Temperature + Precipitation :-

CLIMATE SCENARIOS FOR IRELAND

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General Circulation Models and Future Projections of Irish Climate

Global scale general circulation models (GCM) can currently only provide a rough guide to the likely future course of Irish climate in an enhanced greenhouse effect-warmed world. Such computer models use basic physical laws to describe changes in momentum, heat and water vapour as a consequence of atmospheric motion and have evolved from elementary and rather crude constructs to complex and demanding affairs which require some of the most powerful computing platforms in existence. For the purposes of simulating the effects of a hypothetical change in climatic inputs, the atmosphere is divided into a number of vertical levels (up to 19) and spatially organised into a series of horizontal grid points (300-1,000km apart). For each of these layers, and each grid point, a number of climatic parameters are calculated by running the model forwards in a series of simulated time steps (of the order of 30 minutes) starting from some initial condition. Normally equilibrium results are obtained after a few tens of years and comparisons between the equilibrium climate and a control run can be made.

The technique has only become possible due to the advances which have been made in computing speed over the past two decades. Typically, in the late 1970s the most powerful computers could cope with approximately 10 million floating point operations per second (MFLOPS) while today the figure is approximately 10,000 MFLOPS. This is important since each iteration of the model requires the retrieval, calculation and storage of approximately 10^5 numbers for each grid point for each atmospheric variable. Such advances mean that seasonal and regional details are just beginning to emerge as output possibilities, as is the vital question of future climatic variability.

Early generations of GCMs showed considerable inconsistencies, particularly for low latitude pressure and high latitude precipitation simulations. These have now begun to diminish. It is also now possible to run models which incorporate transient changes, i.e. annually changing a parameter such as CO_2 instead of arbitrarily doubling it in one initial step. This provides a much more realistic view of how gradual changes in climate are likely to occur.

It is however, fair to say that models have not yet evolved to cope adequately with a variety of feedback effects, and this continues to limit their utility, particularly in providing the regional scale forecasts which policy makers require. They also have been less than satisfactory in incorporating the interaction of the ocean with the atmosphere and in coupling the two systems' role in regulating climate change.

Feedbacks

A positive feedback acts to magnify an initial perturbation while a negative feedback dampens change. The most important feedbacks implicated in climate change are those relating to ice-albedo, water vapour and clouds.

Ice-albedo

The current planetary albedo (or reflectance fraction) of 0.30 is determined largely by the amount of snow and ice existing. Such surfaces may reflect up to 90% (albedo 0.90) of incoming insolation and as a consequence play a large role in determining the net radiation balance of a place. During a period of warming it can be expected that the melting of snow and ice at high latitudes will decrease the albedo in these locations, further enhancing warming and accelerating the retreat of the ice margin. Such a positive feedback mechanism may partly explain the newly-discovered rapid climate warming which occurred at the end of the last glaciation.

Water Vapour

Water vapour is the main greenhouse gas and absorbs terrestrial radiation in the 5-7μm wavelength range. Should temperatures rise as anticipated, increased evaporation from the oceans and other moist surfaces might be expected to reinforce a warming trend, a further example of a positive feedback mechanism.

Water Vapour = ↑ warmth

Clouds

②

Clouds are the source of greatest uncertainties with GCMs since it is not even clear in which direction feedback operates with them. Highly reflective to incoming insolation, clouds might be expected to behave rather like a snow or ice-covered surface, and so greater evaporation in a warmed world leading to more clouds might be expected to increase the planetary albedo and slow cooling - a negative feedback effect. However, additional water vapour amounts might also be expected to absorb more terrestrial radiation, enhancing warming - a positive feedback consequence. It is also important to realise that changes in cloudiness may not necessarily be the same as changes in cloud cover. More stratiform clouds may mean greater cloud cover than more cumuliform clouds, an important consideration for deciding the direction of the overall feedback effect.

To date GCMs have been conspicuously unsuccessful in handling cloud formation, especially in terms of height. Clouds occur at scales below the resolution of all the current generation of models and cannot be easily

Prediction: 1990-2030 CO_2 doubling · 2°C ↑ · ↑ winter rain · ↑ summer ↓ Rain

incorporated other than as parameterised variables.

Feedbacks in Combination

Since several feedbacks are apparent, some positive, some negative, there is a need to determine their additive effect. If this is achieved it will determine how sensitive the climate system is to CO_2 forcing.

One way of addressing this 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, ΔQ, across the tropopause ?' To answer this the following expression can be considered (Henderson-Sellers and McGuffie, 1987):

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

where: C is the system heat capacity,

and: $\lambda\Delta T$ is the net radiative change at the tropopause resulting from the internal characteristics of the climate system; 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:

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

Some of these quantities have been established. For doubling of CO_2, it is known that $\Delta Q = 4.0\ \mathrm{W\,m^{-2}}$, 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:

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

Current 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 calculated. 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. This range of results clearly implies that cloud feedbacks must be better understood before GCM results may be accepted with confidence.

Response times

Some components of climate adjust themselves very quickly in response to a given perturbation. For the lower atmosphere, equilibration may occur in a few days, while for the deep oceans and ice sheets several centuries may be required. This poses problems for the modeller since the oceans act both to remove CO_2 from the atmosphere and also to absorb and redistribute heat throughout their great volume. Indeed the upper three metres of the ocean store as much heat as the entire atmosphere, making the oceans an essential part of any climate model. Early GCMs treated the oceans simplistically and it is only recently that coupled ocean-atmosphere models have had any success in meshing these two vastly different systems.

Model Estimates for Irish Climate

As models have improved, their estimates of total global temperature change consequent on effective CO_2 doubling have reduced and greater consistency between the major products has become apparent (Figure 1). This is partly a consequence of the models' ability to handle new negative feedback influences, such as the effects of stratospheric ozone depletion and of greater plant growth and carbon storage. These have been incorporated into the latest generation as has the role of other anthropogenic influences such as increased sulphate aerosols from the industrialising countries of the Third World. The net effect is to diminish the magnitude of warming suggested by earlier generations. Thus, while global warming of 4°C by mid century was widely 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 (Leggett *et al.*, 1992).

For areas in the vicinity of Ireland, there is broad agreement among the major models that a similar range of figures to the global values may be appropriate. However, the coarseness of the typical GCM grid size does not provide adequate resolution for policy makers. An approach which has helped rectify this deficiency has been to use the output from a particular set of grid cells to drive a second spatially-detailed regional model. This nested regional model approach is still in its infancy but it does appear to offer promise in providing regionally detailed output (Figure 2).

It can be suggested that 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 major 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 this value exceeds 500m (Rowntree, 1990). Thus, even if the European continent warms up as it did in the Holocene post glacial optimum, the existence of a cool sea surface around Ireland will inhibit warming in summer, just as it did in the post-glacial optimum climates of 6000 B.P.. During winter, since isotherms run north-south across Ireland, a

Figure 1: Surface temperature change consequent on doubling effective CO_2 as shown by four coupled ocean-atmosphere transient general circulation models

(a) Geophysical Fluid Dynamics Laboratory, Princeton
(b) Max-Planck Institute, Hamburg
(c) National Centre for Atmospheric Research, Boulder
(d) United Kingdom Meteorological Office, Bracknell

(after Gates *et al.*, 1992)

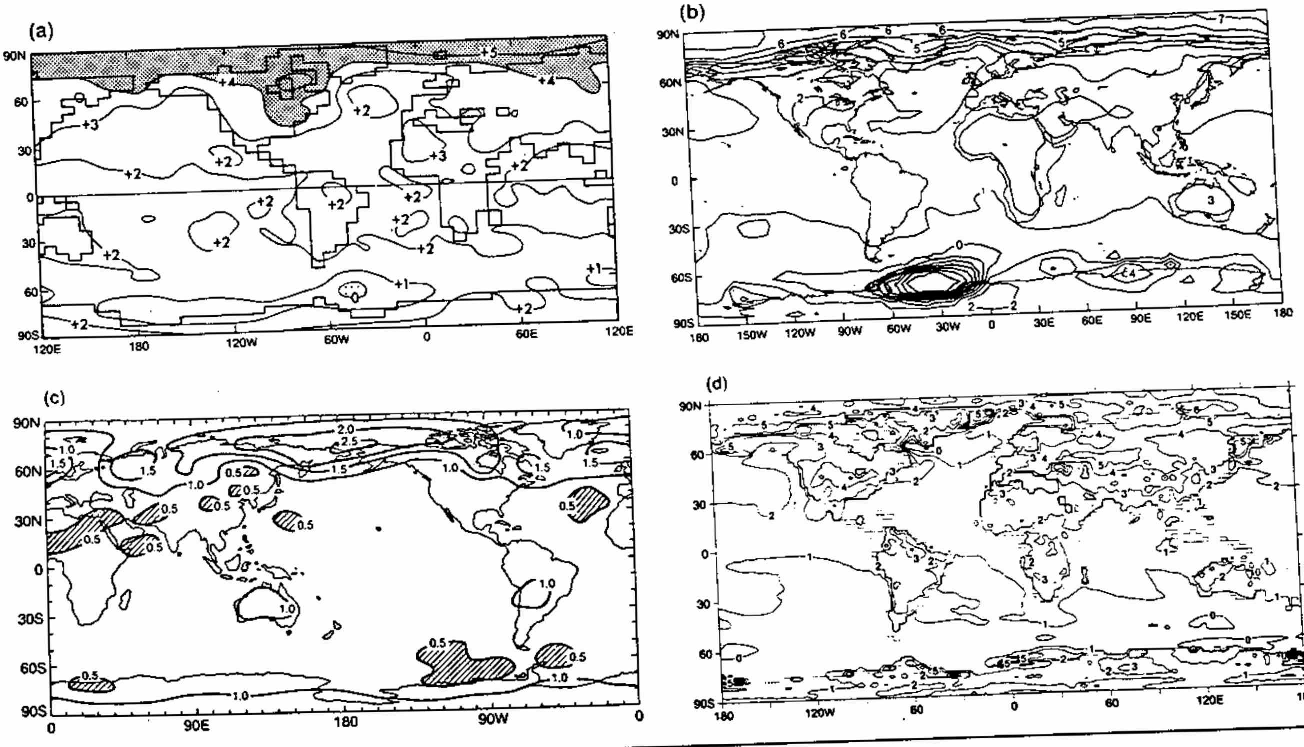
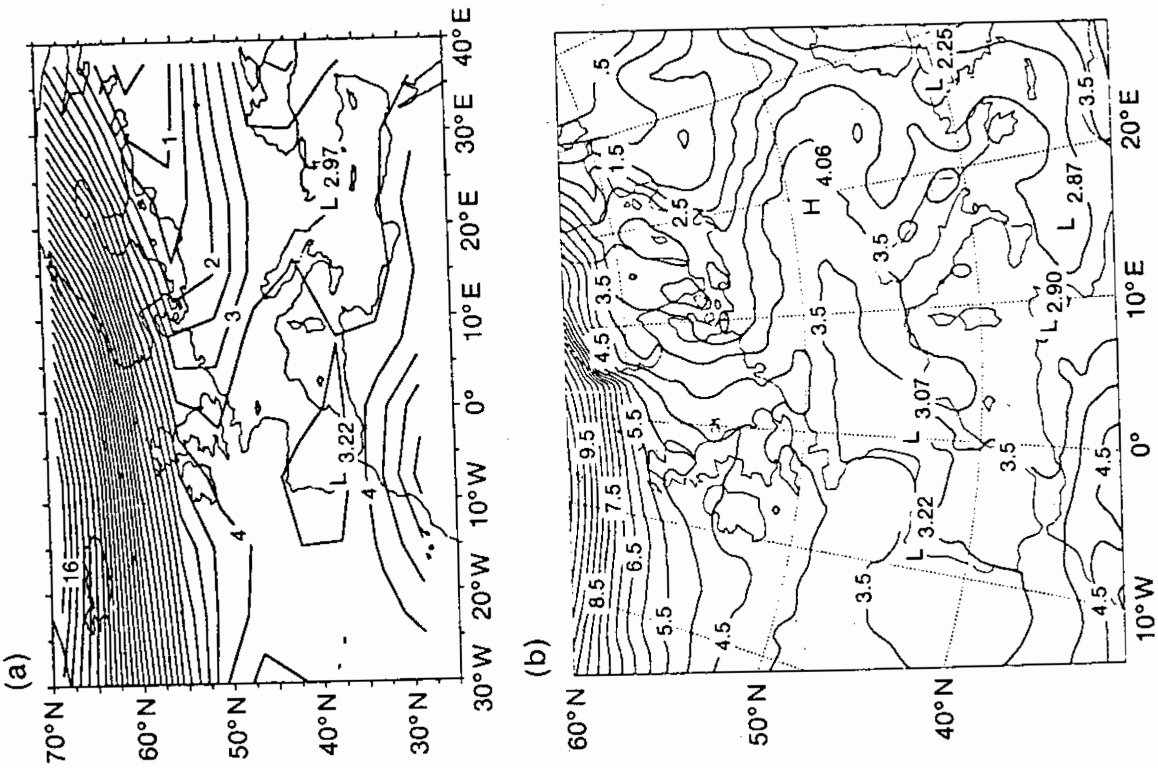


Figure 2: Increase in January temperatures in Europe as a result of effective doubling of CO_2

(a) National Centre for Atmospheric Research General Circulation Model
(b) Nested Mesoscale Model

(after Gates *et al*., 1992)



poleward shift in winter isotherms will have less effect than further east in Europe. Some support for these suggestions can be found in the latest generation of transient GCMs which incorporate deep ocean mixing (Stouffer *et al.*, 1989; Washington and Meehl, 1989). They are also supported by the work of Karoly (1987) who in a study of actual temperatures at the 700mb level between 1960-80, showed that warming was apparent 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 primarily by changes in circulation frequencies.

② Predictions of changes in precipitation are much less consistent than temperature and tend to be founded on the atmosphere's capacity to hold approximately 7% more water vapour per 1°C rise in temperature. Since the high middle latitudes warm most, the highest increases in precipitation are suggested as occurring here, particularly in winter (Figure 3). However, the models are not consistent in identifying the precise areas where precipitation changes may occur and locations such as Ireland tend to show contradictory signals in different models. This is especially the case in summer. This is unfortunate since summer precipitation is of critical importance for Irish water resource management in areas ranging from agriculture to effluent dilution. Indeed, even in the absence of precipitation changes, significant increases in evapotranspiration will occur from additional warmth (Lockwood, 1993). In Ireland such increases, if accompanied by even modest reductions in summer precipitation, will lengthen considerably the periods of soil moisture deficit with potentially very significant impacts on crop yields possible on occasion. Figure 4 shows the effects on moisture balances of a simulated 3°C rise in summer temperature accompanied by a 5% reduction in summer precipitation on typical inland and coastal locations in Ireland. (Evapotranspiration estimates were estimated only for the summer months using the approximation method of Crowe (1971))

Evidently, while some confidence may be possible that a doubled CO_2 climate in Ireland will be accompanied by winter and summer temperatures approximately 2°C warmer, little confidence exists in projected precipitation estimates for Ireland at present. In particular the important issue of summer precipitation changes cannot be addressed satisfactorily by the models as yet, and so an alternative approach is necessary. One such strategy involves an analogue climate approach.

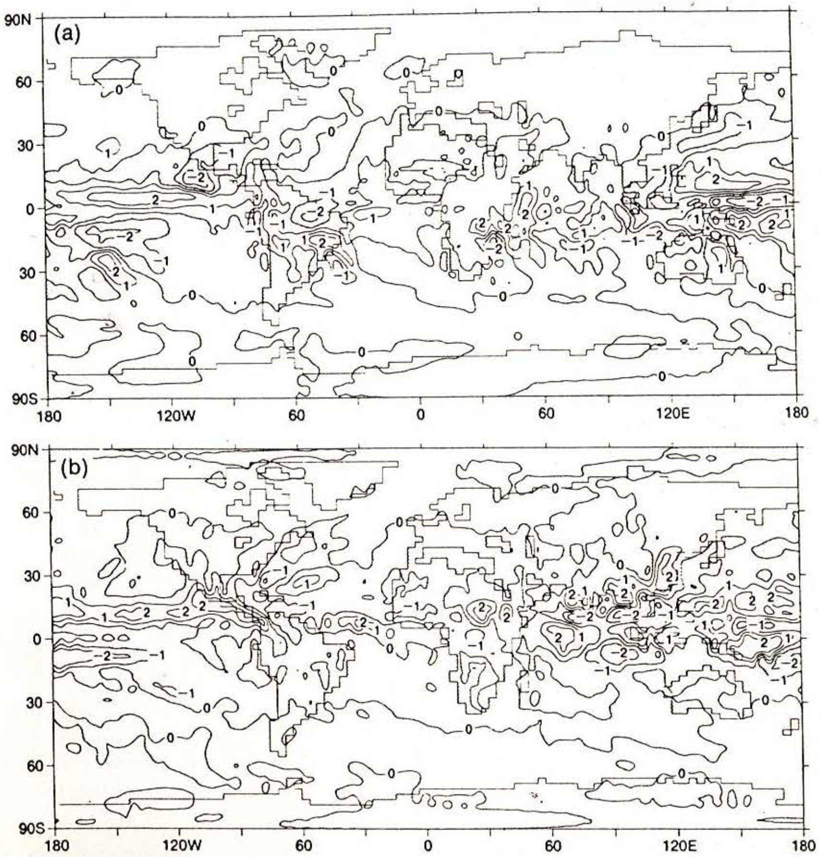
Projecting Future Irish Summer Rainfall using a Synoptic Circulation approach

Short term future climate change in Ireland will be determined principally by changes in circulation frequency. Indeed significant changes in frequency have

Figure 3: Changes in precipitation consequent on doubling of effective CO_2 as modeled by the UK Meteorological Office model

(a) December, January, February (b) June, July, August

(after Gates *et al.*, 1992)



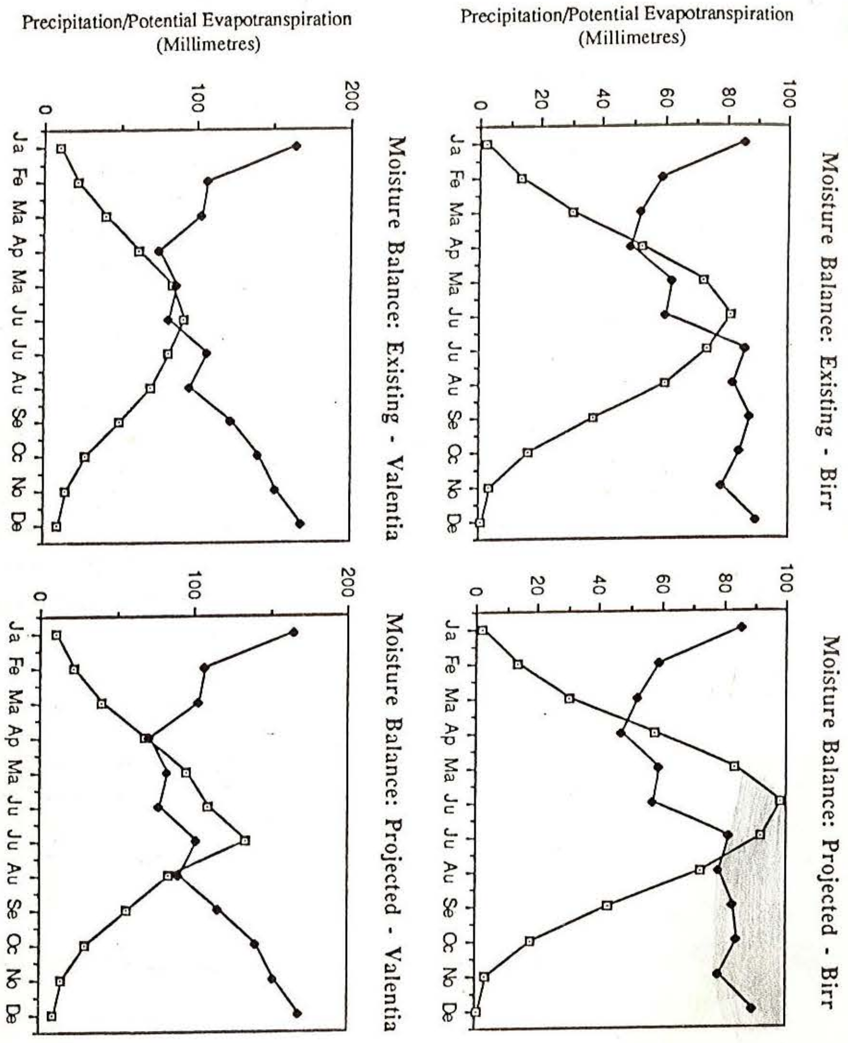


Figure 4: Present and projected soil moisture balances for Birr and Valentia

already occurred (Briffa *et al.*, 1990) and have been implicated in changes in rainfall geography within Ireland (Sweeney, 1985). If present relationships between circulation types and rainfall geography can be established, it may thus be possible to simulate precipitation patterns for hypothetical scenarios of circulation which may accompany greenhouse-led climate change. ✱

The first requirement is to achieve some form of categorisation of synoptic circulation type for airflows affecting Ireland. The best known such classification was derived by Lamb (1950, 1972) who identified seven primary circulation types: anticyclonic, cyclonic, north-westerly, westerly, northerly, easterly, and southerly. Subsequently he added a further nineteen secondary categories (together with an unclassified category) incorporating more complex circulation types into a daily catalogue extending from 1861 and still updated by the author daily. 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, 1992). ✱

Using daily rainfall data from 34 stations in Ireland for approximately a 40 year period, mean rainfall yields were calculated seasonally and annually for each of the Lamb circulation categories. This revealed significant spatial contrasts in rainfall receipt with different circulation types (Sweeney, 1985). For example an anticyclonic northerly airflow produces on average less than 0.5mm of daily rainfall across Ireland while a cyclonic southerly yields approximately 5mm. Similar spatial contrasts are also apparent across Ireland, however, even for the same circulation type (Figure 5).

wind/rain

Present Circulation-Precipitation Relationships

Anticyclonic ①

This airflow produces little precipitation anywhere in Ireland, as might be expected with stable, subsiding air. Amounts received are generally below 1.0mm. The south-westerly flow of air on the western flank of anticyclones may allow some fronts to skirt western Ireland and slightly higher amounts are in evidence here.

Cyclonic ②

More than any other circulation type, cyclonic airflow promotes an even distribution of rainfall across Ireland, with only slight reductions away from coastal locations apparent as the oceanic water vapour supply is presumably reduced. Clearly, should an increase in cyclonic airflow frequency increase consequent on global warming, the characteristic west-east contrast in annual rainfall receipt in Ireland would be expected to diminish.

Westerly ③

A marked spatial contrast between west and easterly locations is apparent

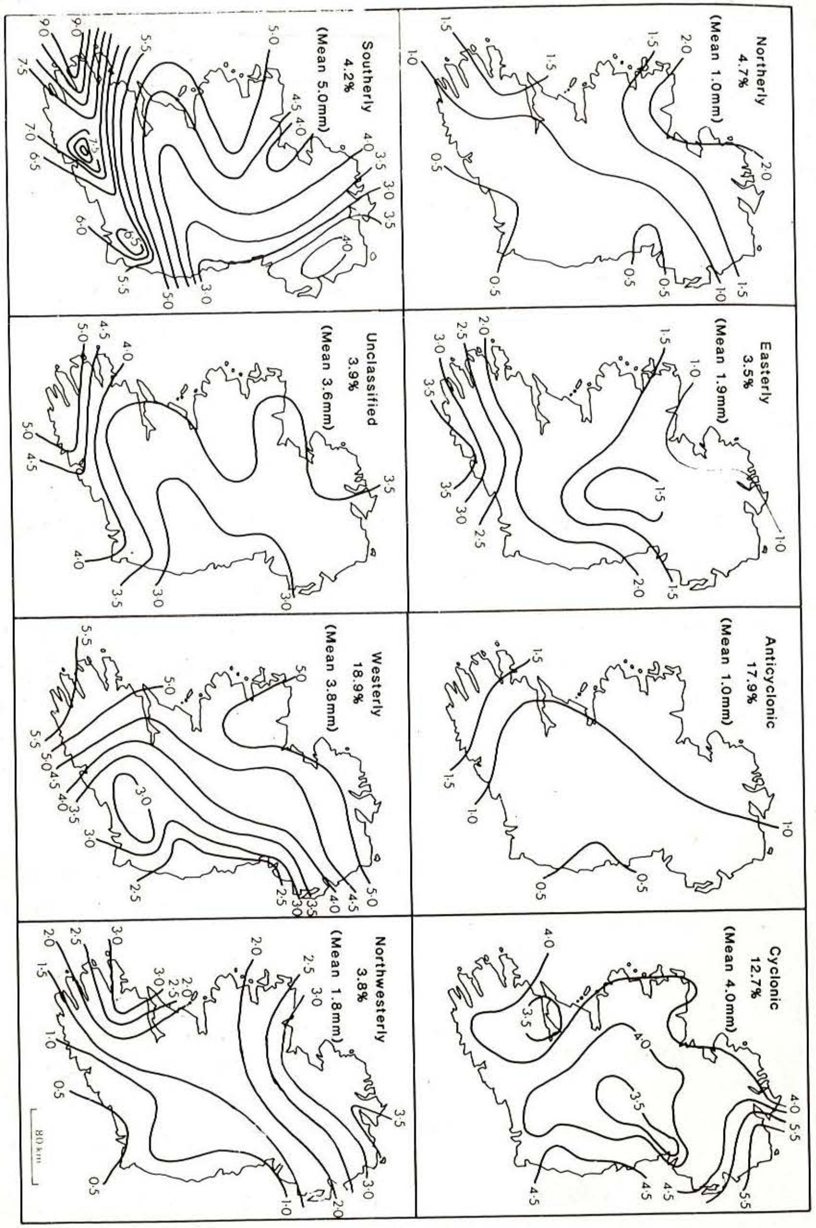


Figure 5: Precipitation yields in Ireland with principal Lamb synoptic circulation categories

with this airflow which, because of its frequency (18.9%) is therefore responsible for the west-east gradient in the annual rainfall distribution. Parts of Connaught receive three times as much rain with this airflow than sheltered parts of the Leinster coast. Pronounced rain shadow areas are also apparent downwind of the mountain ranges. It can be concluded that the effects of a decline in the westerly circulation, something which has already been occurring for several decades, would again diminish west-east rainfall contrasts. Such a scenario is of course likely as the equator-pole thermal gradient reduces with global warming.

North-westerly ④

Ridging, behind a depression or by extension of the Azores anticyclone, produces falls of over 3.00mm in the north-west and on exposed coasts in Munster. Elsewhere this is quite a dry airflow, especially along the south coast where it is the driest airflow experienced.

Northerly ⑤

With high pressure to the west of Ireland, a northerly airflow occurs at present about 4.7% of the time. Northern coasts in Ulster and Connaught receive most precipitation with significant rain shadow areas to the south of the Mournes and Wicklows.

Easterly ⑥

The longest sea passages for easterly air occur along the Celtic Sea. Depressions passing south of Ireland are mostly involved in producing this airflow which may also be accompanied by westward-moving fronts. Co. Cork and much of the south coast get higher yields from easterlies than they do from westerlies. Rain shadows are distinctive of the west side of mountain ranges.

Southerly ⑦

Maritime tropical airmasses arrive in Ireland heavily laden with moisture and it is therefore not surprising that southerly circulation types are the wettest airflows to affect Ireland. As air cools passing northwards over the North Atlantic Drift, stratiform cloud is produced and this readily yields copious rainfall when lifting over the mountains of southern Ireland occurs. With any warming of the Atlantic, southerly airflows would become more capable of carrying water vapour, and increases in rainfall especially in southern areas would be likely.

Circulation-Precipitation Relationships for Greenhouse-Effect Summers in Ireland

Changes in circulation frequency, and thus in precipitation, can be expected to occur in Ireland as greenhouse-led warming proceeds. Such changes will dominate the climatic response for the next few decades (Rowntree, 1990). In order to anticipate what impacts are likely on rainfall receipt during summer, one approach would be to examine what mix of circulation types was associated with warm summers in the past. To address this question, the long instrumental record developed by Manley (1974), and since then continuously updated, was utilised. Though symptomatic primarily of temperature conditions in central England, Manley's record is generally held to be fairly representative of general temperature conditions over Britain and Ireland extending back to the mid 17th century, and is the longest instrumentally observed record of temperature available globally. A long record is essential to avoid the distortions which anomalous blocking might produce in a shorter data run.

Summers exhibiting positive temperature departures of +1 (warm) and +2 (hot) standard deviations from the mean were extracted from the Central England Temperature record (Table 1). The average temperature of the latter corresponded to additional summer warmth of 1.7°C, close to the likely warming predicted for Ireland by GCMs within the next forty years. The frequency of circulation types during those years of the Lamb record which met this criteria are shown in Table 2.

Table 1: Warm and hot summers in the Central England Temperature Series

Warm Summers

(>1δ above mean average June/July/August temperatures 1659-1992)

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

Hot Summers

(>2δ above mean average June/July/August temperatures 1659-1992)

1781,1826,1846,1899,1911,1933,1947,1975,1976,1983

Hot summers in Britain and Ireland are clearly associated with a significant increase in the frequency of anticyclonic circulations and a significant decline in the westerly and cyclonic category. This of course implies blocking and a tendency for the upper westerly circulation to exhibit a more cellular pattern. Such a tendency for increased low zonal index circulations can be expected in

Table 2: Lamb Circulation Frequencies 1880-1992

	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

Note : Warm Summers are defined as greater than 1 std. dev above CET mean 1659-1992.

Hot Summers are defined as greater than 2 std. dev above CET mean 1659-1992.

③ a greenhouse-forced climate as differential warming of the poles more than the equator reduces the equator-pole thermal gradient and diminishes the vigour of the westerly circulation. Declines in the westerly circulation have been occurring over Ireland and Britain for several decades, though short term reversals of this occur from time to time. (Lamb)

The relationship between circulation type and rainfall yield was discussed earlier. This was based on approximately 40 years of rainfall data. During this interval changes in circulation frequency were obviously occurring. However, an examination of decadal breakdowns of the data showed that the average yield did not show significant variations for a particular circulation category over time. Therefore, it is possible to project a hypothetical rainfall climate for each station using the 'hot summer' circulation frequencies. This gives a projection for rainfall receipt by circulation category in a simulated greenhouse-forced climate situation which can be mapped to show regional variations (Figure 6).

Reductions in summer rainfall of in excess of 15% are indicated for Ireland with the largest diminution occurring in the north and east. Belfast, for example, shows a reduction in summer rainfall receipt of approximately 20% using this approach. Along the south coast, by contrast, little change is apparent primarily due to the ability of warm, moist southerly circulations to compensate for the effects of reductions in westerly and cyclonic rainfall contributions.

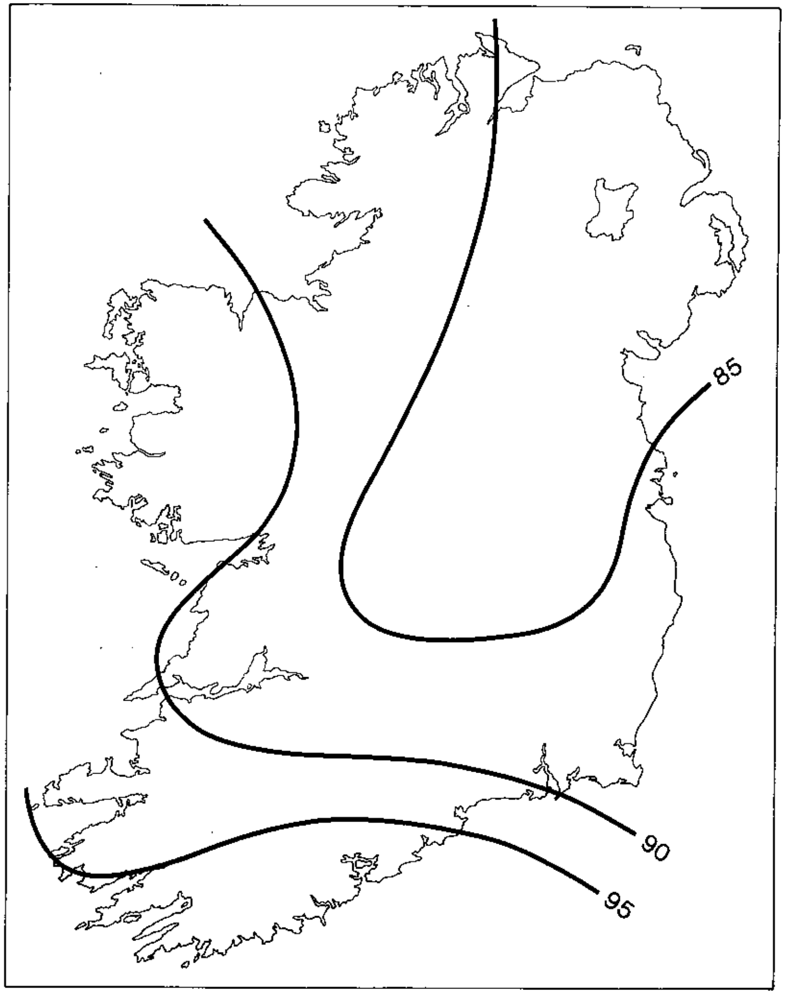
Increases in summer evapotranspiration of approximately 8% will accompany greenhouse-led temperature changes. Should rainfall reductions occur these are likely to be even more important considerations for water resource management, and Figure 6 thus shows where public water supply, agricultural water management planning, and effluent disposal, concerns might be concentrated.

Some decreases in summer rainfall have in fact occurred in Ireland over the past two decades, though some reversal of this trend occurred in northern and western areas during the 1980s. In Britain, eastern and southern parts also experienced the greatest reductions, and Mayes (1991) has suggested that these are associated with changes in anticyclonic and westerly circulation frequencies. Such changes provide some observational support for the scenario indicated here for Ireland which diverges from the predictions of most GCMs concerning summer precipitation changes.

Conclusion

Greenhouse-led climate change is likely to be detected later in Ireland than in much of the remainder of the northern hemisphere due to the sluggish

Figure 6: Projected summer precipitation in Ireland as % of present as a result of 2°C warming



slow

response of the Atlantic Ocean. Winter temperatures can be expected to rise more slowly and less than their summer counterparts and to be accompanied by modest increases in precipitation. Summer precipitation changes are less clear and contradictory evidence is provided by general circulation models at present. On the basis of analogues during the past century, circulation changes would appear to imply that a modest reduction will occur, mostly in eastern and northern areas. Coupled with changes in evapotranspiration this poses potential problems for some aspects of water resource management. The climatic scenario outlined for 2040 in Table 3 suggests a warming in both summer and winter slightly less than that suggested from averaging of five GCM results for north-western Europe by Warrick and Barlow (1991). It does however show many similarities with the working assumptions used by the only national study commissioned on this question to date (McWilliams, 1992), though divergence on the question of summer rainfall changes is apparent. Deciding policy options on the basis of one approach to future climate projection, namely GCM output, may however be risky, and while regional detail may ultimately improve on these approaches, alternatives such as the analogue type approach detailed here should also be used to provide a form of 'ground truth' at the scale of Ireland for climatic simulations which originate from global scale simulations.

Table 3: A Climate Scenario for Ireland for c. 2040

	Temperature	Precipitation
AVERAGE ANNUAL	+2.0°C	Little change
AVERAGE WINTER	+1.5°C	5-10% increase
AVERAGE SUMMER	+2.5°C	5-15% decrease

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