climate
change
challenge

OCCASIONAL PAPER 3

The Science of Climate Change

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> ***“Warming of the climate system is unequivocal, as is now evident from increases in global average air and ocean temperatures, melting of snow and ice, and rising sea level”***
>
> (IPCC, 2007)

INTRODUCTION

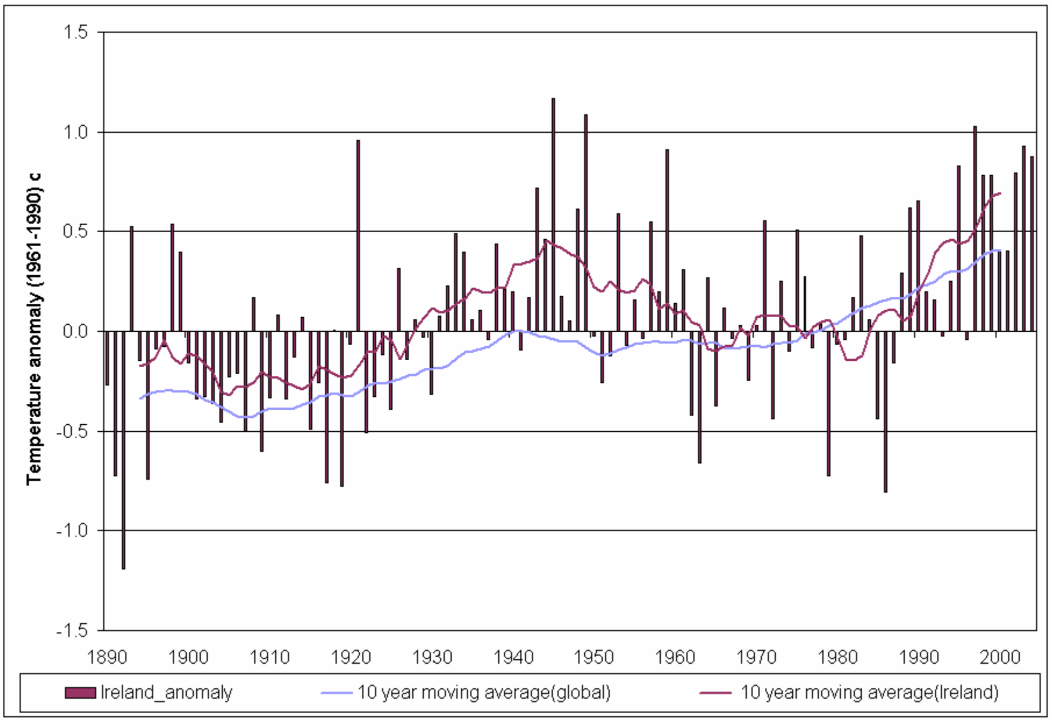
The Earth's thermostat is a complex and delicate mechanism, at the heart of which lie the greenhouse gases in the atmosphere. Carbon dioxide (CO_2), a colourless and odourless gas, is the principal well-mixed greenhouse gas. It is through emissions of this gas that human activities exert their greatest influence on climate. Increased concentrations of carbon dioxide disturb the natural radiative balance of the atmosphere and lead to warming of the Earth's surface.

The latest report from the Intergovernmental Panel on Climate Change, the Fourth Assessment Report (2007), has confirmed the assertion that “warming of the climate system is unequivocal” and that most of the observed 20th century increase in globally averaged temperatures is “*very likely*” due to the observed increases in anthropogenic greenhouse gas concentrations. A discernable human influence on the climate system is now apparent and extends to oceanic warming, temperature extremes and wind patterns. Concentrations of the main greenhouse gases (GHGs) are higher than at any time in the past 650,000 years. CO_2 concentrations are presently over 380 ppmv (parts per million volume) compared with pre-industrial levels of 280ppm, while methane concentrations have already doubled from their pre-industrial values. In the absence of strict emissions controls, a doubling of atmospheric concentrations of CO_2 is likely by the end of the present century. As a consequence, global temperatures are projected to increase by between 1.8 to 4°C over the same period depending on the climate sensitivity to increased levels of GHG.

OBSERVED GLOBAL CLIMATE CHANGE

Over the 1906-2005 period, globally averaged surface temperatures display a linear increase of 0.74°C ±0.18°C. This warming largely occurred in two periods, 1910-1940 and 1970 to present, with a brief cooling phase experienced during the 1940s and 1950s (Figure 1). The rate of warming also appears to be increasing with the linear warming trend of the last 50 years almost double that for the last 100 years. Twelve of the last thirteen years (1995-2007) rank as the warmest years on record since the 1850s, while seven of the eight warmest years have occurred since the turn of the century. The period 2001-2007 was warmer, by 0.21°C, than the previous decade of the 1990s (1991-2000) (Climate Research Unit, 2008), which had constituted the warmest decade of the warmest century of the last millennium based on a combination of instrumental and proxy records. Prior to 2005, the warmest year on record was 1998, which stood out because it coincided with a strong El Nino event. However, with the inclusion of additional station data from the Arctic, scientists at the Goddard Institute for Space Studies (GISS) place 2005, a non El Nino year, as equal first or clear first in the series (Kennedy *et al*, 2006). Additionally, satellite and balloon borne measurements of the lower and mid-tropospheric temperatures show warming rates that are consistent with the surface temperature records (IPCC, 2007a). Warming rates have been found to be greatest over land areas and particularly at high Northern latitudes. Average Arctic temperatures have increased at almost double the global average rate over the last 100 years primarily due to ice albedo feedback processes.

Figure 1 Global and Irish temperature anomalies 1890-2004 relative to 1961-1990



(*Source:* McElwain and Sweeney, 2007b)

Importantly, urban heat island effects, while real, have been quantified and are considered to have a negligible effect on the globally averaged surface temperature increases (IPCC, 2007a).

The observed increase in global surface temperature has resulted in a widespread decline in mountain glaciers and snow cover in both hemispheres. This decline in terrestrial water storage has contributed 0.50 ±0.18 mm yr^{-1} to sea level rise over 1961-2003, which increased to 0.77 ±0.22

mm yr^{-1} since 1993 (IPCC, 2007a). Glacier meltwater coupled with thermal expansion of the oceans, resulting from an increase in the temperature of the oceans to depths of up to 3000 m, has resulted in an annual rise in sea level of 1.8 ±0.5 mm over the 1961-2003 period (IPCC, 2007a). Since 1993, a higher rate of 3.1 ±0.7 mm yr^{-1} has been observed. Over the course of the 20th century, sea level is estimated to have risen by 0.17 ±0.05 metres.

Changes in regional precipitation have also been found to be occurring over the observational period of record from 1900 to 2005. A significant increase in precipitation amounts has been detected in eastern parts of North and South America, northern Europe and northern and central Asia, while a tendency for increased drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia (IPCC, 2007a). Changes in extremes have also been found to be occurring with the frequency of intense precipitation events having increased over most land areas while more intense and prolonged droughts, particularly in the tropics and sub tropics, have been observed since the 1970s (IPCC, 2007a). These changes are likely being driven by a combination of factors such as changes in humidity, atmospheric circulation patterns and increased storm activity, all of which are likely to change as a consequence of global warming. Changes in precipitation and evaporation over the oceans have also resulted in the freshening of mid- and high- latitude waters with increased salinities apparent in low-latitude waters (IPCC, 2007a).

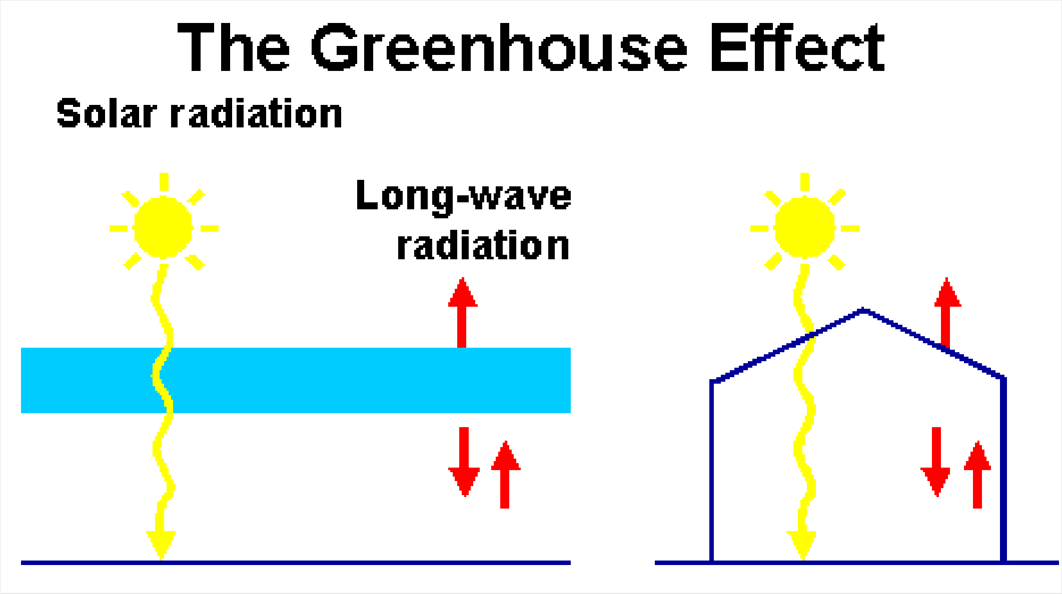
GLOBAL CLIMATE CHANGE

Atmospheric concentrations of CO_2 are currently over 380 ppmv which represents an increase of over 35% above pre-industrial levels. Despite the fact that CO_2 and the other greenhouse gases comprise only a very small fraction of the dry atmospheric composition, changes in the atmospheric abundance of these gases are capable of altering the energy balance of the climate system (IPCC, 2007a) through their radiative properties, which are most effective at the low temperatures and low pressures found in the upper troposphere. This effect was first recognised in 1824, by Jean Baptiste Fourier who used the analogy of the glass in a greenhouse to describe the radiative warming of the Earth's surface due to these gases, which later led to the name 'greenhouse effect' being given to this process (Box 1). This assertion was confirmed in 1860, by John Tyndall, a native of Leighlinbridge, County Carlow, who measured the absorption of infrared radiation by CO_2 and water vapour and definitively established the radiative properties of these gases. Model experiments show that even if all emissions of greenhouses were held constant at year 2000 levels, warming of the climate system would continue at a rate of about 0.1°C per decade for the next two decades, due to the delayed response of the oceans.

Box 1 The Greenhouse Effect

The greenhouse effect is the heating effect exerted by the atmosphere on the earth's surface because of the presence in the atmosphere of certain gases ("greenhouse gases") that trap some of the long-wave radiation being emitted upward by the surface and re-emit it back to the surface (Figure 2). The long-wave radiation is heat radiation of the kind emitted by a warm object, which we can feel at a distance from the object but our eyes cannot see. In contrast, the sun's radiation is short-wave radiation that we can both feel and see. This radiation passes downward through the atmosphere largely unimpeded and is absorbed by the surface, tending to raise the surface temperature. If there were no greenhouse gases in the atmosphere, a long-term equilibrium temperature would be reached where the downwelling solar radiation would be balanced by the upwelling long-wave radiation at the surface, with *all* the long-wave radiation being lost to space. The mean temperature at the surface would then be about 33° C colder than the temperature we know, and the whole earth would be covered with ice. The presence of the naturally occurring greenhouse gases, trapping some of the long-wave radiation and preventing it from being lost to space, is thus essential for life on earth as we know it, and the 33° C warming that they cause is known as the *natural greenhouse effect*.

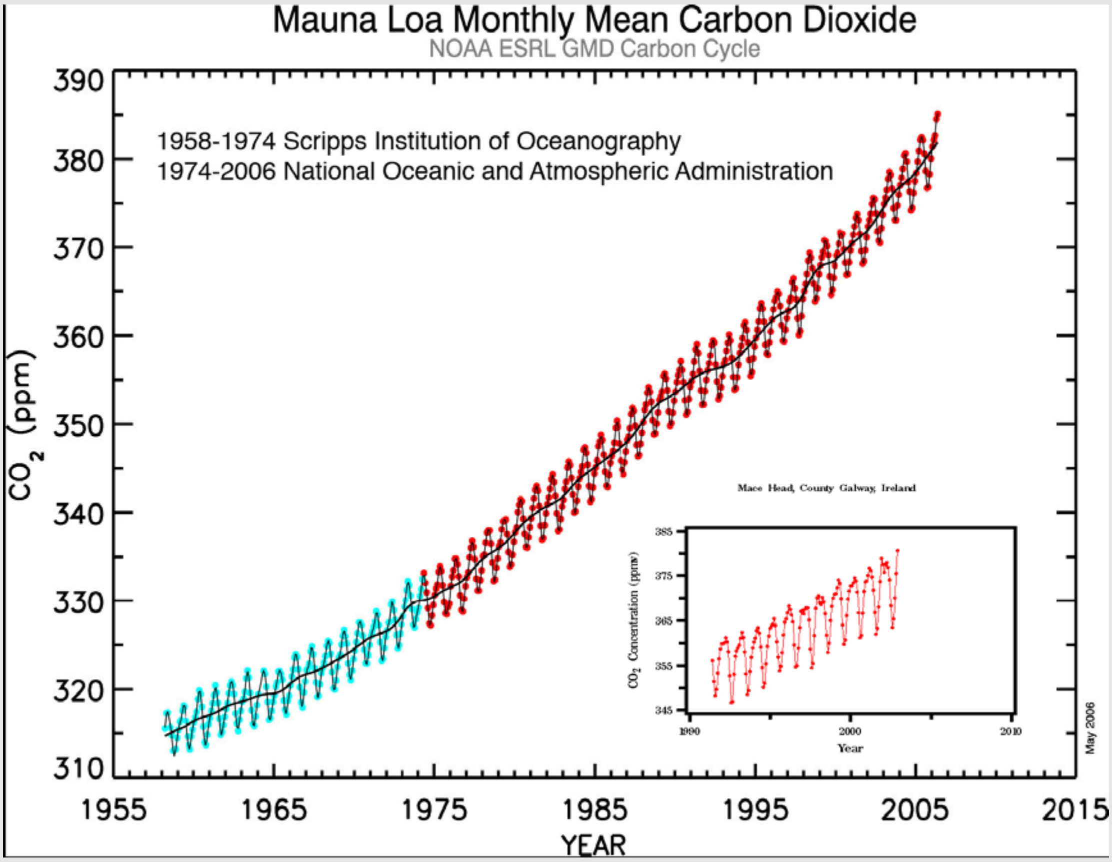
Figure 2 The Greenhouse Effect



It is the *enhanced greenhouse effect* due to extra man-made greenhouse gases, mainly carbon dioxide, being emitted into the atmosphere that is the cause for concern.

These man-made gases are raising the earth's temperature above its natural equilibrium. The concentration of carbon dioxide in the atmosphere in pre-industrial times was 280 parts per million, and it has now risen to over 380 parts per million due to man's activities (Figure 3). These measurements, taken from Mauna Loa, located in a 'clean air' site in the Pacific, are confirmed from a global network of such observational sites, such as, Mace Head, Co. Galway, Ireland (inset Figure 3). If present trends continue, the concentration of carbon dioxide will reach twice its pre-industrial value within the present century. Since carbon dioxide is a major greenhouse gas, this represents an unprecedented external interference in the natural workings of the climate system.

Figure 3 Measurements of the concentration of carbon dioxide at Mauna Loa Observatory, Hawaii and Mace Head, Ireland (inset)



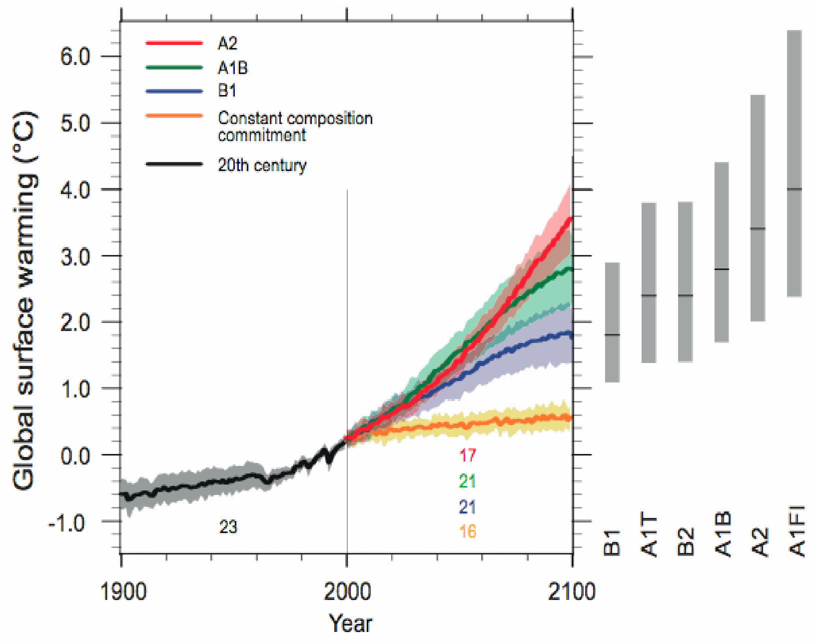
(Source: NOAA/CMDL)

Global climate models are the best available tools for predicting the future consequences of the man-made greenhouse gases. Climate models referenced by IPCC (2007a) project that global surface temperatures are likely to increase by between 1.8 and 4.0 °C by the year 2100. The range of values results from the use of differing scenarios of future greenhouse gas emissions (Box 2) as well as models with differing climate sensitivity, or response, to increased atmospheric concentrations of CO_2. Warming and sea level rise are expected to continue for more than a millennium even if greenhouse gas levels are stabilised. This reflects the fact that the oceans take a very long time to come to equilibrium due to their large heat capacity, which is almost four times that of a land surface.

The term "greenhouse effect" is something of a misnomer. In an actual greenhouse, heat entering due to sunlight is prevented mechanically from escaping (via convection) by the glass enclosure. In the atmosphere, heat is trapped not mechanically but radiatively.

If current rates of emissions continue, CO_2 concentrations are likely to be double those of present day concentration levels by the end of the century. If we include the global warming potential (GWP) of all greenhouse gases, or the warming potential of a GHG converted to the effective warming of 1 tonne of CO_2, a doubling of effective CO_2 levels is likely to occur much earlier. Current atmospheric concentration levels of all GHG, calculated according to their global warming potential, equates to approximately 425 ppmv CO_2 equivalent. As a consequence of the radiative forcing due to the increased levels of these gases in the atmosphere, global climate models (GCMs) project that the surface averaged global temperatures are likely to increase by between 1.8°C to 4.0°C by 2080-2099, relative to 1980-1999 (Figure 4), depending on which emissions scenario is considered likely (Box 2).

Figure 4 Global surface warming for six emissions scenarios



(*Source:* IPCC, 2007a)

Confidence in the ability of global climate models to project future climate is largely based on their ability to reproduce past changes in climate when forced with natural and anthropogenic sources of radiative forcing. Figure 5 compares the ensemble mean, or multi-model average, of 58 different simulations based on 14 global climate models with mean observed surface temperature. The ensemble mean appears to adequately capture the increasing trend and rate of increase in observed surface temperatures and also the short lived cooling associated with volcanic eruptions.

Box 2 SRES (Special Report on Emissions Scenarios)

The **A1** storyline and scenario family 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 A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

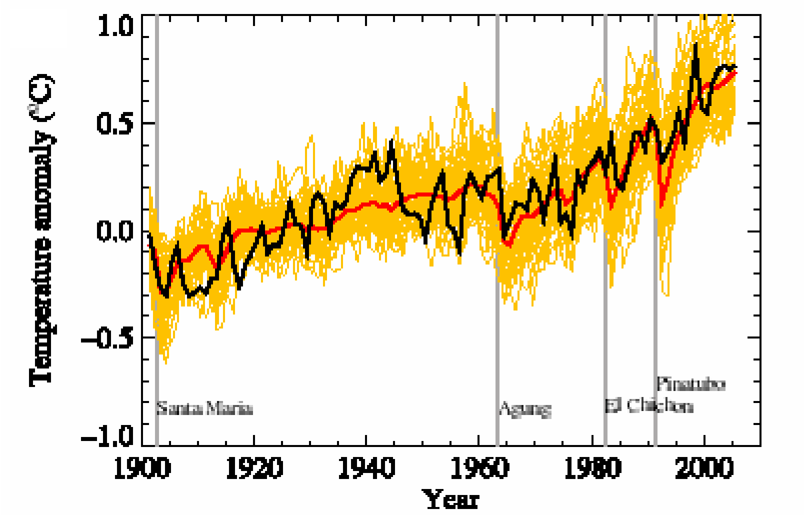
The **A2** storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily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

The **B1** storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, 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** storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with 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 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

(Source: IPCC, 2001a)

Figure 5 Comparison between global mean near-surface temperature anomalies, relative to the 1901 to 1950 mean, from observations (black) and AOGCM simulations (yellow), based on 58 simulations from 14 models, forced with both anthropogenic and natural forcings and multi-model ensemble mean (red)



(*Source*: IPCC, 2007a)

GCMs project that there will be significant regional variation of the projected warming, which is likely to be greatest over high Northern latitudes, due to changes in the surface reflectivity resulting from a decrease in snow cover at high-latitudes (ice-albedo feedback), and over continents due to the small thermal inertia of land surfaces. Due to increased temperatures, an increase in the frequency of extremes, such as hot days and heat waves, is also projected. GCMs also suggest that increases in precipitation are likely in mid to high-latitudes, with reductions in the lower latitudes. Interannual, or year-to-year, variability of precipitation amounts is also likely to increase. Changes in atmospheric humidity and increases in tropical sea surface temperatures are likely to result in more intense tropical cyclones with associated increases in heavy precipitation events.

Increases in thaw depth in permafrost regions and reductions in snow cover are projected to occur over high latitude regions, while the widespread and ongoing retreat of terrestrial based glaciers is likely to continue (IPCC, 2007a). The retreat of mountain glaciers will be greatest in regions where the supply of moisture is reduced, coupled with the projected increases in temperatures. Increased atmospheric humidity is likely to result in enhanced snowfall in Antarctica, leading to a gain in mass. In contrast, Greenland is projected to lose mass due to a greater increase in runoff, arising from increased melting over accumulation. The contrasting response between Antarctica and Greenland is largely due to the difference in temperatures between these regions. A temperature increase over Antarctica will enable an increase in the moisture holding capacity of a column of air while still remaining below melting point, while temperatures over Greenland are much closer to the melting point of ice.

These widespread reductions in the terrestrial storage of water, coupled with the thermal expansion of the oceans is projected to increase sea level by between 0.28 m and 0.43 m by the end of the present century, relative to 1980-1999 (IPCC, 2007a). While not contributing to sea level rise, Arctic sea ice extent is likely to decrease with summer sea ice completely disappearing within a few decades, according to some model projections. While this may open up the possibility of new shipping routes, it will have a significant impact on Arctic ecosystems and is likely to affect air and ocean circulation systems.

A decrease in the number of tropical cyclones per year is likely, however an increase in cyclone intensity is projected. Increased cyclone intensity will result in higher wind speeds and greater frequency of heavy precipitation events. A pole ward shift in storm tracks is also considered likely.

DANGEROUS CLIMATE CHANGE

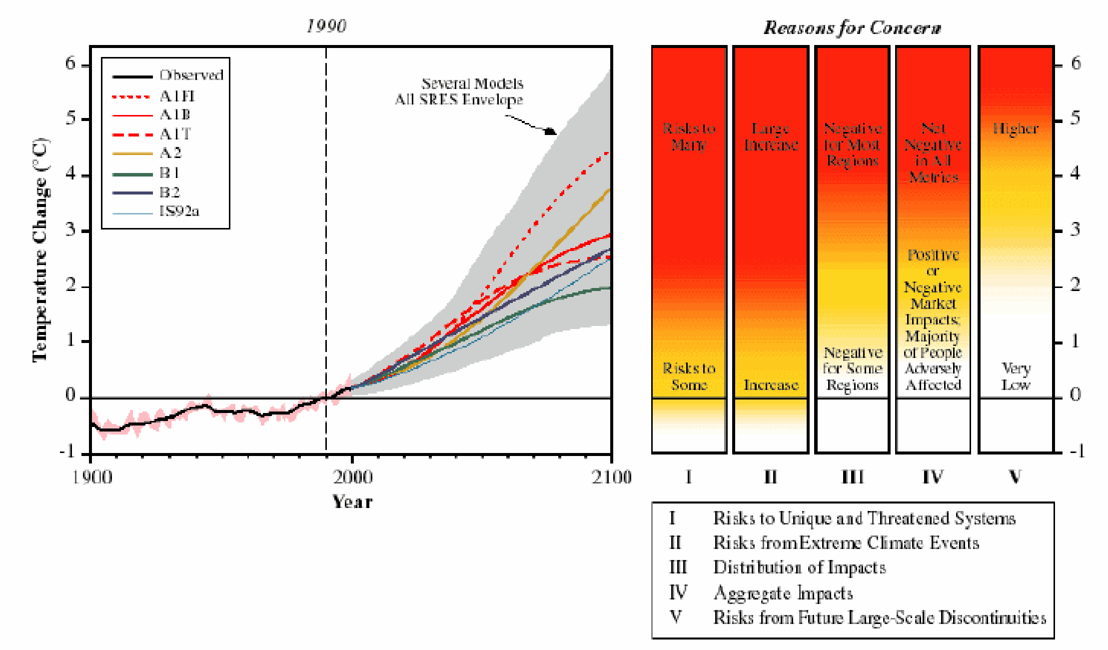
The ultimate objective of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) is to “stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”. The convention also outlines the following conditions in relation to the time frame and level of stabilisation as sufficient to “allow ecosystems to adapt naturally to climate change, to ensure food production is not threatened and to enable economic development to proceed in a sustainable manner”.

In 1996 the EU adopted a target of 2°C global temperature rise above pre-industrial times as a means of limiting severe climate change impacts. This climate protection target was reaffirmed at an EU Environment Council meeting in December 2004, March 2005, and more recently March 2007.

However, there is still considerable uncertainty with respect to the definition of what is ‘dangerous’, at what level greenhouse gas concentration levels should be stabilised and the specific time frame to do it in, as these are not specified by the Convention.

What is ‘dangerous’ climate change is open to much deliberation. Understanding what constitutes dangerous climate change is important for both scientific analysis and policy decisions (Schneider, 2001, 2002; Dessai et al., 2003). It is based on value judgements which may be perceived differently based on location and assessment of vulnerabilities (Schneider and Lane, 2005). For some it is based on a trigger point for abrupt change in the physical climate system while for others it is based on socio-economic impacts which might apply in a climate which changes gradually (Tirpak et al., 2005).

Figure 6 ‘Reasons for concern’ about the projected impacts of climate change



(*Source:* Mastrandrea and Schneider, 2004; adapted from Figure SPM2, IPCC (2001) SPM of WG II)

‘Dangerous’ in the context of Article 2 is related to both impacts of climate change and also levels of greenhouse gas concentrations which are responsible for this climate change.

The IPCC’s Third Assessment Report ‘reasons for concern’ concept offers further insight as to what is ‘dangerous’. This highlights the relationship between increases in global mean temperature and the risk of adverse impacts including those to unique and threatened systems, risk from extreme events, distribution of impacts, aggregation of impacts and risk from future large-scale discontinuities (Figure 6).

Why a temperature target?

A limit to global mean temperature has been defined as it can be easily related to impacts and vulnerabilities. Other options included an atmospheric greenhouse gas concentration level, a combined target of change in mean global temperature with sea level rise, changes in regional climate variables and changes in extreme events (IPCC, 2001a). However, global mean temperature was preferred as it can be directly related to changes in greenhouse gases, impacts of concern such as sea level rise and changes in extreme events can be directly linked to global temperature rise and it is more understandable to the general public (McElwain and Sweeney, 2007a),

What level of greenhouse gas concentrations corresponds to the 2°C temperature target?

Since the Industrial Revolution CO_2 concentrations have risen from 280 parts per million by volume (ppmv) to around 380 ppmv today. At current greenhouse gas levels the earth's surface is already committed to warming of 0.4 to 0.7°C (Hansen, 2004). Based on warming since pre-industrial levels of 0.7°C, this means that we are already committed to a warming of 1.1 – 1.4°C, greater than half of the EU climate protection target (McElwain and Sweeney, 2007a). Climate sensitivity is the expected increase in global mean temperature following a doubling of CO_2 concentrations above pre-industrial levels (CO_2 levels of ~560 ppmv). Current ranges of climate sensitivity are between 1.5 and 4.5°C based on current climate models. This means that the 2°C target may be reached at varying levels of CO_2 equivalent concentrations depending on actual climate sensitivity. At 550 ppm CO_2 equivalence the risk of temperature rise greater than 2°C is very high (with a mean probability of 85%) (Meinshausen, 2005). At 650 ppmv CO_2 equivalent there is only a 1 in 16 chance of staying within the target (CEC, 2005). At current levels there is a 2 in 3 chance of staying within the 2°C target.

It is apparent that to be confident of staying safely within the 2°C target, CO_2 concentrations need to be stabilised at levels much lower than 550 ppmv, more probably at levels closer to 400 ppmv. Furthermore, delaying action to stabilise greenhouse gas concentration levels will ensure that greater action will need to be taken in the future and less confidence can be placed in remaining within the target level.

'Dangerous' Climate Change Impacts

Impacts of climate change as a result of increasing global mean temperatures can be classified in two ways. Impacts as a result of gradual or smooth warming of the climate system are relatively predictable and allow systems time to adapt. Impacts as a result of abrupt climate change have a likelihood of much greater impact, but lower probability of occurring. Such abrupt changes in climate have occurred in the past and are likely to do so in the future. The recent research report by McElwain and Sweeney (2007a) highlighted major changes that occurred in Ireland about 8,000 years ago when a relatively sudden influx of fresh water from melting ice in Northern Canada is considered to have temporarily reduced the strength of the North Atlantic component of the Thermohaline Circulation, the Gulf Steam. This resulted in an abrupt and widespread cooling event in and around Ireland.

High-impact events are by their nature difficult to predict. They are largely non-linear singular events that occur when a specific threshold is crossed. Examples include the collapse or weakening of the Thermohaline Circulation, disintegration of the West Antarctic Ice Sheet (WAIS) and melting of the Greenland Ice Sheet. These events would have significant global and regional effects with possible irreversible impacts (Patwardhan et al., 2003). A global mean temperature increase of 2°C or greater above pre-industrial levels could trigger these events. For example, studies on the West Antarctic Ice Sheet have found that recent thinning and ice shelf loss have not been reproduced in climate models, and thus may be more sensitive to warming than suggested by current models. A number of authors believe that the threshold beyond which the ice shelves are vulnerable to collapse could be passed by 2100 (Wild et al., 2003; McElwain and Sweeney, 2007a). Oppenheimer and Alley (2004,2005) have also found that global warming of 2-4°C could cause destabilisation of the WAIS.

OBSERVED CHANGES IN CLIMATE IN IRELAND

In an analysis of the indicators of climate change in Ireland, McElwain and Sweeney (2007b) detected a linear increase of 0.7°C in the Irish temperature records over the 1890-2004 period (Figure 1). Warming was found to have occurred in two periods, 1910-1949 and 1980-2004. The rate of warming in the latter period of 0.42°C/decade is nearly double that of the earlier period. While the Irish records were found to display a large degree of interannual variability they are largely consistent with the global data. However, in contrast to the global temperature trends the warmest years in the Irish records occurred in 1945, followed by 1949 and 1997 (McElwain and Sweeney, 2007b).

Mean annual temperatures were found to have increased significantly at all stations. The greatest seasonal increases have occurred in winter temperatures at most stations, while autumn temperatures display the lowest rate of increase (McElwain and Sweeney, 2007b). Increases in seasonal mean maximum and minimum temperatures were also found to be occurring (McElwain and Sweeney, 2007b). The greatest increases in mean maximum temperature was found to be occurring during the winter months, in contrast to global trends, where increasing minimum temperatures are associated with increased night time cloud cover during this season. Since 1961, annual mean maximum temperature has increased by 1.1°C. The greatest increases in mean minimum temperatures are associated with the summer months in Ireland, with an increase of 1.34°C over the 1961-2005 period. Changes in minimum temperatures are also reflected in changes in the annual number of frost days occurring, with reductions ranging from 14%, at the Phoenix Park, to 88% less frost days at Shannon.

Changes in precipitation amounts and intensity have also been found to be occurring in Ireland, consistent with European precipitation trends towards increased receipts at mid- to high- latitudes and reduction evident in low-latitudes. Annual precipitation at Malin Head has increased by 40% between the 1890s and 1990s, with four of the five wettest years on record at Malin Head having occurred since 1990 (McElwain and Sweeney, 2007b). Analysis also suggests that interannual variability is increasing with two of the lowest annual totals occurring since 2000. An increasing trend in winter precipitation at locations in the north and west of the country is in contrast to a decreasing trend in summer precipitation for locations in the south and east, over the period analysed, leading to a changing seasonal and spatial distribution of precipitation in Ireland. An increase in the frequency of intense precipitation events, greater than or equal to 10 mm, appear to be contributing to the increasing annual totals, particularly in the west and north where significant increases in the frequency of extreme events was found to be occurring (McElwain and Sweeney, 2007b).

While the Irish climate records display a large degree of variability on time scales from annual to multidecadal, largely due to our Atlantic location, changes occurring in the key climate variables are consistent with those at the global scale. The identified changes in the Irish climate should give cause for concern particularly if these trends continue over coming decades. While increased temperatures may facilitate new opportunities, particularly in the agricultural sector, the rate of increase may prove too quick to allow time for natural systems, such as ecosystems and habitats, to adjust. The character of Irish precipitation, analysed by McElwain and Sweeney (2007b), which has traditionally been associated with long duration and low intensity events, is increasingly being characterised by more intense, short lived precipitation events and is likely to result in increased incidence of flooding during all seasons and give rise to water quality issues. Many of the problems associated with more intense precipitation have become more apparent in recent years, as was evident during the summer months of 2007 and 2008.

REGIONAL CLIMATE PROJECTIONS FOR IRELAND

GCMs provide the only means of projecting global scale changes in climate, but their resolution (~250 x 350 km) is too coarse for regional scale impact analysis. The limiting factor for higher output resolution arises due to the mathematical complexity and hence computational requirements for operating a global climate model. As a consequence, a number of methodologies have been developed that translate the large-scale output from GCMs to regional or local scale. Two of the most widely employed approaches are dynamical and statistical downscaling, both of which are employed by the C4I and ICARUS climate modeling centers, located in Met Eireann/UCD and NUI Maynooth, respectively, as well as in a number of other modeling centers around Ireland.

Table 1. Comparison between statistical and dynamical downscaling techniques (modified after McGrath et al., 2008)

Statistical downscaling
Advantages:
Requires minimal computational resources
High resolution point scale scenarios
More than one GCM can be readily employed
Disadvantages:
Method is dependant on good quality, long term, observations to derive transfer functions
Future projections may lack coherency between downscaled variables
Dynamical downscaling
Advantages:
Not limited by available observations
Full model outputs - amenable to climate sensitivity studies or to drive applications requiring synoptic scale atmospheric data (e.g. storm surge).
Provides a coherent signal among multiple climate variables
Disadvantages:
Requires significant computational resources
Regional model physics may not be tuned for a future climate
Ultimately, projections from both approaches will be limited by the accuracy of the parent global climate model employed.

(Modified after McGrath et al., 2008)

Figure 7 Seasonal warming: mean of 8 ensemble simulations showing the temperature change (°C) between periods 2021-2060 and 1961-2000 for winter, spring, summer and autumn (from left to right). The warming is greatest in the summer/autumn (1.2-1.4°C) (Caption and Figure after McGrath et al., 2008).

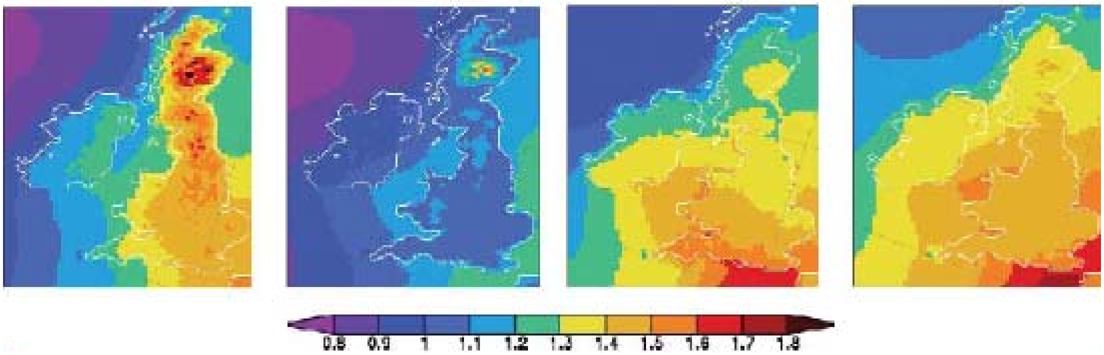
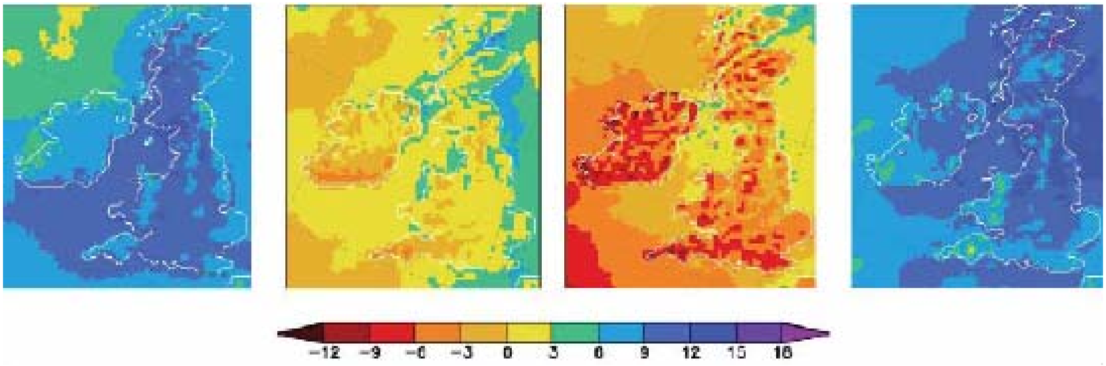


Figure 8 **Seasonal changes in precipitation: mean of 8 ensemble simulations showing the percentage change between periods 2021-2060 and 1961-2000 for winter, spring, summer and autumn (from left to right). Autumn and winter are wetter (5-10%), summer drier (5-10%); spring is also slightly drier (2-5%). (Caption and Figure after McGrath et al., 2008).**



Dynamical downscaling is based on the application of a regional climate model (RCM) which is fundamentally similar to a global climate model in that they are physically based models. The advantage to employing an RCM for regional scale analysis is that they are ‘embedded’ within a parent GCM and therefore can operate on a much smaller domain or area of interest, thereby freeing up computer resources to enable higher resolution output than their parent GCM. Typically, the output resolution of an RCM is in the order of 10-15 km^2. While dynamical regional climate modeling has become much more widespread in recent years due to decreasing costs of high performance computing resources, essential to running these models, initial set up costs are still high.

Statistical downscaling, due to low associated operational costs versus an RCM, has become a viable alternative for many researchers for downscaling coarse resolution output from a GCM to produce detailed regional or local climate scenarios. Statistically downscaled climate scenarios have been shown to be on a par with output from an RCM. An advantage to this methodology is that the downscaled output can be generated for specific points. Additionally, due to the ease of implementation of statistical downscaling techniques, more than one parent GCM can be employed to produce multi-member ensembles, or averaged, downscaled scenarios, a crucial methodological requirement in order to cater for uncertainties inherent in climate modeling.

Climate projections from both C4I (McGrath et al., 2008), who employed a dynamical downscaling technique, and *ICARUS* (Fealy and Sweeney, 2007; 2008; in press), who employed a statistical downscaling approach are illustrated in Figure 7-10. Despite the different methodologies and GCMs employed by these centres, output from both modelling centres indicate projected changes in the Irish climate of a similar order of magnitude, suggesting a degree of confidence with regards to the regional scenarios produced. More direct comparisons are difficult due to the difference in the baseline or ‘control’ (1961-2000 employed by C4I and 1961-1990 employed by ICARUS) and future time periods (1921-2060 employed by C4I and 2010-2039, 2040-2069, 2070-2099 employed by ICARUS).

The C4I temperature projections for mid-century show warming everywhere relative to the present, the warming being accentuated in summer and autumn (1.2 to 1.4 °C warmer). The warming shows a spatial gradient, with the greatest temperature increases projected for the south and east. The projections for precipitation show increased values in autumn and winter (5% to 10% wetter) and decreases in spring and summer (5% to 10% drier). Unlike the temperature projections, however, the precipitation projections show no distinct spatial gradient.

Figure 9 Ensemble mean seasonal temperature increases projected for the 2020s, 2050s and 2080s (Source: Fealy and Sweeney, 2008; in press).

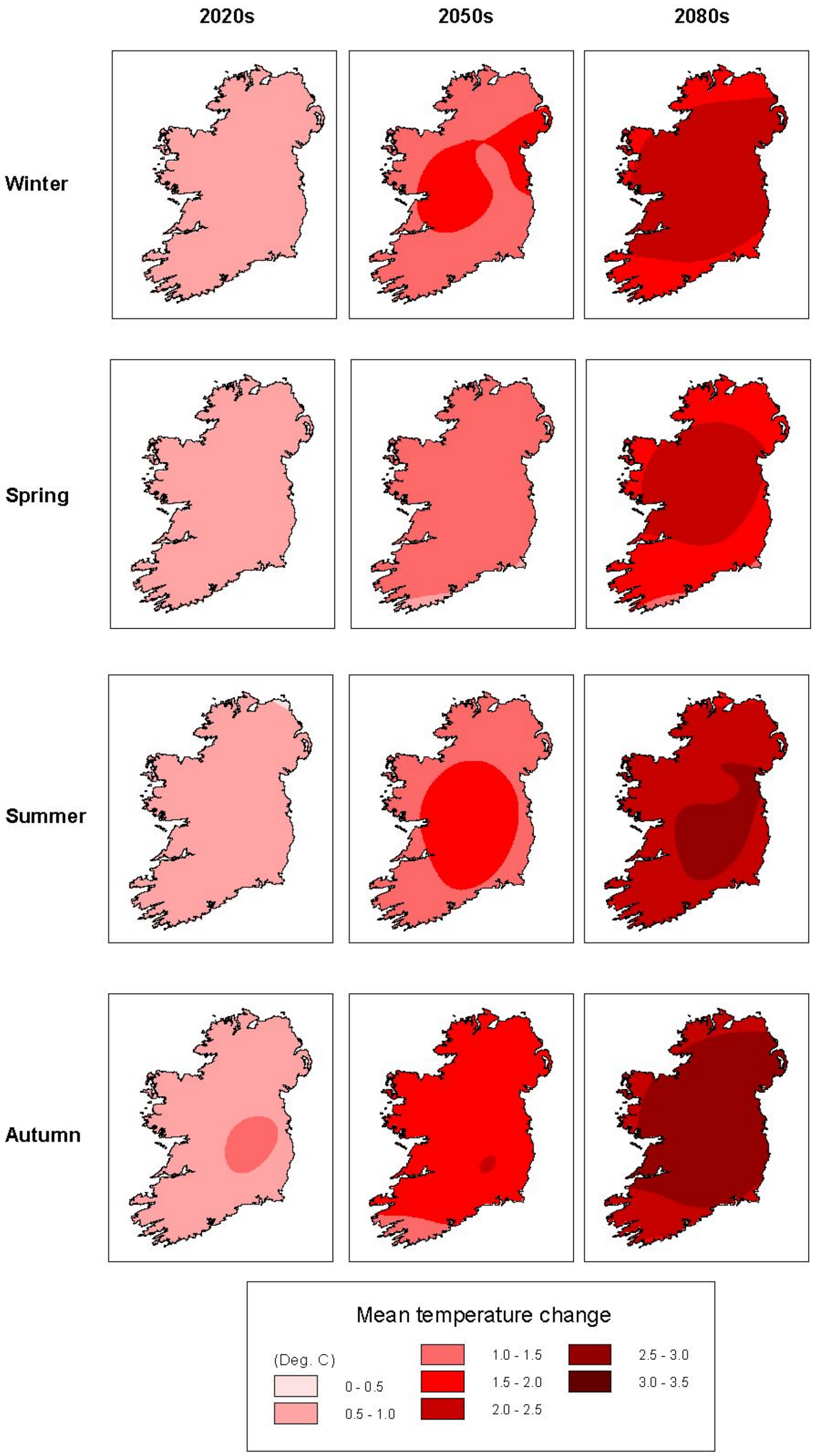
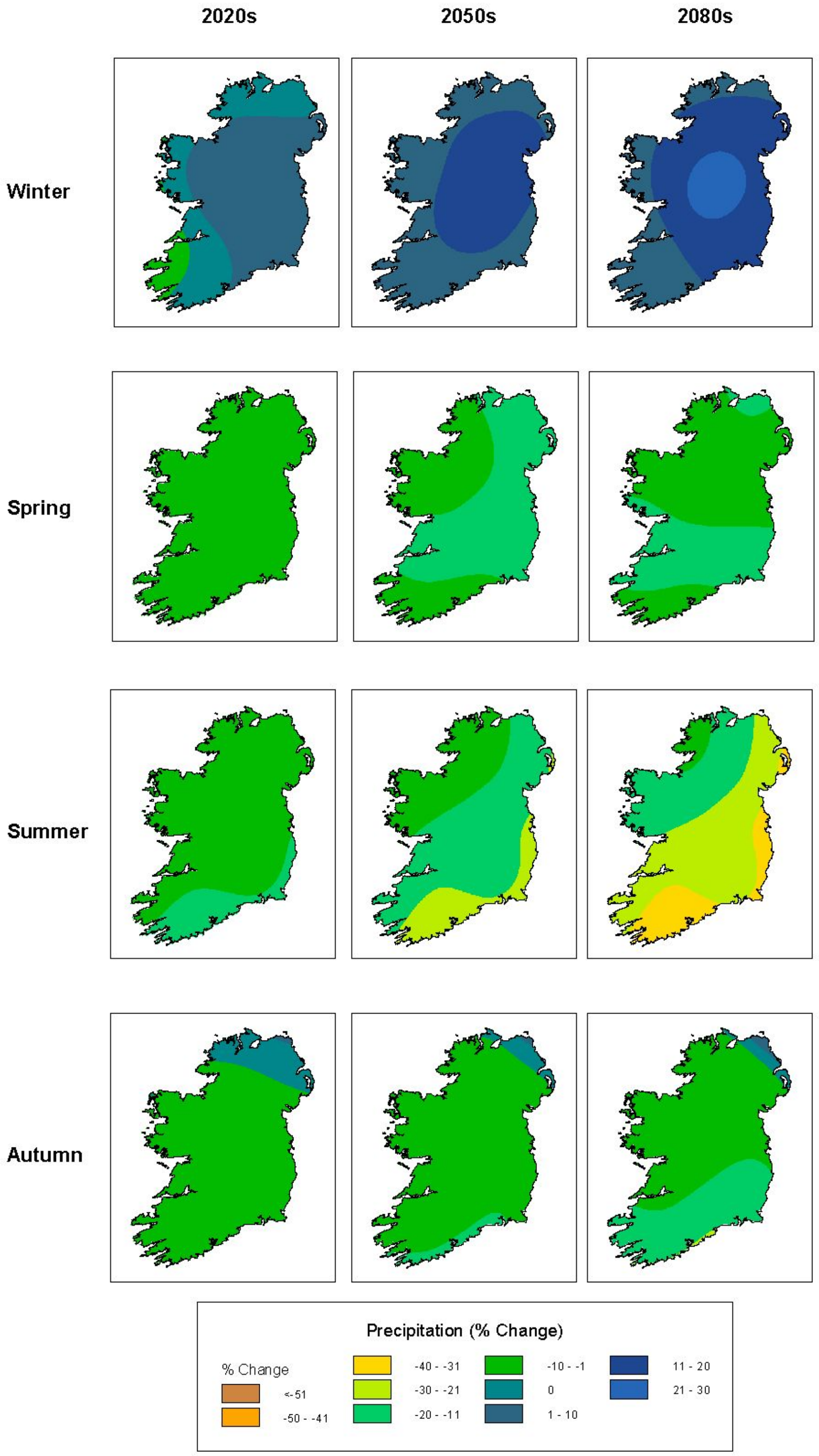


Figure 10 Ensemble mean seasonal precipitation changes projected for the 2020s, 2050s and 2080s (Source: Fealy and Sweeney, 2007; in press).



Based on the multi-model ensemble model derived by Fealy and Sweeney (2007; 2008; in press), results for seasonal changes in temperature and precipitation are presented for three 30-year time slices centered on the 2020s, 2050s and 2080s. Regional climate model projections for Ireland suggest that, over the present century, this warming rate is likely to increase to between 0.2-0.3°C/decade. As a consequence, an increase of between 0.7-1.0°C is likely to occur in all seasons by the 2020s (Fealy and Sweeney, 2008). This increase is projected to be more or less uniform across Ireland (Figure 9). By the 2050s, mean seasonal Irish temperatures are projected to increase by between 1.4 to 1.8°C, with the greatest warming in the autumn months. This increase is likely to be associated with a greater warming of the interior of the island resulting in an enhanced 'continental effect'. Coastal areas are likely to be slightly cooler than inland areas in summer due to the presence of sea breezes during the summer months. This continental effect becomes further enhanced by the 2080s, with temperature increases of between 2.0°C to 2.7°C.

Changes in precipitation over the course of the present century are likely to have a greater impact on Ireland, than changes in mean temperature, due to the potential of increased flooding during the winter months and reductions in stream flow during the summer months. Nationally, only small percentage changes in precipitation are projected to occur by the 2020s, with slight increases of +3% in winter and slight reductions, of between –1.0 to –3.2%, likely in all other seasons (Fealy and Sweeney, 2007; in press).

By the 2050s, winter increases are suggested to be in the order of +12%, with a similar order of magnitude reductions likely during the summer months (Figure 10). Both the shoulder seasons of spring and autumn are also likely to experience reductions in precipitation. An increasing seasonal and spatial disparity also becomes apparent by this time period, with greater winter increases likely to be experienced in the midlands and north west of the country, while the greatest decreases in summer, in the order of 20-30%, are likely for regions along the south and east coasts (Fealy and Sweeney, 2007; in press). The seasonal contrast in precipitation receipt, between winter and summer, is likely to become further enhanced by the 2080s, with winter increases of +15% projected with reductions of almost -20% projected for the summer months. Extreme precipitation events are likely to increase in all seasons in the future (Fealy and Sweeney, 2007; in press).

IMPACTS OF CLIMATE CHANGE IN IRELAND

While a reasonable degree of confidence exists as regards temperature projections, greater uncertainty characterises the projected changes in precipitation. Winter rainfall increases of approximately 10% and summer reductions of approximately 25% for some parts by the 2050s constitutes the most important aspect of future climate change for Ireland. Changes in the frequency of more extreme events will also have significant impacts. A substantial reduction in the number of frost days, lengthier rainfall events in winter, and more intense downpours in summer are projected together with an increasing summer drought problem, especially for eastern and southern parts of Ireland. Arising from these projected changes a number of key impacts can be anticipated.

Impacts on Water Resources

Modeling of catchments using the projected climate scenarios described earlier is inevitably a process entailing uncertainties. These arise from uncertainties in future global emissions, the reliability of global climate model outputs and the uncertainties existing in hydrological modeling itself (Murphy et al, 2006; Steele-Dunne et al., 2008). Nonetheless, this cascade of uncertainty does not absolve researchers from the necessity of providing forward planners with the best available estimates of how water resources will respond to the projected climate changes. Using a conceptual rainfall-runoff model to simulate river flow for a number of catchments in Ireland, and incorporating their particular characteristics of geology, soils, land use etc. a number of consistent signals emerge for some key hydrological aspects, while uncertainty remains in others (Murphy and Charlton, in press, Steele-Dunne et al., 2008).

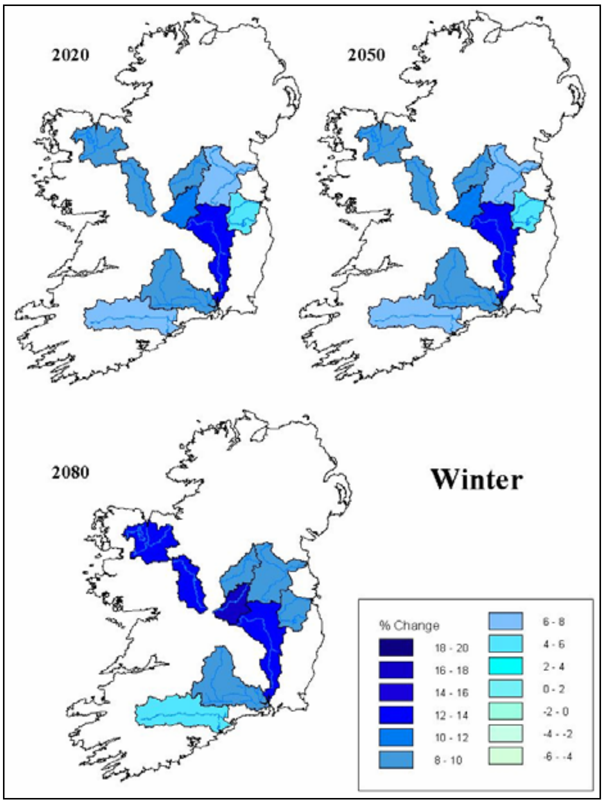
Based on the climate scenarios outlined, both Murphy and Charlton and Steele-Dunne et al. reveal that robust increases in winter and spring streamflow are apparent (Figure 11). This typically amounts to about 12-15% extra by mid century, especially pronounced in the wetter west where significant implications for flood management are implied. Murphy and Charlton highlight for the A2 emission scenario, for example, that catchments such as the Boyne, Moy and Suck show substantial increases in the magnitude of the 50-year flood. In the case of the Boyne this increase is of the order of 50% by mid century.

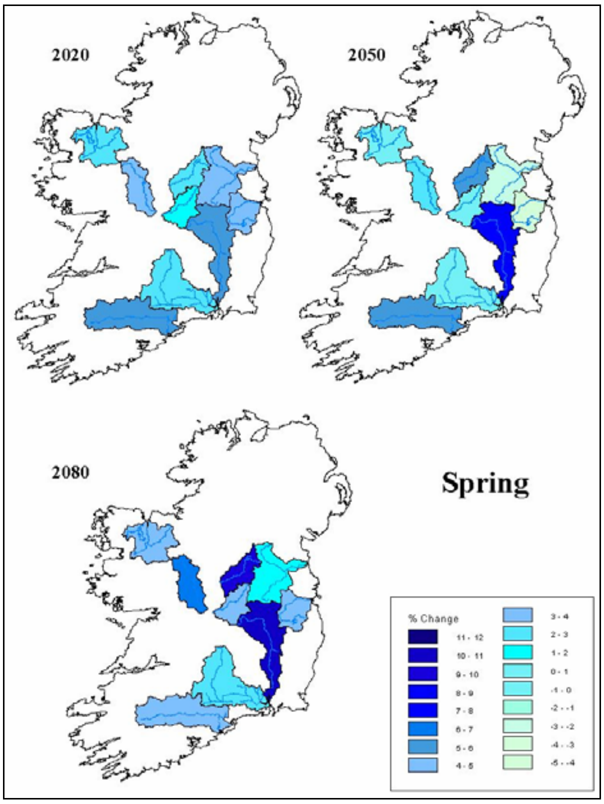
As might be expected, higher peak flows result in a reduction in return periods for floods of a particular magnitude. Almost all the catchments studied confirm a decrease in return periods. In the case of the River Barrow for example the once-in-a-fifty year flood has fallen to an 18-year event by mid century, and for the Blackwater to just over an 11-year event by mid century. These changes raise concerns regarding the integrity of flood defenses, the capacity of urban storm drainage systems, the need for greater caution concerning planning and development of vulnerable areas as well as insurance implications for commercial and private properties. In a situation where more frequent winter flooding is likely, concerns regarding the maintenance of water quality also arise.

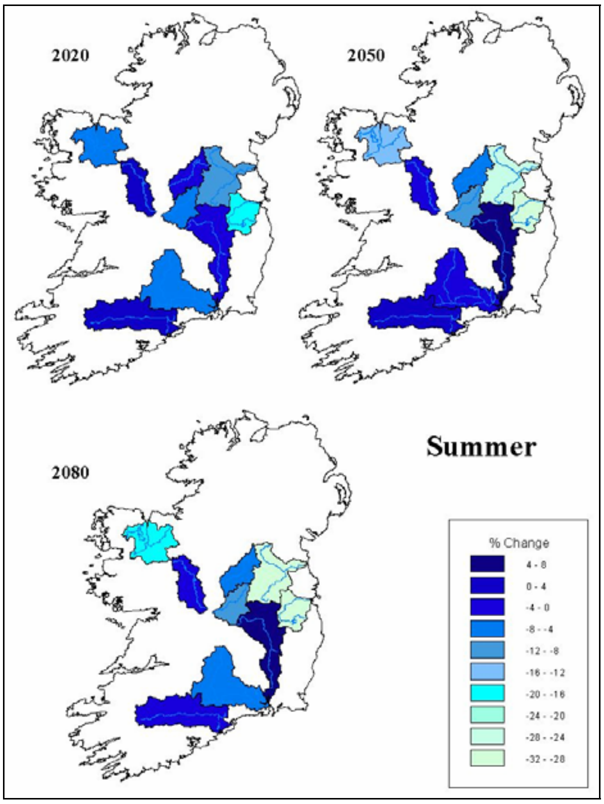
Reductions in summer rainfall are likely to have a significant influence in reducing storage and ultimately streamflow in most catchments. The extent of these decreases is largely dependent on the soil characteristics of individual catchments. Soils with a lower capacity to hold moisture will show the greatest sensitivity to climate change. Soil moisture deficits will begin earlier and end later in the year while 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 (Murphy and Charlton, in press).

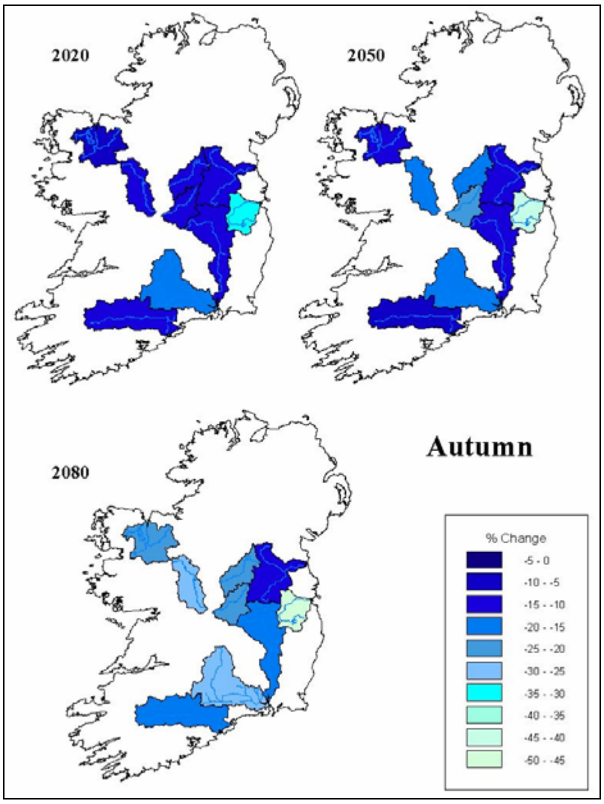
Results derived by both Steele et al and Murphy and Charlton show greatest reductions in streamflow for the summer and autumn months in the majority of catchments. Uncertainty exists as to the timing of greatest reductions, with results by Murphy and Charlton indicating that catchment storage will play a more important part in offsetting summer decreases. This uncertainty is likely due to the different model structures used in each study. In the spatial context of impacts, differences exist in the magnitude of change simulated between catchments with the greatest reductions suggested for the Boyne and the Ryewater in the east, while greatest increases are likely for the most westerly catchments, the Suck and the Moy.

Figure 11 Seasonal changes in streamflow for selected catchments


2020
2050
2080
Winter
% Change
18 - 20
16 - 18
14 - 16
12 - 14
10 - 12
8 - 10
6 - 8
4 - 6
2 - 4
0 - 2
-2 - 0
-4 - -2
-6 - -4


2020
2050
2080
Spring
% Change
11 - 12
10 - 11
9 - 10
8 - 9
7 - 8
6 - 7
5 - 6
4 - 5
3 - 4
2 - 3
1 - 2
0 - 1
-1 - 0
-2 - -1
-3 - -2
-4 - -3
-5 - -4


2020
2050
2080
Summer
% Change
4 - 8
0 - 4
-4 - 0
-8 - -4
-12 - -8
-16 - -12
-20 - -16
-24 - -20
-28 - -24
-32 - -28


2020
2050
2080
Autumn
% Change
-5 - 0
-10 - -5
-15 - -10
-20 - -15
-25 - -20
-30 - -25
-35 - -30
-40 - -35
-45 - -40
-50 - -45

(*Source*: Murphy and Charlton, in press)

Water quality management is likely to be more problematical as a result of 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.

TABLE 3 **Return period for the 50-year flood under A2 and B2 Emission scenarios for selected catchments for the 2050s and 2080s**

SRES	Time Period	Barrow	B'water	Boyne	Brosna	Inny	Moy	Ryewater	Suck	Suir
A2	50s	18.3	11.1	8.2	6.4	10.6	13.9	8.1	17.8	34.4
	80s	11.5	7.3	2.9	3.8	3.3	4.0	10.2	4.0	6.2
B2	50s	13.2	4.1	12.0	6.1	9.1	19.6	18.5	29.7	7.2
	80s	6.5	10.1	4.2	3.1	4.1	15.0	25.5	35.9	4.5

(*Source*: Murphy and Charlton, in press)

Adaptation Measures

Water resource management clearly requires climate change considerations to be integrated. Requirements under EU directives such as the Water Framework and Nitrates Directives necessitate climate change proofing in policies such as the National Spatial Strategy, National Development Plan, statutory Development Plans and a variety of other activities. Infrastructure at risk from flooding must clearly be identified, delineated and protected where possible. Flood plains require delineation and inappropriate development within them curtailed. Water conservation and water distribution network maintenance requires to be better emphasized and budgeted for.

Impacts on Agriculture

Climate change will impact on Irish agriculture both directly and indirectly. Directly, increased CO_2 in the atmosphere is beneficial to most agricultural crops and acts as a form of fertiliser, stimulating growth. Indirectly, the changes in climatic parameters such as temperature and rainfall may either enhance or negate the direct CO_2 influence. Ultimately, these impacts will also be tempered by the extent of adaptive responses taken by farmers e.g. in storing water for irrigation, changing crop types, seed varieties and planting/harvest dates or by changing management practices such as paddock rotations, animal housing etc.

Using the projected climate scenarios to drive crop growth models reveals that changes are likely in the distribution and viability of current agricultural crops in Ireland, though most of the present crops will continue to be viable in a changing climate (Holden and Brereton, 2003). Spring wheat and barley productivity will continue to be maintained though water stress in the south east may be problematical (Holden and Brereton, 2003). Future yields will be closely linked to precipitation. However, it is likely that reductions in fertiliser inputs will be possible without having a detrimental effect on yields in many cases, thus enabling profitability to hold up. Maize will also suffer some water stress, though will show significant yield increases and extend its distribution markedly as climate changes (Holden and Brereton, 2003). Its suitability as a high energy forage crop will further boost its popularity, particularly west of the Shannon where more summer rain will be available than in the south east. Soyabean, currently a submarginal crop, will make modest inroads into the maize area later in the century (Holden and Brereton, 2003). Potatoes are projected to have an irrigation requirement in the driest parts of the east and may become commercially unviable due to increased competition for water resources (Holden and Brereton, 2003). Elsewhere, in areas such as Donegal and south Cork, irrigation may not be required, but high nitrogen applications may be required instead (Holden et al., in press). Harvesting is likely to become more problematical due to the onset of winter rains in October as is planting in wet soils in spring and possible increases in pest and diseases.

For livestock production the critical consideration is grass productivity. Drought losses are likely to be most marked in the east and south of the country. Should housing requirements increase as a result of wetter soils in spring (and even on occasion periods of summer housing may be required as pastures dry) more land will have to be given over to fodder production. Stocking rates may not increase much in this situation. Again the west will be less disadvantaged and livestock production will dominate more west of the Shannon with arable production concentrated in the east. In the latter area in particular,

Adaptation Measures

Opportunities for maintaining present output levels while reducing nutrient inputs as climate changes will be required, to maintain profitability. Such extensification is presently occurring as part of EU policies.

Planning for irrigation is needed to ensure that water costs are acceptable and summer surface and ground water resources are not over-used. More active paddock management and increased storage facilities for slurry will also be required (Holden et al., in press).

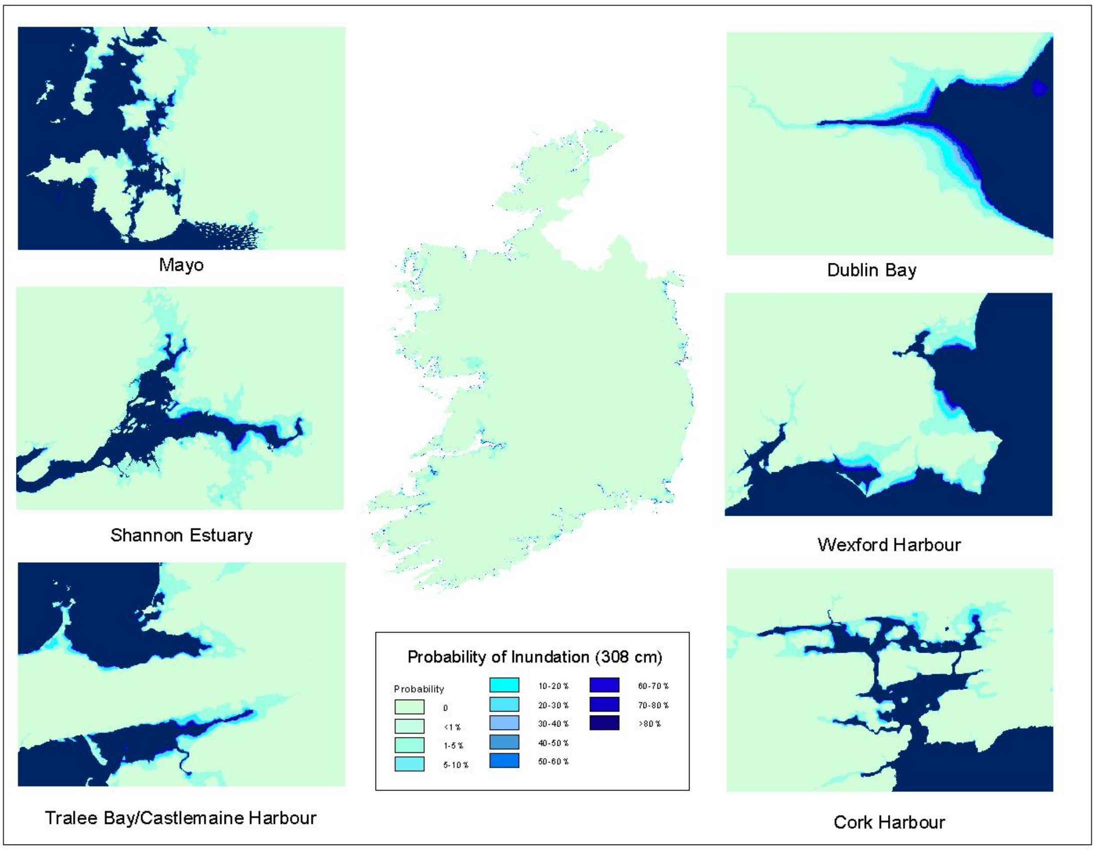
Impacts on Coastal Environments

An acceleration in the current rate of global sea level rise of 3.1mm/year is expected over the present century as warming induces expansion of the oceans and land-based glaciers continue to melt. Global sea level is projected to rise by between 0.28 to 0.43 m over the course of the present century though considerable uncertainties persist as regards the contributions which will eventually result from key areas such as Antarctica (IPCC, 2007a).

In addition to sea level rise, significant increases in wave heights have been observed from ships and buoys in the North Atlantic in recent decades (Gulev and Hasse, 1999). Storminess changes in the north-east Atlantic are however most likely to be related to natural variability and a sustained spell during which the North Atlantic Oscillation (an index of westerliness) was in strongly positive mode (IPCC, 2001). Some regional climate models (McGrath et al., 2005) however suggest that the frequency of intense storms over the North Atlantic area in the vicinity of Ireland is projected to increase by approximatley 15% by mid-century.

The combination of higher sea level and more intense storminess raises the probability of some coastal locations around Ireland being subjected to increased flooding (Figure 12) and erosion risks. For hard rock coastlines such as predominate along much of the west coast this is not of major concern. However for coasts composed of unconsolidated glacial materials and sand, which exist most commonly along the east coast, increased vulnerability exists. Such coasts typically exhibit marked annual retreat. In the case of some parts of the Wexford coast this may amount to up to 2 metres per annum. About 20% of Ireland’s coast is at risk of increased erosion and Farrell (2007) estimates that the current rate of coastal erosion and the current economic impact can be expected to treble or quadruple over the next one hundred years. However, material eroded from a location on the coast, if not held in near- or off- shore deposits, may provide material for deposition elsewhere along the coast. Ultimately, occurrence and rates of erosion or deposition will depend on whether or not the coastline is in equilibrium with the amount of energy coming into the coastal zone environment and whether or not there is an adequate supply of material.

Figure 12 Probability of inundation associated with a sea level rise of 0.48 m and a storm surge of 2.6 metres



(*Source*: Fealy, 2003)

Coastal inundation may become a more frequent event because of the combination above. Low lying areas close to the coast will be the principal areas of concern, especially the Shannon Estuary and the rias of the south and west. Coastal wetlands and saltmarsh areas are also vulnerable and some cities which have grown seaward on reclaimed land (such as Dublin) also merit risk analysis. Fealy (2003) estimated that approximately 300km^2 of land has a greater than 50% chance of being flooded over coming decades.

Adaptation Measures

Accommodation to a retreating coastline centres on retreating or using engineering technology to modify the wave environment. Outside of high value urban areas the costs of defending land against coastal erosion frequently is uneconomic and should not be contemplated in the majority of cases. ‘Hard’ engineering solutions have also often proven to have unforeseen consequences often at distances removed from the affected area. Precautionary planning, involving planned retreat in some instances, represents the optimum response for most areas.

Improved surge forecasting as part of a coastal flood warning system is a highly desirable objective for coping better with the increased risks associated with coastal hazards. This is particularly important where critical infrastructural assets may be involved. Indeed such infrastructure as power generation, water supply and treatment plants, transport and communications facilities require to be reviewed for climate proofing to avoid catastrophic failure during future storm or flood events.

Impacts on Biodiversity

Ireland has obligations under several EU Directives and a number of international agreements to safeguard the loss of species and habitats against threats, including climate change. Ecosystems are dynamic entities constantly responding to pressures such as land-use change, human population change or the demands made on them for particular biomass resources. The projected increases in temperature, combined with a longer growing season, is likely to have significant effect capable of changing the internal organisation of ecosystems and the competitive balance between organisms. Climate also plays a central role in determining the spatial distribution and abundance of species.

Changes in Irish species are likely to occur where species are close to the limits of their distribution range. In the aquatic environment, Arctic and Boreal relicts such as the Arctic char, smelt and pollan as well as some copepod species are most vulnerable, while terrestrial species might include the oyster plant and sandbowl snail (Byrne et al., 2003). In contrast, species at their northern margin could be expected to extend their range. Among the winners might be cottonweed, glaucous shears moth, natterjack toad and the lesser horseshoe bat (Byrne et al., 2003). Warming is also expected to benefit many insect species, especially butterflies, though this may inevitably also include agricultural insect pests and predatory insect species. Invasive plant species, such as montbretia, New Zealand willowherb and rhododendron, may become more of a problem while in the animal world the Budapest slug, the slow worm, the bank vole and the dragonfly colonist migrant hawker may increase in abundance (Byrne et al., 2003).

Behavioural responses in several species and ecosystems will also occur in response to changing climate conditions. Increased generations of insects, greater winter survival rates of many invertebrates, earlier breeding of amphibians, changes in fish migration, hatching, development and spawning and changes in bird migration are just a few of the likely impacts of the projected climate changes (Byrne et al., 2003).

Climate change is also likely to produce significant alterations to habitat conditions. Some of these are likely to be very sensitive to climate change and may require particular attention. These include sand dunes, lowland calcareous grassland, raised bogs, calcareous fens, bog woodlands and turloughs. For example, salt marshes and sand dune habitats are particularly vulnerable to sea-level storminess changes. Many montane heath species are at the southern limit of their distribution and cannot adjust easily to warmer, dryer summers. Similarly, peatlands may suffer considerably from summer drying. An increase in decomposition, a reduction in peat formation, more erosion, changes in species composition, loss of stored carbon and an increase in acid runoff may occur in this already fragile resource.

Adaptation Measures

Appropriate protective measures are urgently required to retain unique and distinctive aspects of Irish biodiversity for future generations where vulnerable habitats and species are involved.

OTHER IMPACTS

Climate change impacts extend in many other sectors which cannot be adequately treated in this summary. All are worthy of detailed analysis in order to assist formulate policies and management strategies to enable Ireland to adapt to a changing economic as well as physical environment. Among the more important impacts are:

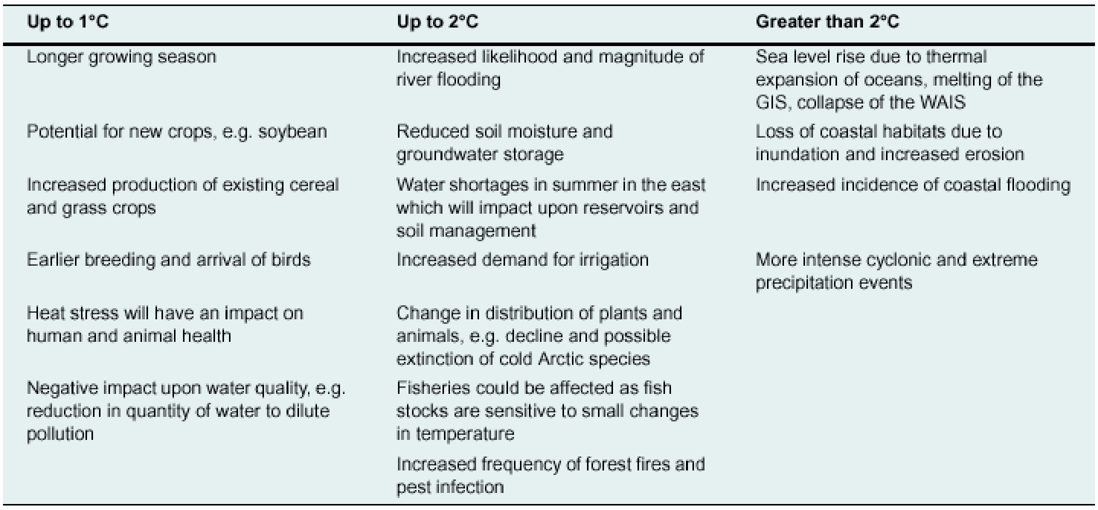
- Impacts on Irish forests from reduced winter chilling, increased CO_2, changed frost and wind regimes and changed incidence of pests and disease. Pests such as the green spruce aphid, the pine weevil, the great spruce bark beetle, the European sawfly, and fungal infections such as honey fungus, fomes and Phytophthora, may pose an increasing threat to productivity (Purser et al., 2003).
- Impacts on aquaculture and the marine environment. Salmon production in Ireland is near the southern range of the species distribution and temperature increases, together with changes in the incidence of algal blooms, pests and diseases, may have considerable commercial impacts.
- A marked reduction in heating degree days will occur in milder winters with a less pronounced winter peak demand for electricity and gas. Ongoing tightening of building insulation standards will further reinforce this trend.
- Considerable reductions in winter cold related mortality will occur in Ireland as warming proceeds. Heatwave-related mortality in summer will not counteract this to any extent and adjustment to health service provision will be necessary to exploit this favourable situation. Other adverse health impacts may however increase in importance such as increases in the incidences of water and food related diseases.

SUMMARY

It is likely that the greatest impacts of climate change in Ireland will arise from changes in the seasonal distribution of precipitation rather than from changes in temperature. Increased winter precipitation, particularly in the midlands, north and west of the country is likely to result in an increased frequency of flood events, particularly if the current observed trends towards more intense precipitation events continue throughout the present century. Significant reductions in precipitation are likely to be experienced during the summer months. This is likely to give rise to reductions in water availability. Reductions in soil moisture availability are also likely due to the projected increases in temperatures giving rise to increased evaporation during the summer and autumn months. Ironically, a decrease in total precipitation but accompanied by an increase in convective precipitation may give rise to an increase in the number of local summer flooding events.

It is clear from the scientific findings outlined that the impacts of climate change will be profound in many sectors. Accordingly it would be prudent to consider adaptation measures now, in association with mitigation measures, that Ireland will be required to take in the post-Kyoto period i.e. after 2012, as a responsible member of the international community, to limit the potential negative effects that climate change will have, not just on Ireland, but globally.

TABLE 4 Summary of potential impacts for Ireland for various increases in global surface averaged temperature



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	

(*Source*: McElwain and Sweeney, 2007a)

Table 4 summarizes the potential impacts and vulnerabilities for Ireland associated with various increases in global temperatures (McElwain and Sweeney, 2007a). If global temperatures can be maintained below the ‘guard rail’ of 2ºC above pre-industrial times, it may be possible to limit the severe impacts of global climate change. However, the potential for catastrophic or ‘dangerous’ impacts of climate change become ever more likely as we approach or exceed this ‘guard rail’. While there are many uncertainties with regard to thresholds and targets above which dangerous climate change may occur, the precautionary approach should be the main guide in assessing at what level global mean temperature rise should be limited and stabilisation of GHG concentrations achieved. The prediction of occurrence and timing of high-impact, low-probability events is not currently possible but it is evident that warming above 2°C may make these events more likely.

KEY MESSAGES

- Global temperatures are projected to increase by between 1.8 and 4.0 degrees Celsius by 2100, above the 1980-1999 levels, in the absence of binding international agreements which significantly reduce greenhouse gas emissions.

- Global mean temperature rises of +2 degrees Celsius above pre-industrial levels, may increase the likelihood of non-linear high-impact events being triggered. In order to have a degree of confidence of staying within the +2 degree Celsius target above pre-industrial levels, CO_2 concentrations in the atmosphere would need to be stabilised at levels close to 400 ppmv.

- A precautionary approach should be the main guide in assessing at what level global mean temperature rise should be limited and stabilisation of greenhouse gas concentrations achieved.

- It is likely that the greatest impacts of climate change in Ireland will arise from changes in the spatial and seasonal distribution precipitation rather than from changes in temperature. Infrastructure at risk from flooding must clearly be identified and suitable adaptation measures need to be implemented to minimize loss.

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