Chapter 14

Global Warming Scenarios for Ireland and their Implications for Environmental Management

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ABSTRACT

Regional climate forecasts cannot yet be derived with confidence from general circulation models of the atmosphere, particularly in terms of projecting precipitation changes at middle latitude locations such as Ireland. This paper employs several large datasets relating to Irish precipitation and synoptic circulation types to examine past and present precipitation-circulation relationships. These relationships are then used to make preliminary inferences concerning likely changes in seasonal parameters in a greenhouse-warmed Irish climate. It is concluded that increases of 5-15% in winter precipitation will be accompanied by significant reductions in summer values, especially in eastern Ireland. These projections, allied to the global predictions concerning sea level rise are then used in an examination of some implications, particularly in civil engineering aspects of environmental management.

Introduction

Environmental managers, particularly in civil engineering-related fields, have, in the past, implicitly worked on the assumption that climate is a relatively conservative, stable commodity which can be characterised by a set of data derived from a long period of observations. Conventionally, a 30-year span of such observations has been used to derive the means, extremes and frequencies of the various weather elements which give a location its unique climatic 'fingerprint'. Thus, climatologists could supply information, for example, on the likely return period of extreme wind gusts, rainfall amounts, or temperature extremes - considerations important in endeavours ranging from building design through to water resource management. It is now clear that such baselines cannot be extended into the past, or more seriously into the short term future, with any degree of certainty. That the climate of even extremely equable temperate regions such as Ireland, as of the globe in general, changes on all scales is now an accepted fact, and that it may change more radically over the next forty years than over the last millennium is increasingly likely. It is no surprise, therefore, that the issue of climate change has been described as "potentially the greatest global environmental challenge facing mankind" (Houghton, 1990). Furthermore, arising from the investigations of the Greenland Ice Core Project, climate change appears to be on occasion a step-functional phenomenon and not necessarily the gradual phenomenon which the results of computer modelling tend to suggest (GRIP, 1993).

In 1988 the World Meteorological Organisation and the United Nations Environment Programme jointly established the Intergovernmental Panel on Climatic Change (IPCC) to examine the nature, implications, and possible options for mitigation, of the anthropogenic impact on climate associated with the enhanced "greenhouse effect". The IPCC reported in August 1990 and 137 countries represented at the World Climate Conference in November of that year urged an immediate commencement of negotiations to agree a framework convention for ratification during the 1992 United Nations Conference on Environment and Development in Rio de Janeiro. As became only too apparent during this conference, regional interest groups sought to broaden the arguments to incorporate long standing grievances concerning the relationships between developed and developing countries, and the ultimate product was a considerably watered down convention which was mostly aspirational. The convention became a piece of binding international legislation on 21st March 1994, 90 days after having been ratified by fifty countries. Given the likelihood that no effective international agreement on limiting CO_2 emissions is likely in the immediate future, particularly in the light of the fruitless Rio+5 follow up Earth Summit in June 1997, there is no reason to alter the latest IPCC "Business-as-Usual" scenario which envisages a globally-averaged temperature rise of 1.5-3.5°C within the next century (Leggatt *et al*, 1992).

General Circulation Models

Projected changes in Irish climate can as yet only be crudely inferred from the output of global scale computer models of the general circulation (GCM). These are based on the physical conservation laws which describe changes in momentum, heat and water vapour as a consequence of atmospheric motion and, for the purposes of running them, the atmosphere is divided into a number of vertical levels (2-19) and spatially organised into a series of horizontal grid points (300-1000km apart). The value of the predicted variables (wind, temperature, humidity, surface pressure, rainfall etc.) is calculated for each layer and grid point by running the model forwards in discrete time steps, approximately 30 minutes, starting from some initial condition. Typically, equilibrium results using a normal and CO_2-enriched atmosphere are compared. The technique has only become possible with the advent of very fast computers since the output for one step at each point is used as the input for the next at every other point. Thus to compute each of the basic atmospheric variables at each grid point requires that roughly 10^5 numbers be stored, recalled, recalculated and stored again. Today's most powerful computers are about 1,000 times as fast as their predecessors of the 1970s, enabling the incorporation of more sophisticated information into numerical models and also permitting increasing resolution in their treatment of climate. Currently, seasonal and regional details are just beginning to emerge as output possibilities, as is the important question of the variability characteristics of future climate.

The range of performance of GCMs has narrowed substantially in recent years. Fairly good agreement with observational data is now apparent, particularly for low latitude pressure distributions. Polewards of 60° a considerable problem still exists due to the as yet unresolved difficulties of the ice-albedo feedback effect detailed below. In contrast, with precipitation modelling, the greatest uncertainties lie at low latitudes, where large discrepancies with observational data continue to exist. In this case also a feedback problem is responsible, namely the failure of most models to incorporate successfully the role played by clouds.

Feedback Mechanisms Limiting the Effectiveness of GCMs

A feedback occurs when a change in a particular component of a system provokes a further series of changes in other elements, the consequence of which eventually causes a further effect on the initial component. Positive feedback reinforces change and means the system tends towards instability. Negative feedback, on the other hand, is a damping mechanism and systems characterised by negative feedback often have a large capacity for self regulation. The climate system has many feedback loops, both positive and negative, and successful modelling entails the accurate incorporation of these into the procedure.

Ice-albedo feedbacks. The present global albedo is 0.30, meaning that 30% of incoming short wave insolation is reflected back to space, an amount which determines how much absorption (and thus warming) of the earth-atmosphere system can occur. A strong determinant of this reflectivity is how much snow and ice exists, since such surfaces have albedos of 0.7-0.9. A decrease in ice coverage during a period of global warming decreases the global albedo, causing increased absorption, a further retreat of the ice margin, and a further decrease in albedo. This self-sustaining mechanism is a positive feedback which of course also operates in the opposite direction during global cooling periods and was suggested by Budyko (1980) to have almost produced a catastrophic total glaciation of the globe during the Pleistocene epoch.

Water vapour feedbacks. The principal greenhouse gas in the atmosphere is not CO_2 but rather water vapour which blocks outgoing terrestrial long wave radiation very effectively in the 5-7μm wavelength range. When temperatures rise, evaporation from the oceans and other moist surfaces, and transpiration from vegetation, is increased and more water vapour is carried in the lower atmosphere. This enhances the effectiveness of the long wave trapping, allowing the surface to warm further. Again a positive feedback mechanism is in evidence which reinforces a warming trend.

Cloud feedbacks. Cloud feedbacks are more difficult to appreciate since it is not clear even in which direction feedback occurs. This is a consequence of the fact that clouds are both highly reflective, thus influencing global albedo, and composed of water vapour, thus influencing the greenhouse effect. The question of whether in a warmer world more clouds mean more reflectivity, and therefore cooling, or more absorption, and therefore warming, has not yet been completely resolved. Current thinking is that mid/low altitude clouds may be more significant for the albedo while high clouds such as cirrus may be more important for absorption.

But while increased temperatures will certainly lead to more cloud formation, global cloud cover may not increase correspondingly. Increased evaporation may manifest itself in the form of more cumulus cloud, with little change in overall albedo. An increase in stratus clouds on the other hand would imply an increase in total coverage and a cooling tendency - a negative feedback effect overall. GCMs are not currently very successful in handling cloud formation, particularly in terms of height, since it occurs at a scale much smaller than their grid size and much work needs to be done before complete confidence in their output is possible.

Feedbacks in Combination

Multiple feedbacks, operating in different directions need to be added up to determine their overall effects. The magnitude of the total will determine the sensitivity of the climate system to change. One way of addressing this (Henderson-Sellers and McGuffie, 1987) is to ask the question: "What temperature change ΔT will occur in response to a prescribed (e.g. doubled CO_2) net radiative flux change across the tropopause, ΔQ?" The system can be simplified as follows:

$$C\,[\,\delta(\Delta T)/\delta t] + \lambda\Delta T = \Delta Q$$

where: C is the system heat capacity, $\lambda\Delta T$ is the net radiative change resulting from the internal characteristics of the climate system, and t is time.

An appropriate value for λ is λ_B which is the value the earth would have if it was a black body with its present day albedo, so that:

$$\lambda_B = 4\,\sigma T_e^4 = 3.75\ \mathrm{W\,m^{-2}\,K^{-1}}$$

where: σ is the Stefan-Boltzmann constant,
and: T_e is the earth's effective temperature.

The total sensitivity of the earth's climate can now be obtained by adding the internal feedback factors as follows (Henderson-Sellers and McGuffie, 1987):

$$\lambda_{Total} = \lambda_B + \lambda_{water\ vapour} + \lambda_{ice\ albedo} + \lambda_{clouds}$$

Some of these quantities are known. For doubled CO_2, it is known that $\Delta Q = 4.0\ \mathrm{Wm^{-2}}$, while $\lambda_{water\ vapour} = -1.7\ \mathrm{W\,m^{-2}K^{-1}}$ and $\lambda_{ice\ albedo} = -0.6\ \mathrm{W\,m^{-2}K^{-1}}$.

Thus:

$$\lambda_{Total} = 1.45 + \lambda_{clouds}$$

Estimates for λ_{clouds} range from 0 to $-0.8\ \mathrm{W\,m^{-2}K^{-1}}$ (Henderson-Sellers and McGuffie, 1987).

Substituting λ_{Total} into the first equation above, the equilibrium temperature $[\delta(\Delta T)/\delta t = 0]$ for doubled CO_2 can be derived.
A zero value for λ_{clouds} gives ΔT=2.8°C, while a value of $-0.8\ \mathrm{W\,m^{-2}K^{-1}}$ gives a temperature change of 6.1°C. Clearly, cloud feedback effects must be better understood before GCM results may be accepted with confidence.

Response times The response time (or equilibration time) is that time a part of the climatic system takes to accommodate itself to a perturbation. These vary enormously from a matter of days for the lower atmosphere to several centuries for the deep oceans and ice sheets. Modelling the ocean's response to increased atmospheric CO_2 is especially important since it acts to remove CO_2 from the atmosphere and also to absorb and redistribute heat throughout its great volume. The upper three metres of the ocean store as much heat as the entire atmosphere. Incorporating these slow responding components into models based on 30 minute time steps has proven extremely difficult and successful resolution awaits the development of more powerful computers.

GCM Estimates for Irish Climate

Model predictions for global temperature change have been reducing as greater sophistication has been achieved. Whereas estimated rises of 4°C by mid century were being suggested in the late 1980s (Hansen *et al*, 1988), the 1992 supplementary IPCC report suggests a best estimate for the period 1990-2100 of 1.5-3.5°C (Leggatt *et al*, 1992). Such scaling down has occurred also as awareness has grown concerning other negative feedback factors. For example, it is now believed that depletion of stratospheric ozone will have a cooling effect on the atmosphere, as will continuing increases in sulphate aerosol pollution as industrialisation proceeds in countries such as China. It is also recognised that increased atmospheric CO_2 will induce greater plant growth and carbon storage, helping to reduce the rise in atmospheric concentrations.

However, as far as Ireland is concerned, many models show consistencies which give grounds for making reasonable estimates of the course of future climate. Firstly, its mid latitude position suggests that Ireland should, other things being equal, experience similar changes to the global mean. Most global warming will occur at higher latitudes due to the ice-albedo feedback effect. However, the climate of Ireland may be relatively slow to respond to greenhouse forcing due to the moderating influence of the Atlantic Ocean. The Atlantic is a particularly effective heat sink, with summer heat being dissipated each winter through a depth in excess of 200m and over a large area off the west coast of Ireland in excess of 500m (Rowntree, 1990). Thus even if the European continent warms up, the existence of a cool sea surface around Ireland will inhibit warming in summer, while a poleward shift in winter isotherms will have a less positive effect on Irish winter temperatures than further east in Europe. These suggestions are partially supported by other GCMs which incorporate deep ocean mixing (Stouffer *et al*, 1989; Washington and Meehl, 1989) and by the work of Karoly (1987) who examined actual warming at the 700mb level between 1960-80. This study showed consistent warming almost everywhere except the north Atlantic and Pacific Oceans where considerable winter mixing depths also exist. If indeed the Atlantic around Ireland is slow to warm, the consequences for Irish climate will be determined by changes in circulation frequencies, an aspect considered in some detail below.

All GCM models predict higher annual precipitation in the high and low latitudes and higher winter precipitation in mid latitude locations such as Ireland. This is to be expected since the atmosphere's capacity to hold water vapour increases by approximately 7%°C. However, little agreement is apparent from the models on where significant changes will occur and in particular what can be anticipated for summer precipitation changes. For Ireland, while there is general agreement that winter precipitation will increase, contradictory signals are in evidence when it comes to summer values.

It is thus apparent that regional climatic forecasts based on GCMs are not yet possible to make with any degree of confidence and while some credibility may be placed on temperature estimates, projected precipitation changes cannot be relied upon in any way as yet. Indeed as Wigley and Santer (1990) point out, GCMs are not able to simulate present precipitation patterns at fine scales, let alone future patterns. A great deal of work is therefore required before authoritative statements can be made. One approach to overcoming these regional inadequacies and to estimating summer precipitation changes in Ireland follows.

Synoptic Circulation Analogues for Projecting Future Irish Summer Precipitation

Examining the association between precipitation and circulation type enables the component contributions of a place's annual precipitation regime to be disaggregated according to the circulations producing it. This is important given the growing awareness that significant circulation changes have occurred in recent times (Briffa *et al.*, 1990) and that short term future climatic changes in Ireland will be determined principally by changes in circulation frequencies. If it is possible to anticipate the nature of these, more authoritative estimation of the environmental significance of climatic change may be made.

In relating precipitation yields to synoptic circulation types, the first requirement is for some form of daily categorisation of airflow types across Ireland. A number of approaches have been made to achieving this, ranging from early tabulations of surface wind direction frequencies (Brooks and Hunt, 1933), through more sophisticated air mass analysis (Belasco, 1952) to perhaps the best known catalogue of airflow types devised by Lamb (1950;1972). This scheme involves seven primary types: anticyclonic, cyclonic, northwesterly, westerly, northerly, easterly and southerly. Subsequently, a further nineteen hybrid categories (together with an unclassified category) were added, incorporating more complex circulation types into a daily catalogue extending from 1861. Updating has enabled a register of over 130 years of daily circulation types to be compiled. The categories are considered to be reasonably representative of an area (50-60°N and 10°W-2°E) which includes Ireland, though problems of intra regional variation do occur (O'Hare and Sweeney, 1993; Mayes, 1994).

Precipitation Data Daily rainfall observations were assembled initially for 53 stations in Ireland for a period of approximately 40 years, selected on the basis of their length, reliability and location. Some were found to be suspect on individual days and for longer periods of time and these were discarded; ultimately 34 stations were retained. A nearest neighbour statistic of 1.14 was calculated indicating that the network could be considered significantly random at the 0.01 level and could thus be considered reasonably representative of precipitation conditions in lowland Ireland.

Mean daily rainfall amounts were calculated for each of the Lamb-classification circulation categories for each station for the 40 year period. In this respect the exercise was similar to that carried out using 15 years of data for southern England by Stone (1983a,b) and one year of data for Ireland by Houghton and O Cinnéide (1976).

Substantial contrasts in rainfall yield are apparent with individual circulation types. An anticyclonic northerly airflow, for example produces only about 0.4mm on average across Ireland while a cyclonic southerly flow yields about twelve times this amount. The marked rainfall gradients which occur in relation to circulation trajectories are best appreciated, however, when mapped (Figure 1). One of the advantages of using a very long run of data is that such maps are generally based on a very large number of days and therefore may be considered relatively undistorted by particular disturbance trajectories. In the case of the three most common circulation types: anticyclonic, westerly and cyclonic, the number of days used in the calculations exceeded 2,800 at some stations.

Circulation Types and Precipitation Yields

Anticyclonic. Pressure is typically high over Ireland and subsiding air inhibits precipitation almost everywhere. Generally daily amounts are less than 1.0mm and only in the west with Atlantic fronts skirting the western seaboard do average falls exceed this value.

Cyclonic. A cyclonic circulation type involves the movement of an Atlantic/Biscay depression centre across Ireland. Over a long period of record the actual track taken by such lows may vary considerably, producing a fairly uniform distribution of precipitation. Only in the interior is there a hint that oceanic water vapour supplies may be diminished somewhat. With such a quite uniform distribution of rainfall by comparison with other airflows, it could be suggested that should an increase in the frequency of cyclonic airflows occur across Ireland with global warming, the characteristic west-east contrast in rainfall receipt could be expected to diminish.

Westerly. Westerly circulations are the most frequent synoptic type in the Lamb-classification register, occurring 18.9% of the time With low pressure to the north and high pressure to the south of Ireland, there is obviously going to be a north-south as well as west-east decline in precipitation receipt. Indeed parts of the west coast receives almost three times as much precipitation with this airflow as the Leinster coast where

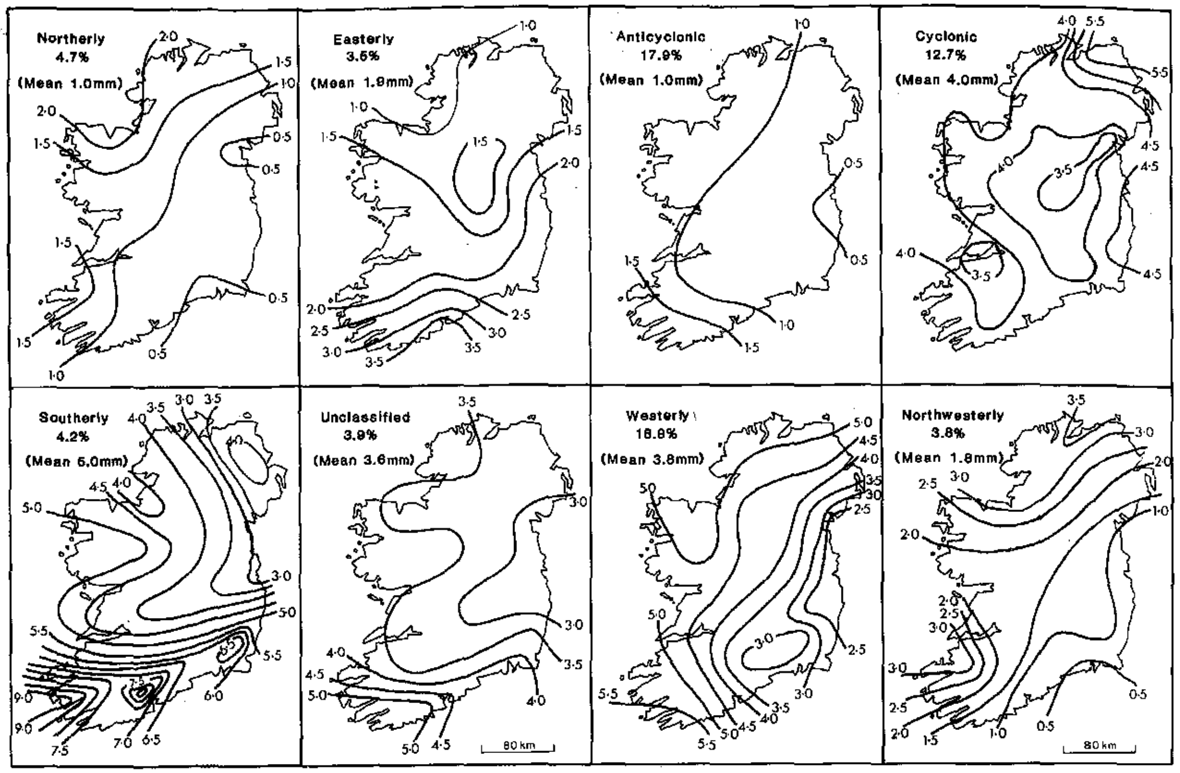


Figure 1: Precipitation yields in Ireland with principal Lamb synoptic circulation categories

a very prominent rain shadow can be seen to the lee of the Wicklow mountains. Again the effects of a continued decline in the frequency of westerly circulations could be expected to diminish west-east contrasts in the annual rainfall, particularly if the replacement of such flows by cyclonic airflows occurred.

North westerly. A ridge, often extending from the Azores anticyclone, is the most common cause of northwesterly airflow, causing depressions to move in a north west to south east direction to the north of Ireland. Falls over 3.0mm are observed in the north west and on exposed coasts in Munster, though elsewhere yields are small. A notable rain shadow area exists along the south coast of Ireland where the driest area with this airflow is located.

Northerly. High pressure located west of Ireland means that Ireland is generally drier than Britain with this airflow which occurs about 4.7% of the time. The north west coast receives the greatest amounts with the main areas of significantly reduced yield being around Dundalk (south of the Mournes) and in south Leinster (south of the Wicklows).

Easterly. Low pressure over France or the Bay of Biscay and high pressure to the north of Ireland is the most common cause of an easterly airflow. Fronts frequently move from east to west across southern parts, often becoming slow moving, and consequently, precipitation is highest on the south coast where a passage across the Celtic Sea enables moisture collection and encourages convective overturning in winter and autumn. Indeed, perhaps somewhat surprisingly, much of the Co. Cork coastline receives greater yields from an easterly flow than from a westerly airstream. A distinct rain shadow can be observed west of the Wicklows.

Southerly. Maritime tropical air masses come heavily laden with moisture and southerly circulation types are the wettest airflow to affect Ireland. Stratiform cloud

produced by air passing over the progressively cooler waters of the North Atlantic Drift yield copious amounts of precipitation when any lifting occurs such as over the mountains of Cork/Kerry and the southern Wicklows.

Circulation-precipitation Scenarios for Irish Greenhouse Summers

What summer circulation frequency changes (and thus precipitation changes) can be expected to occur in Ireland as greenhouse warming proceeds? One way of addressing this is to examine what circulation types have been associated with warm summers in the past. For this, as long a temperature record as possible is desirable to avoid distortions due to anomalous blocking situations, and the long instrumental record developed by Manley (1974) and since continuously updated, for temperature conditions symptomatic of central England was chosen rather than a shorter run of data from Irish locations. Manley's record is generally held to be fairly representative of conditions in both Britain and Ireland and represents the longest reliable instrumentally observed temperature record available globally, extending back to the mid 17th century. From this, summers exhibiting departures of +1 (warm) and +2 (hot) standard deviations in temperature were extracted (Table 1). The latter corresponds to extra summer warmth of about 1.7°C, close to that hypothesised for the vicinity of Ireland in GCMs for approximately 2050. Analysis of the average frequency of circulation types (Table 2) shows that they are associated with substantial increases in anticyclonic circulations and marked declines in westerly types.

Warm summers (>1δ above mean average June/July/August temperature 1659-1997)
1666,1676,1679,
1701,1706,1707,1718,1719,1727,1728,1731,1733,1736,1747,
1759,1762,1772,1775,1778,1779,1780,1781,1783,1794,1798
1800,1808,1818,1826,1831,1834,1835,1846,
1857,1859,1868,1870,1887,1893,1899
1911,1921,1933,1934,1935,1947,1949,
1955,1959,1975,1976,1983,1984,1989,1995
Hot Summers (>2δ above mean average June/July/August temperature 1659-1997)
1781,
1826,1846,1899,
1911,1933,1947,1975,1976,1983,1995

Table 1: Warm and hot summers in the central England temperature series

Since at this point both the rainfall yield by circulation type (summer yields were distilled from the annual data discussed above) and the frequency of circulation types which produce warm and hot summers are known, it is possible to project the changes in summer rainfall which may accompany a switch to a greenhouse summer climate by simulating summer rainfall receipt at each location according to the circulation frequencies concerned (Figure 2(a)).

Diminutions in summer rainfall of approximately 5-15% are indicated for Ireland with greatest reductions occurring in eastern parts, particularly the north eastern regions. Along the south coast, warmer southerly circulations will carry greater water vapour loads and little change is apparent. Water availability implications from future climate change are thus most likely to occur in eastern Ireland in summer. It should of course also be remembered that these reductions may be accompanied by increases in potential evapotranspiration of approximately 8%.

The scenario suggested in Figure 2(a) appears also to have some support from recent observational data. Over most of Ireland and Britain summer rainfall has decreased over the last two decades, though increases over north western areas during the 1980s has partially offset this. Greatest reductions have occurred in southern and eastern parts and Mayes (1991) has suggested these are associated with changes in anticyclonic and westerly circulation frequencies. In Ireland a crude regression on summer rainfall totals at Valentia and Dublin Airport suggest that a more marked downward trend is apparent in recent summers in eastern parts, in line with the suggested changes based on the synoptic circulation analysis above (Figure 3(a)).

Using a similar approach, projected changes in winter rainfall are seen to be generally increases, particularly in western parts (Figure 3(b)). The records from Valentia and Dublin Airport (Figure 3(b)) again provide support, with a more substantive upward trend at the former in evidence, though such generalised analyses provide only a tentative 'first pass'.

Lamb circulation frequencies 1880-1996	All Year	All Summers	Warm Summers	Hot Summers
Unclassified	4.0	3.8	3.3	3.3
Anticyclonic	18.0	19.0	31.1	33.1
AC/N.E	1.3	1.3	1.8	1.7
AC/E	2.5	2.4	3.7	4.3
AC/S.E.	0.9	0.7	1.5	1.4
AC/S	1.1	0.9	1.0	1.4
AC/S/W	0.8	0.8	0.7	0.6
AC/W	4.6	5.4	6.1	4.8
AC/N.W	1.4	2.1	2.8	2.5
AC/N	1.9	2.2	2.7	2.0
North East	0.9	1.0	0.6	0.3
Easterly	3.5	1.9	2.4	3.0
South East	1.8	0.7	1.2	1.4
Southerly	4.4	2.4	3.3	3.6
South West	2.8	2.1	2.1	2.3
Westerly	18.5	17.8	13.3	10.9
North Westerly	3.8	4.8	3.4	3.7
Northerly	4.8	5.0	2.7	2.0
Cyclonic	13.0	15.9	9.3	9.8
Cy/NE	0.4	0.3	0.2	0.3
Cy/E	1.1	0.9	0.7	0.8
Cy/SE	0.5	0.2	0.2	0.2
Cy/S	1.2	1.0	1.4	1.1
Cy/SW	0.5	0.5	0.3	0.3
Cy/W	3.8	4.4	2.6	3.0
Cy/NW	0.9	1.1	1.0	1.4
Cy/N	1.4	1.3	0.7	0.9

Table 2: Lamb Circulation Frequencies 1880-1996

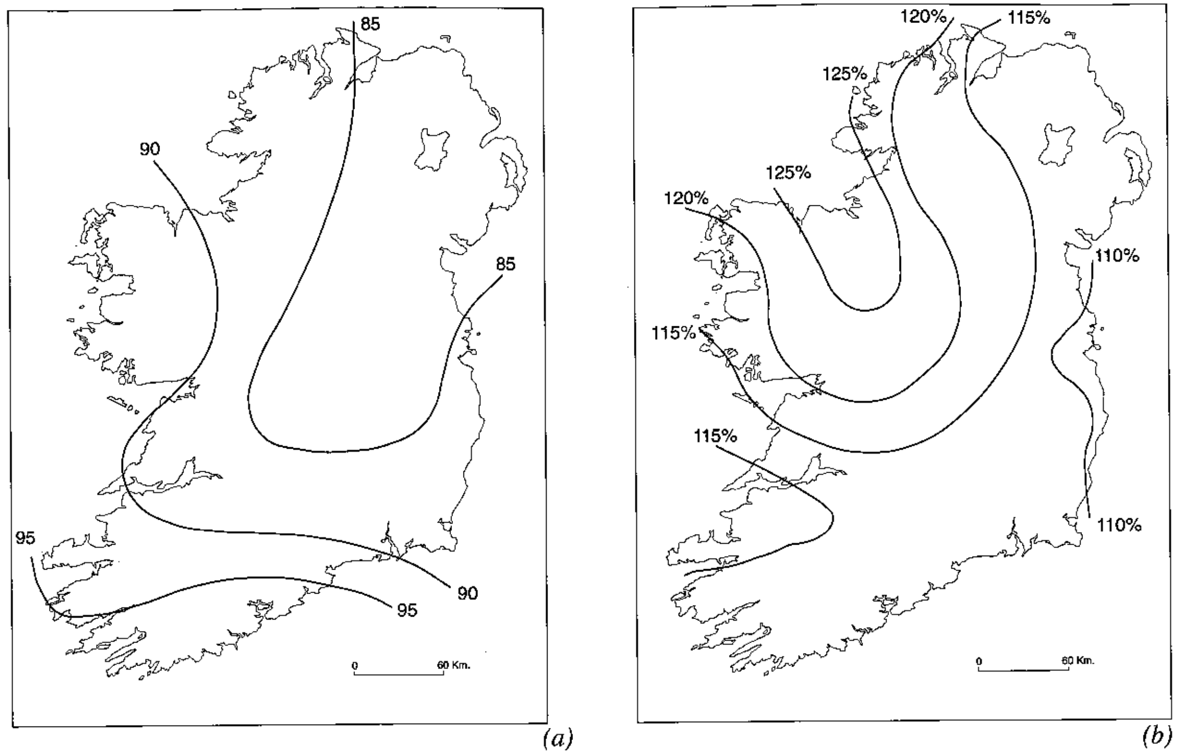


Figure 2: Projected changes in Precipitation for Ireland for approximately 2050, (a) summer (b) winter

In summary, a scenario for Irish climate for 2050 might be as follows:

Average annual temperature change (°C):	1.0
Average annual precipitation:	little change
Average winter temperature change (°C):	0.5
Average winter precipitation change :	+5-10%
Average summer temperature change (°C):	1.5
Average summer precipitation:	-5-15%

The values are not too dissimilar from those used as working assumptions by the Department of Environment report on climate change (McWilliams, 1992) though do emphasise the likelihood of larger reductions in summer rainfall. Warming in both seasons is slightly less than that suggested from averaging of five GCM results for north western Europe by Warrick and Barrow (1991).

Implications for Environmental Management

Global change will necessitate adjustments to environmental management practices throughout the world. In Ireland, the most significant impacts are likely to relate to the management of coastal areas and water resources.

Sea-level rise and Coastal Management in Ireland

Various studies (Gornitz and Lebedeff, 1987; Barnett, 1983;1984) have suggested that a sea level rise of 10-15cms has occurred in the past 100 years, at least some of which may be attributable to the global warming of 0.5°C which has taken place over the same period (Wigley and Raper, 1987). Over the next century, thermal expansion of the oceans will provide about 37% of the contribution to an anticipated rise of 58cms (Watson *et al*, 1992), the melting of land-based glaciers in temperate latitudes a further 39%, and the thinning of the Greenland ice-cap the remaining 24%.

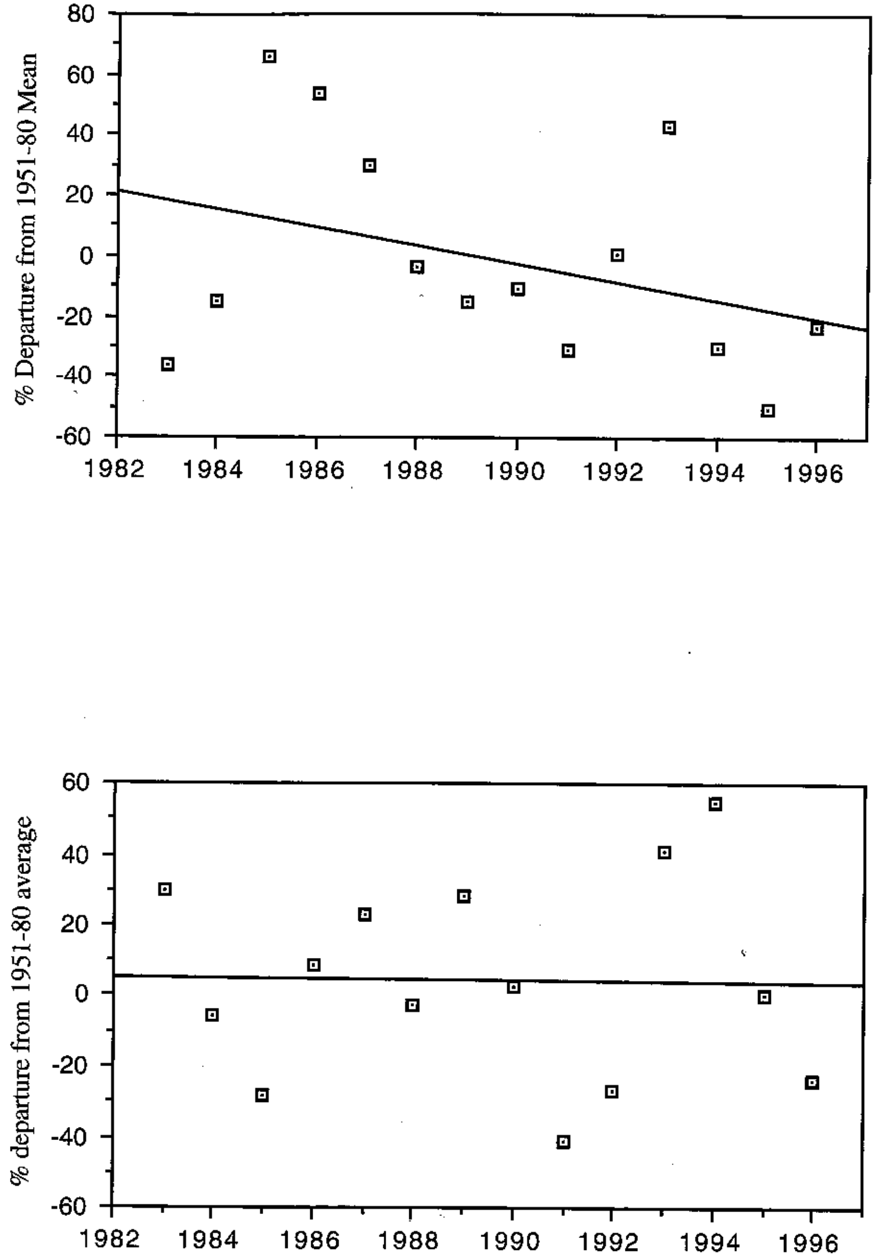


Figure 3(a): Summer Precipitation Trends at Dublin Airport (top) and Valentia Observatory (bottom) 1983-1997

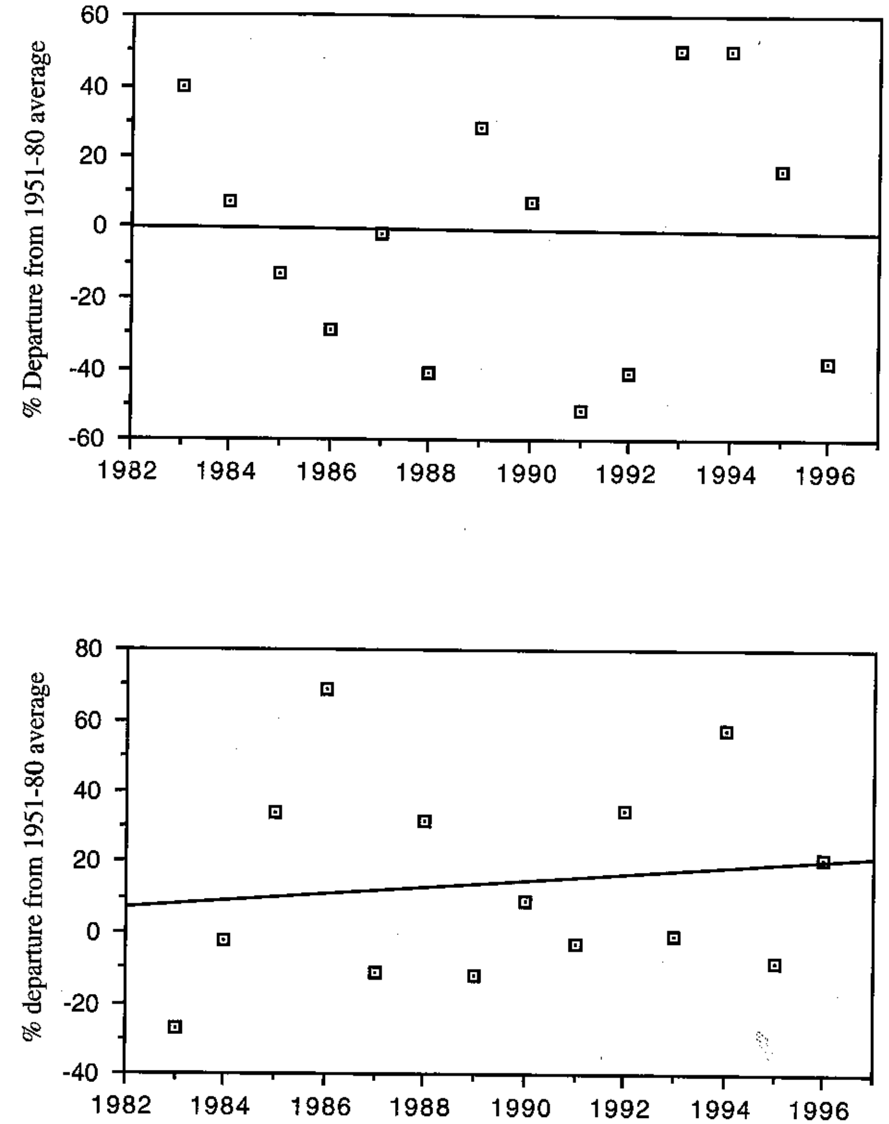
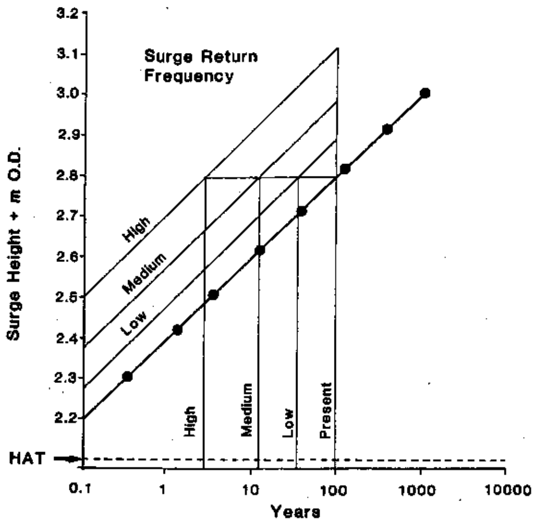


Figure 3(b): Winter Precipitation Trends at Dublin Airport (top and Valentia Observatory (bottom) 1983-1997



(HAT= Highest Atmospheric Tide) (after Carter (1991)

Figure 4: Surge Return Frequency at Malin Head

Estimates of sea level rise up to 2100 have been revised downwards consistently from figures in excess of 5 metres in the late 1970s as it has become clear that earlier fears regarding the catastrophic melting of the partially grounded/partially floating West Antarctic ice shelf were probably exaggerated. It is now believed that even a one metre rise due to melting of this ice shelf would take up to 500 years to occur (Budd *et al*, 1987).

Examination of the four tide gauge records in Ireland which span a full nodal tide period of 19 years show only a very slight rising trend of 0.3-0.5mm/year. Difficulties in interpretation arise, however, due to land rebound still occurring north of a line from Galway to Dublin as the effect of the removal of the Pleistocene ice sheet is still felt. Any greenhouse-led coastal changes are therefore likely to be experienced south of this line in the first instance.

The principal impact will be felt in terms of increased storm surge activity. Figure 4 shows the expected surge return frequency at Malin Head with various sea level scenarios. It is apparent that even with small sea level changes (<0.3m) the return period changes appreciably, diminishing from a present 1:100 year event to 1:33, 1:11 and 1:2 year return for the three estimates shown. Engineering structures thus will require a higher level of protection but also a design capability for coping with a winter storm magnitude which may recur more frequently than presently.

The response of the coast to sea-level rise is influenced by its structural geological/geomorphological characteristics and its relative exposure to wave and tidal processes. Increased coastal erosion, estuarine infilling, coastal flooding, saltwater intrusion of coastal aquifers, barrier changes, dune changes and wetland inundation are obvious consequences of an accelerating in sea-level rise. In Ireland about 130-160ha of land are lost annually from about 300 localities (Carter and Johnston, 1982), mostly from the glacial drift coastlines of the east coast. Generally recession rates average 0.2-0.5 m/year though in places the rate of retreat currently exceeds 2m/year. In some instances natural processes are exacerbated by human actions in dredging, sand removal, reclamation, stream discharge management, groundwater extraction and unfortunately by injudicious shoreline protection measures.

Areas of particular concern in terms of near future sea-level rise/storm surge activity exist. The Shannon Estuary and the four cities of Dublin, Cork, Belfast and Galway are particularly susceptible. In part this is due to a concentration of arterial communications and industrial developments close to current sea level in their vicinity and also to high capital investments in residential and recreational land uses which may be compromised. Outside of the major cities, industrial zones at Dundalk and Drogheda, barrier beaches in Wicklow, Wexford and Waterford, and embayments in Kerry, Galway and Mayo (such as Clew Bay and the Mullet Peninsula) have been suggested by Carter (1991) as vulnerable.

At its most basic, two responses can be made to coping with sea level rise - retreat or protection. Retreat is normally the most economic strategy though being a variant of a "do nothing" strategy it runs counter to the deeply imbued Irish cultural trait of holding on to land at all costs. Local politics also may elevate minor land losses to major political issues and produce calls for non economic schemes for protection. About 100,000ha of land in Ireland may be at risk from sea level rise by 2050, perhaps amounting to 100km of the total coastline length of 6,500 km (Carter, 1991). For most of this length the cost of relocating inhabitants and infrastructure from lightly settled areas will certainly be significantly less than constructing and maintaining defences which currently cost approximately IR£5M/km.

Undoubtedly, where a high concentration of population, industry and infrastructure exists close to the shoreline, there is little alternative to some form of protection strategy. Even here though, the costs must be carefully appraised. The recent completion of the Thames (£559M) and East Scheldt (£1,500M) barriers, and the soon to be completed Venice barrier (£2,500M) represent investments which Ireland can never and should never contemplate. Indeed the experience of 'hard engineering' solutions in arresting shoreline erosion in Ireland has been disappointing. Many of the measures have been unsuccessful and have required even more expensive remedial work, exemplifying, as Devoy (1992) has claimed, "a vicious circle of scarce resources being sunk in insoluble problems of coastal dynamics". Indeed the building of sea walls at Bray, Portrush, Youghal and Lahinch appear to have enhanced beach removal and left the structures themselves exposed to storm wave attack. As sea level rises other defences will become vulnerable such as the sea walls between Sandymount and Dun Laoghaire in Dublin Bay, some parts of the Liffey Quays, and around the Spanish Arch in Galway where occasional breaching presently occurs.

Engineering responses to greenhouse led sea level rises in Ireland are probably best focused on lower cost 'soft engineering' strategies. These, however, require both a good insight into how sediment transfer is occurring in the area concerned, and careful modelling of what changes may ensue. Although of short term life expectancy, such strategies as set back lines, beach nourishment, gabions, geotextiles, emulsions and sand dune grass planting are more suitable to the financial resources of the local authority, and their political need to be seen to be doing something, although they must not be seen as a long term reassurance to coastal inhabitants that the hazard potential of living in a threatened area has been eliminated.

Changes in Hydrology and Implications for Water Resource Management

The rainfall changes suggested earlier would, if realised, have considerable implications for engineers concerned with hydrological management and water quality. Increases of the order of 10% in winter precipitation and decreases of a similar magnitude in summer represent an unfavourable scenario for many endeavours including: flood control, drought management, urban drainage/sanitary services, and the maintenance of adequate dilution for effluent discharges. In essence they centre on the problems of higher winter river flows and reduced summer flows, the latter further exacerbated by reduced soil moisture storage.

Higher winter flows When the mean of a distribution changes, the extremes change by a greater amount. Wigley (1989) suggests that a change in the mean of approximately one standard deviation produces a seven fold change in the frequency of an extreme. Irish rainfall however typically has a high standard deviation already relative to the mean and so changes of this magnitude are unlikely. Nonetheless, significant changes in river regimes can be expected. The precipitation and evaporation changes suggested in this study correspond quite closely to those of Scenario 2 in Cunnane and Regan's (1991) work on likely changes in the hydrological regime of the River Brosna. For winter, they suggest that the discharge currently exceeded 5% of the time would increase to 6% and that the return period for design floods would reduce by approximately 50%. Changes in the average annual maximum flood in a catchment is significant since one of the foundations of the Flood Studies Report (NERC, 1975) is that the probability of given storms can be calculated from a long term series of such values. If these change significantly, the tenets for water management in the catchment are immediately rendered unsound.

An increased tendency for high flows in winter time in Irish rivers will also have implications in a wider context. Overbank flow will be more common. In addition to increasing flood propensity in already susceptible urban areas such as Bray, Kilkenny, Fermoy, Mallow and Cork city, increased frequency of overtopping of arterial drainage systems is also a consequence. These structures are typically designed to accommodate the 3 year flood and their economic rationale may be further questioned. Likewise, design criteria for urban storm drainage systems will require reformulation though it should be noted that increased flows will permit greater dilution of effluent at this time of the year.

Lower summer flows Reduced summer rainfall has an enhanced effect on river flows due to accompanying depletion in soil moisture and increases in potential evapotranspiration demands. Again Cunnane and Regan's (1991) estimates on the Brosna suggest that the discharge experienced less than 5% of the time will increase in frequency to around 11% of the time and that the 10 year low flow would become the five year event. Such changes have obvious implications in terms of reservoir storage where, particularly at the end of summer, serious delays in recharge could occur. It will be necessary to design for increased capacity both to allow for greater carryover of water from the winter period and to cater for higher summer water demands from both domestic and agricultural consumers. Irrigation economics change significantly with any reduction in summer rainfall and considerable expansion in spray and sprinkler systems seems probable in the drier south east of the country.

Groundwater resources provide less than 25% of Irish water supplies. Drier summers would pose a threat to some shallow aquifers, particularly in karstic areas where throughput of water is quite fast. In such areas deeper wells will be required. Some coastal aquifers may also suffer more frequently from summer sea water intrusion as a consequence of falling freshwater levels and rising sea levels.

Water quality implications Increased summer temperatures and decreased summer rainfall are not conducive to the maintenance of present water quality standards. In awarding effluent licences, a common criterion for an organic effluent might be that it should be discharged in amounts not calculated to cause an increase in Biochemical Oxygen Demand of 3mg/l during the time of lowest flow. But if the likely lowest flow is substantially reduced, the dilution factor for effluent is correspondingly compromised. Unlicensed and accidental spillages also have enhanced effects in such circumstances. A deterioration of up to 20% in average downstream B.O.D. levels is possible in Irish rivers as a result of the change in regime.

Lower summer flows also have the effect of producing higher nutrient concentrations, particularly phosphates (McGarrigle, 1990). This will, together with higher temperatures, encourage eutrophication, ultimately lead to a further reduction in dissolved oxygen and pose additional stresses for salmonid fish. The problems of nutrient loading in the midland lakes has been well researched. Further warming would tend to exacerbate these difficulties by encouraging greater thermal stratification in lake waters and inhibiting oxygenation.

Conclusion

The scenario developed for greenhouse-led changes in Irish climate will have a pervasive effect on many aspects of concern to environmental managers. Only two major families of impacts are addressed in this paper although several other aspects of concern exist. It must be stressed however that greenhouse-led changes will not be so radical as to take us out of our past range of experience for the foreseeable future. Rather it is the pervasiveness of changes which we will have to come to terms with if we are to accommodate to the new environmental stage, or rather take the right decisions which will enable us to survive economically upon it. Either way the maxim of keeping a safety margin as insurance against the unforeseen will more than ever be eminently sensible.

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