sweeney, 2007)

Season	2020	2050	2080
Winter: *Dec, Jan, Feb.*	+3.0 (-4.0 - 9.0)	+12.4 (7.0 - 18.0)	+15.6 (9.0 - 20.0)
Spring: *Mar, Apr, May*	-1.0 (-10.0 - 4.0)	-7.2 (-1.0 - -14.0)	-8.0 (-25.0 - 6.0)
Summer: *June, July, Aug.*	-3.2 (-17.0 - 5.0)	-12.1 (-6.0 - -32.0)	-19.0 (-12.0 - -27.0)
Autumn: *Sept, Oct, Nov.*	-1.7 (-8.0 - 4.0)	-2.6 (-1.0 - -7.0)	-7.1 (-3.0 - -15.0)

Greater seasonality of precipitation becomes evident during the 2050s, with an increase in the order of 12% projected to occur during the winter months. A similar reduction is projected to occur during the summer months (Table 3.4). Regional decreases of between 20-28% are projected for locations along the south and east coasts (Figure 3.4).

These seasonal and spatial changes are further enhanced by the 2080s. An increase in winter precipitation of 15% is projected to occur nationally, with above average increases projected for the midlands. Nationally, summer reductions of 19% are likely, with decreases of between 30-40% along the east and south coasts.

Increases in winter precipitation are projected to occur for all time periods, while reductions are consistently projected to occur for all other seasons. If realised, these changes in the seasonal and spatial distribution of precipitation are likely to result in an increased likelihood of flooding, particularly in the midlands and west of Ireland, while water availability and quality are likely to be adversely affected during the late summer and autumn months in all regions, but particularly along the south and east coasts.

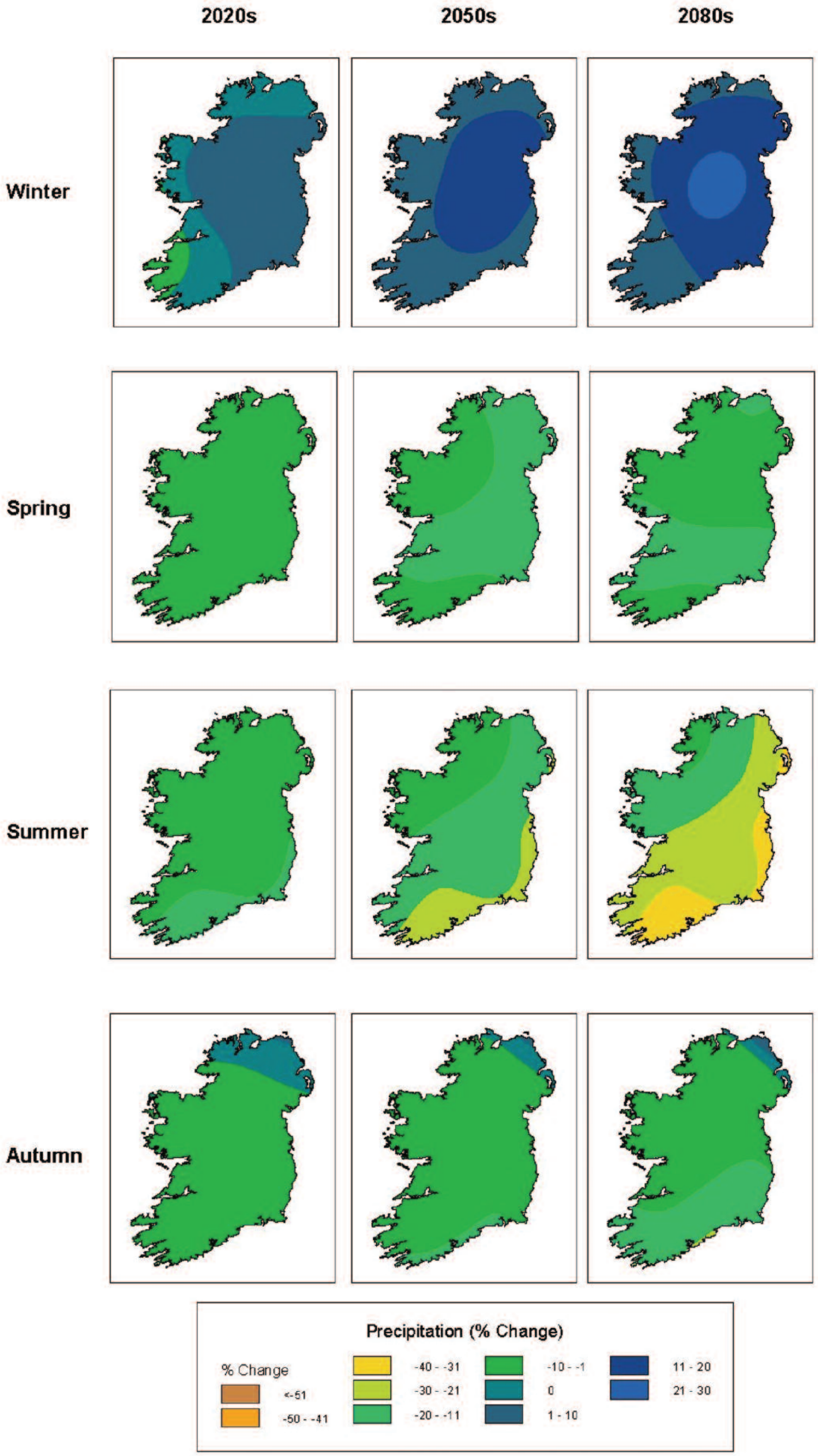
While not directly comparable due to the difference in simulated time periods, spatial differences in projected precipitation are apparent between both the C4I (McGrath *et al*., 2008) and Fealy and Sweeney (2007; 2008b) simulations for the middle of the century. The C4I simulations (McGrath *et al*., 2008) project a greater decrease in summer precipitation along the west coast of Ireland, with reductions in the order of 6 to 9%, while the Fealy and Sweeney (2007; 2008b) projections suggest the greatest decrease in summer precipitation will be experienced along the east and south coast. These differences largely reflect uncertainties in the different models and approaches employed and the greater uncertainty associated with modelling precipitation, as compared to temperature, and stress the importance of employing multiple model simulations in order to develop robust adaptation strategies for the future.

3.4.3 Extremes: temperature and precipitation

Extremes of temperature (frequency, intensity and duration), with all their adverse effects on human societies and ecosystems, are also expected. The prolonged heat wave that occurred in Europe in 2003, one of the hottest on record, resulted in an excess of 35,000 deaths. In the summer months of 2006 Ireland experienced above average mean temperatures which were nearly 2°C higher than the 'normal' for the 1961-90 period in the midland stations of Clones and Kilkenny. Combined with below average precipitation, this resulted in significant soil moisture deficits through out much of the southern part of the country with resultant impacts on agriculture (Met Éireann, 2006).

A number of extreme precipitation events have been experienced in Ireland in recent years, particularly during the summers of 2007 and 2008 when well above average precipitation amounts and intensities were recorded at a number of locations around Ireland. The extreme precipitation resulted in severe flooding, most notably in Newcastle West in County Limerick and in Mallow, County. Cork.

Figure 3.4 Mean seasonal precipitation changes projected for the 2020s, 2050s & 2080s (Fealy & Sweeney, 2007).



While such extreme events are consistent with the natural variability of the climate system, evidence from the observational records suggests there is a tendency towards an increase in frequency of occurrence and intensity of extreme events. A significant increase was found to have occurred in both maximum and minimum temperatures over the 1961-2005 period (McElwain & Sweeney, 2007). This increase in minimum temperatures has resulted in a shortening of the frost season and a significant decrease in the annual number of frost days (by more than half at a number of stations) (McElwain & Sweeney, 2007). While the number of consecutive cold days has been decreasing over the same period at a number of stations in Ireland, the duration of heat waves has also been increasing,

Fealy and Sweeney (2008a; 2008b), in an analysis of likely future changes in extremes based on the A2 (Medium-high) scenario, found that significant changes are likely to occur in the four key indices of extreme events, namely:

- Hot-day threshold (T_{max} 90th percentile)
- Cold-night threshold (T_{min} 90th percentile)
- Number of frost days ($T_{min} < 0°C$)
- Longest heat wave (heat wave duration)

Trends were found to be significant (0.01 significance level) at all stations for all the temperature indices employed in their analysis.

An increase in the intensity of extreme temperatures (the hot day threshold) is indicated for all stations, rising by a rate of more than 0.2°C per decade, particularly for inland stations. An increase in the duration of heat waves is also projected by between 3-4 days per decade, while a decrease in the number of frost days per decade, especially at inland stations, is also likely due to the cold night threshold rising by 0.2-0.3°C per decade. These projected changes are consistent with the observational records.

As global temperatures increase, the hydrological cycle will become more intense and will result in more extreme precipitation events. Changes in intensity or duration are likely to result in an increase in flood frequency and magnitude, while water shortages or drought conditions are likely due to reductions in precipitation. Analysis of extreme precipitation events suggests a significant and increasing trend in the highest five day rainfall totals at eight of the stations analysed. These stations are located in the midlands and along the east coast. An increase in the longest number of consecutive dry days was found to be significant at all stations, with the greatest increases for stations in the east and midlands.

These changes suggest that Irish precipitation, typically characterised as low intensity long duration, is likely to become more intense resulting in increased surface runoff. Increased surface runoff will have implications for both winter and summer flooding risk, as witnessed during the summer of 2007, the wettest summer on record in over 50 years on the east coast (Met Eireann, 2007).

An increase in the length and frequency of dry periods will also have an impact on water quality and availability and hence an increased vulnerability to water deficits such as those experienced during the summer of 2006. The extremes experienced during these two years could indicate that interannual variability is also increasing.

Dangerous Climate Change

The stated objective of Article 2 of the UNFCCC is to 'stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. Stabilisation was to be achieved in a time frame such that natural and human systems would have adequate time to adapt. However, the convention does not state what constitutes 'dangerous anthropogenic interference' with the climate system, a deficiency which has led to much procrastination within the scientific and political communities in implementing targets and policies at which stabilisation of GHG concentration should occur.

In 1996, in an attempt redress this deficiency and to limit the severe impacts of global climate change, the EU adopted a climate protection target to limit global mean temperatures to not more than 2°C above pre-industrial levels. However, there remains uncertainty in the scientific community about the sensitivity of the climate system and the equilibrium response of the climate system to a doubling of CO_2 concentrations. Hence, the 2°C target may be reached at varying levels of concentration levels depending on the actual climate sensitivity of the climate system.

Atmospheric concentrations of CO_2 are currently over 380 ppm (by volume). However, when the global warming potential (GWP) of all GHGs is converted to a CO_2 equivalent, current atmospheric concentrations of all GHGs are over 425 ppm. Globally averaged surface temperatures have already increased by 0.74°C above pre-industrial levels and based on current atmospheric concentration levels we are committed to a further 0.2-0.4°C, resulting in an increase in surface temperatures within the next two to three decades of over half the 2°C protection target adopted by the EU.

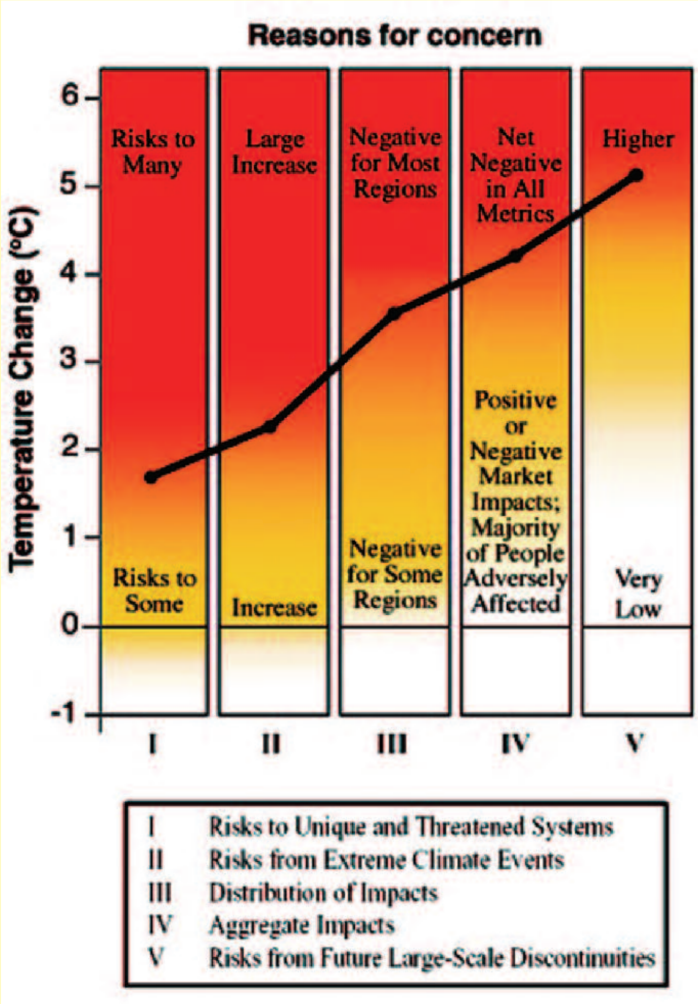
If stabilisation of concentration levels were to occur at current levels, there is a 2 in 3 chance of remaining within the protection guardrail of 2°C. If stabilisation were to occur at 550 ppm, the odds reduce to 1 in 4. Stabilisation at 650 ppm would result in only a 1 in 16 chance of staying within the target (McElwain & Sweeney, 2007).

Table 3.5 illustrates the likely range of impacts associated with various temperature increases above pre-industrial levels. For temperature increases above 2°C, the likelihood of dangerous or catastrophic climate change become apparent. These include increased melting rates of the Greenland Ice Sheet, a slow down of the Thermohaline circulation or Gulf Stream, a collapse of the West Antarctic Ice Sheet and the release of methane clathrates from the ocean floor. The risk of extreme climate events occurring also increases above this threshold (inset figure 3.5).

Table 3.5 Potential impacts and vulnerabilities for Ireland associated with various global temperature increases (McElwain & Sweeney, 2007)

Up to 1°C	Up to 2°C	Greater than 2°C
Longer growing season	Increased likelihood and magnitude of river flooding	Sea level rise due to thermal expansion of oceans, melting of the GIS, collapse of the WAIS
Potential for new crops, e.g. soybean	Reduced soil moisture and groundwater storage	Loss of coastal habitats due to inundation and increased erosion
Increased production of existing cereal and grass crops	Water shortages in summer in the east which will impact upon reservoirs and soil management	Increased incidence of coastal flooding
Earlier breeding and arrival of birds	Increased demand for irrigation	More intense cyclonic and extreme precipitation events
Heat stress will have an impact on human and animal health	Change in distribution of plants and animals, e.g. decline and possible extinction of cold Arctic species	
Negative impact upon water quality, e.g. reduction in quantity of water to dilute pollution	Fisheries could be affected as fish stocks are sensitive to small changes in temperature	
	Increased frequency of forest fires and pest infection	

Figure 3.5 'Reasons for concern' associated with various temperature increases
(Mastrandrea & Schneider, 2004; adapted from Figure SPM2, IPCC TAR SPM of WG II)



There is increasing scientific evidence from palaeo-environmental records to suggest that abrupt changes in temperature have occurred in the past, with large changes occurring over very short timescales. The most documented event occurred during the Younger Dryas (~10,500 years before present), when a freshening of the North Atlantic resulted in a slowdown of the Thermohaline circulation. A widespread and rapid cooling event also occurred ~8,200 years before present, when temperature fell by over 5°C over Greenland for about 200 years.

3.5 Conclusion

This chapter presented a review of global climate model projections and likely regional scenarios for Ireland over the present century. While GCMs represent the most appropriate tool for assessing projected large-scale changes in climate, their relevance is reduced at the regional scale for which higher resolution information is required.

To address this deficiency, Met Eireann and ICARUS have employed dynamical and empirical downscaling methodologies to produce regional scenarios for Ireland. While the two modelling centres have employed different parent GCMs, the similarity of climate scenarios implies that we can have a degree of confidence in the respective climate projections.

Based on the downscaled scenarios, significant changes in temperature and precipitation are projected to occur in Ireland over the present century. Warming of greater than 2°C is likely in all seasons by the end of the century, while significant seasonal and spatial changes are projected to occur in precipitation. It is likely that the projected changes in seasonal precipitation amounts and distribution will present a more significant challenge for adaptation than the projected changes in temperature. The review of scenarios presented in this chapter only reflect changes in the multi-model average climate simulation, based on the downscaled results from Global Climate Models and two emissions scenarios, the A2 (Medium-high emissions) and B2 (Medium-low) scenarios. In the absence of binding international commitments to mitigate future global emissions, end of century atmospheric concentrations are currently more consistent with the A1 (High emissions) scenario. The results presented here could therefore underestimate future changes in climate for Ireland.

References

Fealy, R. and Sweeney, J. (2007) Statistical downscaling of precipitation for a selection of sites in Ireland employing a generalised linear modelling approach, *International Journal of Climatology*, 27, 2083-2094, DOI: 10.1002/joc.1506.

Fealy, R. and Sweeney, J. (2008a) Climate scenarios for Ireland, in Sweeney, J. (ed.) *Climate Change: Refining the Impacts*. Report submitted to the Environmental Protection Agency, Johnstown Castle, Wexford.

Fealy, R. and Sweeney, J. (2008b) Statistical downscaling of temperature, radiation and potential evapotranspiration to produce a multiple GCM ensemble mean for a selection of sites in Ireland. *Irish Geography, 41, 1, 1-27*.

Flato, G. M., Boer, G. J., Lee, W. G., McFarlane, N. A., Ramsden, D., Reader, M. C. and Weaver, A. J. (2000) The Canadian Centre for Climate Modeling and Analysis global coupled model and its climate. *Climate Dynamics,* 16 (6), 451–467.

Gordon, C., Cooper, C., Senior, C.A., Banks, H.T., Gregory, J.M., Johns, T.C., Mitchell, J.F.B. and Wood, R.A. (2000) The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dynamics*, 16, 147-168.

Hulme, M., Barrow, E. M., Arnell, N. W., Harrison, P. A., Johns, T. C. and Downing, T. E., (1999) Relative impacts of human-induced climate change and natural climate variability. *Nature*, **397**, 688-691.

Hulme, M. and Carter, T.R., (1999) 'Representing uncertainty in climate change scenarios and impact studies', in: Representing uncertainty in climate change scenarios and impact studies (Proc. ECLAT-2 Helsinki Workshop, 14-16 April, 1999 (Eds. T. Carter, M. Hulme and D. Viner). 128pp Climatic Research Unit, Norwich, UK.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R., Hill, S., (2002) *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report*. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK.

IPCC, (2001) *Climate Change 2001: The Scientific Basis.* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Houghton, J. T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P. J. and Xiaosu, D. (eds.). Cambridge University Press, UK. 944 pp.

IPCC, (2007a) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New Y ork, NY, USA, 996 pp.

IPCC (2007b) *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry M.L., O.F. Canziani, .P. Palutikof, P., van der Linden and C.E. Hanson, (eds.). Cambridge University Press, Cambridge, UK, 982pp.

Jones, R.N., (2000) Analysing the risk of climate change using an irrigation demand model, *Climate Research*, 14, 89-100.

Mastrandrea, M.D. and S.H. Schneider, (2004) Probabilistic Integrated Assessment of 'Dangerous' Climate Change, *Science*, 304, 571-5.

McGrath, R., and Lynch, P., editors (2008) *Ireland in a Warmer World: Scientific Predictions of the Irish Climate in the Twenty-First Century*. Final report of C4I, Dublin, 2008

McElwain, L. and Sweeney, J., (2007) *Implications of the EU climate protection target for Ireland*. Environmental Protection Agency, Ireland.

McElwain, L. and Sweeney, J., (2007) *Key Meteorological Indicators of climate change for Ireland*. Environmental Protection Agency, Ireland.

Met Eireann (2006) The Weather of Summer 2006, http://www.met.ie/climate/monthly_summarys/summer06.pdf

Met Eireann (2007) The Weather of Summer 2007, http://www.met.ie/climate/monthly_summarys/summer07.pdf

Mitchell, F. and Ryan, M., (1997) *Reading the Irish Landscape.* Town House, Dublin.

Mitchell, T. D., Hulme, M., and New, M., (2002) Climate data for political areas. *Area* 34, 109-112

Murphy, J.M., Sexton, D.M.H., Barnett, D.N., et al. 2004. Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature*, 430, 68-772.

Murphy, C. and Charlton, R., (2008) Climate Change and Water Resources in Ireland in Sweeney (ed) *Climate Change: Refining the Impacts*, Environmental Protection Agency, Johnstown Castle, Wexford.

Polyakov, I.V., Alexeev, V.A., Bhatt, U. S., Polyakova, E. I. and Zhang, Z., 2009: North Atlantic warming: patterns of long-term trend and multi-decadal variability. *Climate Dynamics*. Published online: 10 Jan 2009. DOI 10.1007/s00382-008-0522-3.

Scaife, A. A., Folland, C. K., Alexander, L. V., Moberg, A. and Knight, J. R., 2005: European climate extremes and the North Atlantic Oscillation. *Journal of Climate*, **21**, 72-83.

Watterson, I.G., O'Farrell, S.P. and Dix, M.R. (1997) Energy transport in climates simulated by a GCM which includes dynamic sea-ice. *Journal of Geophysical Research,* 102, 11027-11037.

Wilby, R.L. and Harris, I. (2006) A framework for assessing uncertainties in climate change impacts: low flow scenarios for the River Thames, UK. *Water Resources Research*, 42. W02419, doi:10.1029/2005WR004065.