CLIMATE CHANGE IMPACTS FOR IRELAND PART 1: THE GLOBAL CONTEXT AND MODELLING THE FUTURE

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Abstract: Over the past five years or so research into the impacts of climate change in Ireland has been developing rapidly and we now have more information that ever before on the likely magnitudes and the spatial distribution of likely changes in Ireland. This two part paper presents an overview of the steps and challenges involved in climate change modelling and draws together the main findings from recent reports for key climatic characteristics in Ireland for the coming century. It also asks where the focus of climate change research needs to be pointed next in order to ensure successful adaptation to what are likely to be substantial changes. Part two will be published in the next volume of Geographical Viewpoint.

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INTRODUCTION

The latest report from the Intergovernmental Panel on Climate Change (IPCC), the Fourth Assessment Report (2007a), states that warming of the climate system is now unequivocal and that human activities are *very likely* (i.e. >90% confidence levels) to be the cause of recent warming. Direct measurements of atmospheric levels of CO2 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 CO2 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 CO2 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 greenhouse gases 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 CO2 emissions, a doubling of present day concentration levels is likely to occur by the end of the century. 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. 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 reported by the IPCC (2007a) 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 inter-annual variations in precipitation are also projected.
- Widespread retreat of mountain glaciers is likely, with snow cover projected to contract.
- 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.
- In terms of ocean circulation, 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).

Internationally, such changes would have widespread consequences. 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. 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).

In light of these projections at a global level and the exposure of Ireland, as an island nation, the last number of years have seen a concerted effort by Irish researchers to examine the likely impacts of climate change on a regional basis so as to extract a more refined picture of what climate change is likely to hold for Ireland. This and the companion paper in the next volume of Geographical Viewpoint endeavour to present the key findings that have emerged from this period of sustained research on climate change impacts for Ireland. The objectives of the papers are twofold; to increase the level of understanding of climate change impacts and to articulate the key uncertainties involved in deriving projections of future climate.

This paper begins by providing a simplified schematic of the steps involved in producing climate change scenarios and impact assessments, before outlining the key challenges posed by uncertainty in modelling the future. The paper concludes by examining approaches that are used to manage uncertainty and present the best possible information to decision makers charged with ensuring that we adapt successfully to future impacts. In the companion paper (see Volume 38, 2010), changes in key climatic variables for Ireland are examined for the coming century and the confidence that we as the scientific community currently attribute to these projections is outlined.

MODELLING THE FUTURE

Various methodologies have been developed for modelling future climate. The methodologies involved can be complex but can essentially be distilled down to the four key steps shown in Figure 1.

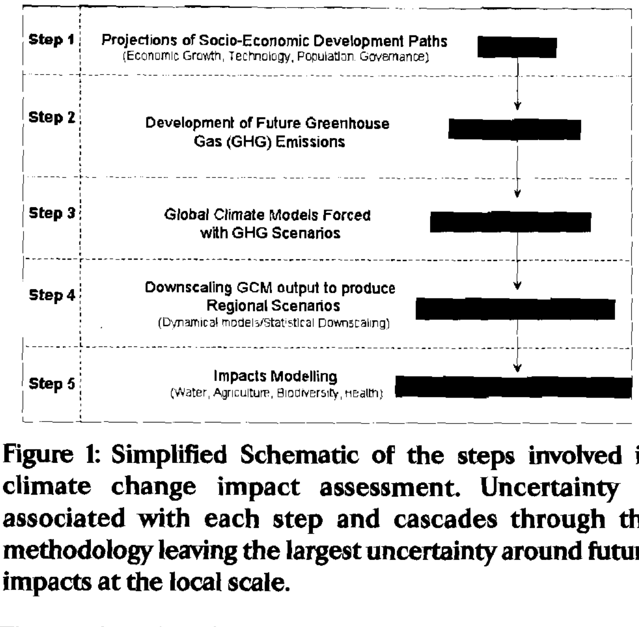

Figure 1: Simplified Schematic of the steps involved in climate change impact assessment. Uncertainty is associated with each step and cascades through the methodology leaving the largest uncertainty around future impacts at the local scale.

This methodology begins with the establishment of future socio-economic development paths based around assumptions of population growth, economic development, technological development in the energy sector and changes in governance, made at the global level.

From these development pathways, future concentrations of greenhouse gases in the atmosphere are derived and used to force Global Climate Models (GCMs) to produce simulations of climate parameters such as temperature and precipitation into the future. These GCMs are extremely complex in nature due to the intricate processes that control global climate and the global scale at which the models operate. In order to derive local projections of climate from these large scale models, some form of downscaling is required to relate local climate (e.g. weather stations in Ireland) to the output produced by GCMs. In the final step this downscaled or localized data of future climate is used to force impacts models for different sectors (water resources, agriculture etc.). The outputs of this process are then used to inform the decision making process of adapting to change to ensure the well-being of society.

THE CHALLENGE OF UNCERTAINTY

While essential to ensuring the well-being of society, producing future climate scenarios and future impacts of climate change is by no means an exact science, hence the use of words like simulations and projections rather than predictions. This terminology is necessary due to the uncertainties involved in modelling environmental systems and as a consequence, future impacts of climate change. Indeed, uncertainty is associated with each step outlined in Figure 1 and is propagated through to local impact assessment where the ranges of uncertainty is greatest, hence the problem is known as the cascade of uncertainty.

Hulme and Carter (1999) discuss two quite separate sources of uncertainty in climate change impact assessment derived from incomplete knowledge and unknowable knowledge. The former is due to our lack of understanding of key processes at present and is found in how we structure our climate models or our impacts models (see below), this type of uncertainty can be reduced through further research. The latter, unknowable knowledge, derives from the indeterminacy of future human societies and of the climate system itself, is irreducible and will be an ever-present in modelling future climates. Even if we had a perfect understanding of the climate system and unlimited computing power, different future climates will always be simulated. Consequently, the presence and degree of uncertainty poses challenges for deriving future impacts and for proving information for decision makers. As such, it is important that the key sources of assumptions are made transparent and the following sections will provide an overview of the key sources of uncertainty in modelling climate change.

Global Climate Model (GCM) Configuration

Despite advances in modelling chaotic behaviour and natural variability in the climate system, it is clear that climate models will never be able to provide a singular prediction of future climate (Jones, 2000). Giorgi (2005) highlights three major sources of uncertainty in GCM simulations: model configuration uncertainty, uncertainty due to internal model variability and uncertainty due to the random nature of natural forcing (from volcanic activity, sunspot cycles etc.). Of these, uncertainty in model configuration is by far the most significant. Model configuration uncertainty relates to the choice of model structure in terms of horizontal and vertical resolution of land, ocean and atmospheric processes, numerical algorithms developed to represent key processes and the parameterisation schemes used to solve those algorithms (See Figure 2 for a schematic of the structure of a Global Climate Model). As a result, there is a plethora of GCMs in existence, with the choice of model based on scientific and computational considerations and as a result outputs can vary widely between models. Figure 3 depicts the scale of uncertainty derived from GCMs, where nine different models are used to predict global average temperatures over the course of the century using only one emissions scenario. By the end of the century the uncertainty due to model configuration produces a significant range of temperature changes.

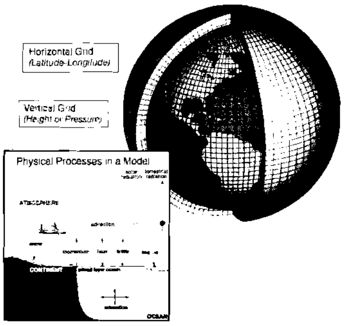

Figure 2: Climate models are systems of differential equations based on the basic laws of physics, fluid motion, and chemistry. To "run" a model, scientists divide the planet into a 3-dimensional grid, apply the basic equations, and evaluate the results. Atmospheric models calculate winds, heat transfer, radiation, relative humidity, and surface hydrology within each grid and evaluate interactions with neighbouring points. (NOAA, 2009)

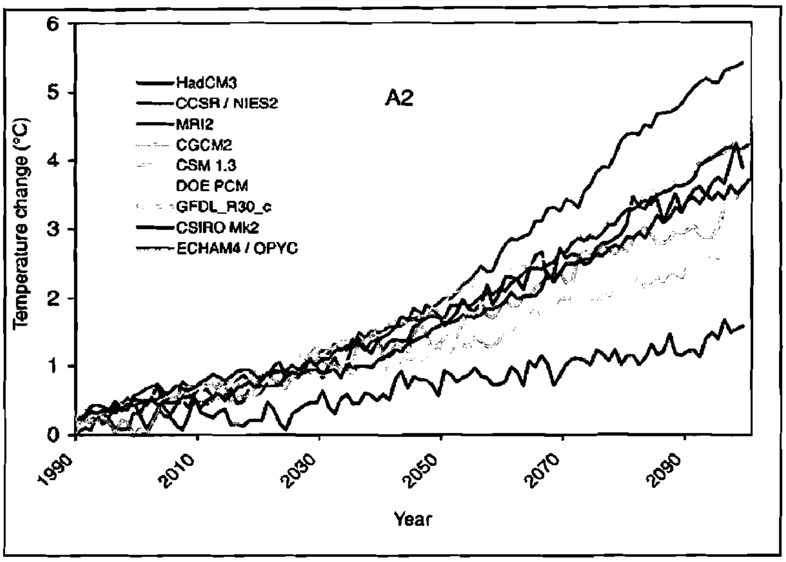

Figure 3: The time evolution of the globally averaged temperature change relative to the years (1961 to 1990) of the A2 SRES simulation (Unit: °C) (IPCC, 2001).

Future Emission Scenarios

In addition to GCM uncertainties, projections intended to represent plausible climate change due to greenhouse gas forcing must rely heavily on future projections of population growth, economic activity and technological change which are inherently uncertain (Webster et al, 2002). These greenhouse gas emissions scenarios are the product of very complex dynamic systems determined by driving forces such as demographic change, socio-economic development and technological change (Nakicenovic *et al*, 2000). The starting point for each projection is a storyline describing the way each of the key driving forces in emissions will develop over the next few decades (Arnell, 2004). Each of the SRES storylines of future development, of which there are 40 presented, can all be related to four marker or family scenarios; A1, A2, B1 and B2. Between them these four marker scenarios account for about 80-90% of the range of future emissions (New and Hulme, 2000), and are described in Box 1. Each scenario leads to substantial differences in projected CO2 concentration trajectories.

Box 1: Exploring Emissions Scenarios

In 1992, the Intergovernmental Panel on Climate Change (IPCC) published the first emissions scenarios, which were the precursor to the present SRES (Special Report on Emissions Scenarios) emissions scenarios employed in both the Third (2001) and Fourth (2007) Assessment Reports. These scenarios assume varying levels of future demographic, technological, environmental, societal and economic developments that result in different future emissions scenarios for the main greenhouse gases and aerosols.

While over 40 emissions scenarios were developed, four central 'families' or sets of **equally probable** scenarios, namely A1, A2, B1 and B2 which span approximately 80% of the range of future emissions contained in the SRES. Modelling the future climate for a given emissions scenario will always result in a range of future scenarios being simulated due to **uncertainties** inherent in the climate and modelling system (Hulme and Carter, 1999).

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 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) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).

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 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** 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 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

Regionalisation or Downscaling

Despite the high degree of sophistication of GCMs, their output is generally too coarse to be useful for regional or local scale impacts analysis, as important processes which occur at local level are not at present sufficiently resolved by these models (Wilby et al., 1999). Due to computational limitations, the grid box output from GCMs is generally in the order of 100s of kms. While this is adequate to capture large scale climate variability, many important processes in the climate system occur at much smaller spatial scales and thus are too fine to be resolved in the modelling process. Therefore regionalisation or downscaling of GCM outputs is required for meaningful impact assessment with uncertainty associated with the approaches taken. In terms of approach uncertainty two categories of downscaling have come to the fore;

- **Dynamic approaches**, in which the physical dynamics of the system are solved explicitly. This approach is carried out by using Regional Climate Models which are based on the same complex structure of the GCM but operate at a higher resolution for a more limited spatial area. The key challenge of this approach is the magnitude of computing resources and costs required to run scenarios for the future.
- **Empirical or statistical downscaling**: involves relating observations from local climate stations to large scale output from GCMs by developing statistical relationships and transfer functions and using these to downscale GCM output for the future. While this approach is computationally cheaper the assumption is made that the statistical relationships derived for observations will remain constant in the future.

Both approaches are subject to benefits and limitations in terms of computational costs and assumptions made, however a substantial amount of research conducted to date has shown that neither emerges as entirely preferable over the other.

Impacts Models

Finally, uncertainty exists in the models used to conduct impact assessments. In the case of impact assessment for catchment hydrology and water resources, for example, conceptual rainfall runoff models have been widely used. These models are firstly trained to represent a chosen catchment and subsequently downscaled output from GCMs is used to force these models for the future. Uncertainty has long been associated with the use of such models because of the difficulties involves in measuring sub-surface hydrology and the simplification that such models make in representing catchment processes. Wilby and Harris (2006) and Murphy et al (2006) show that uncertainty in future river flow changes due to impact model uncertainties is comparable in magnitude to the uncertainty due to different greenhouse gas emission scenarios.

DEALING WITH UNCERTAINTY

The management of uncertainty in climate impact assessment is a complex issue and is the focus of much current research. In order to estimate how much confidence we can have in climate projections we need to examine the different sources of uncertainty. This poses a serious challenge of how to effectively represent uncertainty in future projections so that the best available information can be made available for decision making.

Up until recently a common approach was to suppress uncertainties with projections based on one realisation of climate model output with one value presented for key impact variables. Obviously this is dangerous practice, particularly where important policy decisions are based on output. At the other end of the spectrum the option is to include all sources of uncertainties in impact assessments, however, this is extremely ambitious due to the computing resources required, while extremely wide ranges in impacts can make decision making very difficult.

More usual, as has been the case in recent research in Ireland and internationally, is to select a number of GCMs and emissions scenarios that are representative of the ranges of uncertainty and to use and combine these to form ensembles or combined projections of future climate, with key sources of uncertainty included. For example, Fealy and Sweeney (2008) use output from three GCMs, forced with two emissions scenarios, to produce ensembles of climate change for Ireland. The issues that emerge in such an approach is the choice of GCMs and emissions scenarios to use, with choices being dictated by model vintage, success at capturing observed climate locally, model resolution and availability. In following an ensembles approach, decisions also need to be taken as to how to construct ensembles; whether all models should be weighted equally or should higher weight be given to certain models that perform best against some performance criteria. In the work reported in part 2 of this paper, the results presented are based on ensembles created in this fashion.

This paper has explored some of the difficulties associated with predicting future climate change. In the companion paper in Geographical Viewpoint Volume 38 (2010), the focus will turn to addressing the Irish situation and the possible implications of climate change for the island.

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