NRA South West 2

GREENHOUSE EFFECT

Current knowledge and implications for South West England

Report prepared for the NRA (Exeter)
by Palaeoenvironment Research,
Department of Geography, University of Exeter.
Submitted February 1991

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GREENHOUSE EFFECT: CURRENT KNOWLEDGE AND IMPLICATIONS FOR SOUTH WEST ENGLAND

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1. Greenhouse Effect: Definition, History and Recent Developments

1.1 Definition

1.1.1 The Greenhouse Effect is something of a misnomer in that the natural global effect is not directly equivalent to the workings of a greenhouse. Nevertheless the term is now widely used and the broad similarity in processes provides a useful model for both understanding and communications.

1.1.2 Heating of the lower part of the earth's atmosphere (the troposhere) is due to the influence of solar radiation. Incoming short-wave solar radiation passes through the atmosphere to reach the earth's surface as the gases of the earth's atmosphere are transparent to such radiation. Long-wave radiation which is emitted from the surface of the earth back into the atmosphere is however absorbed by certain trace gases (the greenhouse gases) causing these gases to warm and reradiate heat, thus retaining much of this heat in the lower atmosphere. The effects of these greenhouse gases is to retain a global mean temperature at present of +15°C; without these gases global mean temperature would be -18°C. This process is also found on other planets, especially Venus and Mars.

1.1.3 The major greenhouse gas is water vapour which accounts for almost two-thirds of this additional heating. Variations in water vapour are not controllable but are strongly linked to other trace gases - CO_2, CH_4 (methane), NO_x (nitrous oxides), O_3 (ozone), CFCs, CO and others which occur only in very small quantities.

1.1.4 Greenhouse gases are but one part of the global climatic system and their effect needs to be evaluated in relation to other major elements such as changes in the input of solar radiation and variations in particulate matter in the atmosphere (aerosols) which can be naturally derived.

1.2 History and recent developments

1.2.1 The original idea of the comparison of the workings of trace gases in the atmosphere to that of air in a closed space beneath glass is credited to Fourier in 1827. The basic idea was then refined and extended by physicists such as Tyndall (1861), Langley (1864) and especially Arrhenius (1895) who estimated a 6°C rise in temperature for a doubling of CO_2. In the twentieth century a variety of estimates of temperature change for CO_2 doubling were made from 1.5°C - 9°C, largely as part of an interest in looking at Ice Age climates.

1.2.2 In the 1960s with the development of increasingly sophisticated models of the earth's atmosphere attention focused on the likely effects of increased greenhouse gases on future climates. By the 1980s the problem was clearly in the public domain with widespread concern over the probability of climatic change. By the mid-1980s there was also increasing concern over the need for international cooperation in both the scientific assessment of the problem and in generating responses and action to control what was recognised to be a global phenomenon.

1.2.3 In terms of international awareness the first major meeting of scientists specifically to examine the CO_2 problem took place in Villach in Austria in 1980 (WCP, 1981). This gave an impetus to scientific research and prompted greater general awareness of the importance of the problem. Other groups concentrated in the early 1980's on clarifying the rates and nature of emissions with some estimate of impacts , in the US there was a Carbon Dioxide Assessment Committee (CDAC, 1983) and a report by the Environmental Protection Agency (Seidel and Keyes, 1983), in the Netherlands a report by the Health Council of the Netherlands (CHCN, 1983), and a similar study in the FRG. Most of the early studies relied on global carbon models developed in the US at the Oak Ridge National Laboratory e.g. Emanuel et al., 1981. An important milestone was the second meeting of scientists in Villach, Austria in 1985 whose findings were published in 1986 (Bolin et al. 1986). Following this the Intergovernmental Panel on Climate Change (IPCC) was set up by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) in 1988. The IPCC set up three Working Groups (I - III) which reported to a meeting in Geneva in 1990. Of the three perhaps the most important was Group I which was set the task of assessing the scientific basis of predictions of future climate change. The findings of this group as presented at Geneva are now published (Houghton et al., 1990). The findings of the other groups concerned with the assessment of environmental and socio-economic impacts (II) and with the formulation of response strategies (III) are not at present published formally, although summaries of material discussed at Geneva have been produced.

1.2.4 The importance of the 1990 IPCC findings should not be underestimated, especially the scientific assessment of the problem. The reasons for this are twofold:

i) The 1990 assessment represents the most wide ranging and up-to-date science available and was produced by the collaboration of scientists from 25 countries, precisely those people who had been working in smaller groups over the previous decades.

ii) The findings of the IPCC are integrated into international and national decision-making structures. Any protocols or recommendations from international, supra-national or national bodies are therefore likely to be based on the IPCC findings.

The next stage in the process of formulating an international strategy will be at a meeting in Rio in June 1992 when an attempt will be made to draw up a Framework Convention as a precursor to the definition and agreement of Specific Protocols designed to limit greenhouse gas emission. The pattern for such a procedure has already been established with the Montreal Protocol on CFC emissions. It is hoped that the Rio meeting will be just as successful but the problems are far wider and more difficult to solve.

1.2.5 At a national level in the UK considerable impetus was given to research and public awareness in the late 1980s as seen in the speech of the Prime Minister to the Royal Society in 1988, the DoE publication 'Possible Impacts of Climate Change on the National Environment in the United Kingdom', also in 1988, using data based on the SCOPE report (Bolin et al, 1986), and. following a 1989 EC Environment Ministers' resolution publication of 'Global Climate Change' by the DoE to inform public opinion. Further national commitment has been seen by DoE funding of the Hadley Centre for Climate Prediction and Research at the Meteorological Office which produced its first report in 1990. The wider impacts of climate change have also been examined nationally by various research bodies e. g. Impact of climatic change on freshwater ecosystems by D.G.George, FBA, in 1988; Climatic change, rising sea level and the British coast, Institute of Terrestrial Ecology Research Publication No. 1 in 1989; The greenhouse effect and terrestrial ecosystems of the UK, ITE research publication No. 4, in 1990. Following the

IPCC findings, the United Kingdom Climate Change Impacts Research Group has already produced a report for the DOE, published in January 1991, which is an update of the 1988 report. This is entitled 'The Potential Effects of Climate Change in the United Kingdom' and the chairman of the committee is Prof. Martin Parry of Birmingham University, a member of the IPCC Working Group II.

1.2.6 At the outset it should be recognised that although there is a good degree of agreement amongst scientists about the likely realisation of some degree of global warming, this is not uniform and there is still a lot of scepticism, both within and on the margins of science. A long standing critic of much of the predictive work has been Idso (1989) and many of his reservations, notably concerning the scientific basis of the modelling that has been used, have reached a wide audience as shown in the recent comments of the science editor of The Times following the publication of the IPCC Report - 'Global warming has turned into an inverted pyramid of implications resting on a handful of facts.....(with) a dash towards international action doubts have been forgotten, caveats ignored, and a scientific theory given the status of an ideology'.

2. Greenhouse Gas Emissions - Predicted Changes and Their Role in The Climatic System

2.1 Introduction

2.1.1 The effectiveness of greenhouse gases in regulating the climatic system varies depending upon the rate of change in emissions and their roles in the climatic system. The main greenhouses gases which are considered to be of concern are: CO_2, CH_4 (Methane), CFCs (usually grouped under CFC-11 and CFC-12), O_3 and N_2O (often grouped generally as NO_x) (see Table 1). Each of these trace gases or groups of trace gases affect climate in different ways but their effect is generally estimated in terms of radiative forcing.

2.1.2 Radiative forcing can be defined as the amount by which any gas, or combination of gases, perturbs the radiative balance of the earth, that balance between incoming shortwave solar radiation and outgoing terrestrial longwave radiation. Measurement is expressed as Wm^{-2}; the change in radiative flux (δF) dependent upon changes in concentration can be quite simply estimated with linear relationships for low concentration trace gases, square root relationships for moderate concentrations and logarithmic relationships for high concentrations. The term Global Warming Potential (GPW) is also used to express a similar effect. This is calculated for individual greenhouse gases and is an expression of their radiative forcing potential relative to that of CO_2 i.e. the calculation is based on an emission of a similar amount of the trace gas to that of CO_2, usually 1 kg.

2.1.3 Of particular importance to the effectiveness of individual greenhouse gases are: the absorption strength and the wavelength of this absorption, lifetime in the atmosphere (defined as the ratio of atmospheric content to the total rate of removal), concentration levels and their potential for 'knock-on' effects of producing other greenhouses gases in the atmosphere by chemical reactions. It should be noted that radiative forcing is usually calculated for the troposphere with the measure relating to the effectiveness at the tropopause, the 'lid' of the atmosphere. For some gases, notably O_3, there are important effects in both the troposphere and the stratosphere.

2.2 CO_2

2.2.1 The 'natural' cycle of CO_2 takes place between a number of major stores, in particular the atmosphere, the biotic system and the oceans. CO_2 is well mixed in the atmosphere with a turnover time of about 4 years. However, adjustment of the balance of CO_2 between the major stores is strongly influenced by the ocean and the slow take up of excess CO_2 by the oceans and its subsequent transfer within the ocean system extends the lifetime of CO_2 to between 50-200 years (Table 1).

2.2.2 CO_2 is considered to be the main greenhouse gas (except for water vapour) because it has the greatest effect on radiative forcing. Increases since the industrial revolution have been estimated to account for 61% of total radiative forcing, although in the 1980s this showed a reduction to 56%, largely due to the increasing effects of other gases. CO_2 has no important chemical reactions in the troposphere but can influence atmospheric ozone concentrations and partially affect ozone depletion.

Table 1. Summary Of Key Greenhouse Gases

	CO_2 (ppmv)	CH_4 (ppmv)	CFC-11 (pptv)	CFC-12 (pptv)	N_2O (ppbv)
Pre-industrial level 1750-1800	280	0.8	0	0	288
1990	353	1.72	280	484	310
Current annual rate of atmospheric accumulation	1.8	0.015	9.5	17	0.8
'Atmospheric lifetime' (years)	50-200	10	65	130	150

2.2.3 Radiative forcing due to CO2 is considered to be adequately modelled by the linear expression:

$$\delta F = 6.3 \ln (C/C_o) \quad \text{where } C = CO_2 \text{ in ppmv for } C < 1000 \text{ ppmv}$$

2.2.4 The flux of CO_2 between the atmosphere and the surface of the oceans (the upper 1km.) is determined by water motion and what is known as the 'biological pump' of the ocean biota. The rate of influx can be measured but only with a considerable error. Because transfer of CO_2 to depth in the oceans, mianly in the form of deepwater formation (DWF) or organic detritus, takes between 100-1000 years, most anthropogenic CO_2 is still locked up in the upper ocean circulation.

2.2.5 Modelling of the uptake of CO_2 by the oceans and the atmosphere compared to observed rates of emissions shows a considerable imbalance at present which cannot be explained, with a possible 'missing sink' for CO_2, thought likely to be within the ocean system (Fig.1). Other likely sources are land based, such as enhanced biotic uptake but these cannot be adequately measured at present.

Fig. 1 Estimates of Emissions and Uptake of CO_2 for 1980-89

		GtC / year
Emissions	Emissions from fossil fuels	5.4 ± 0.5
	Emissions from deforestation / land use	1.6 ± 1.0
Accumulation Uptake	Atmospheric accumulation	3.4 ± 0.2
	Ocean uptake	2.0 ± 0.8
	Net imbalance	1.6 ± 1.4

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	Net imbalance	1.6 ± 1.4

2.2.6 Within terrestrial ecosystems CO_2 is an essential component of photosynthesis and respiration and its cycling can be affected by non-climatic effects, especially land use changes such as vegetation removal.

2.2.7 Over long timescales studies on the concentration of CO_2 in polar ice cores have shown a broad positive correlation between temperature and CO_2 concentration (Fig.2). More recently ocean sediments have also been used to confirm the concentrations estimated from the ice data and push the record further back into recent geological time (Jasper and Hayes, 1990). In the Eemian interglacial (ca. 120 kyr B.P. [Before Present]) atmospheric concentrations were around 300 ppmv, whereas in the glacial maximum at ca. 18kyr B.P. this dropped as low as 180 - 200 ppmv. By the 18th century A.D. (pre-industrial period) concentrations had returned to 280 ppmv. With the burning of fossil fuels concentrations have now reached 353 ppmv, and observations have now been made annually since 1958 to trace the continuing rise (Fig.3). It is possible that any economic recession consequent upon the Gulf War could lead to some reduction in atmospheric concentrations but this is unlikely to have any more noticeable effect than previous slight reductions, as happened for instance with the oil crisis of the early 1970s. 95% of CO_2 emissions derive from the northern hemisphere where the rate of increase has gradually slowed (from 3% p.a. 1945-1972, to 1% p.a. 1973-1989) but in developing countries the rate of increase is now 6% p.a.

Fig.2 Evidence from Antarctica for Trace Gas Concentrations Over the Last 160,000 years (after Houghton et al, 1990)

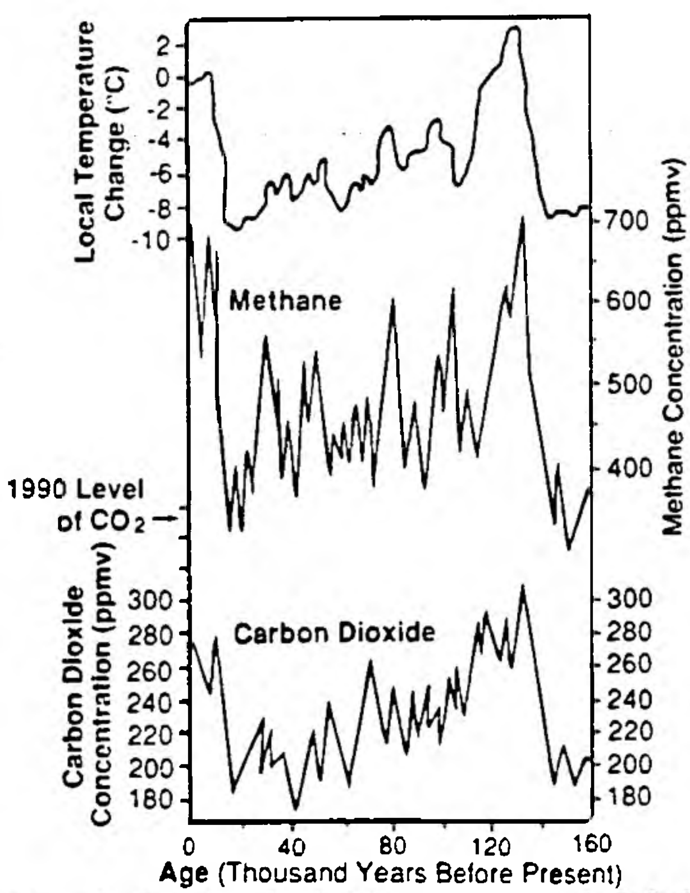
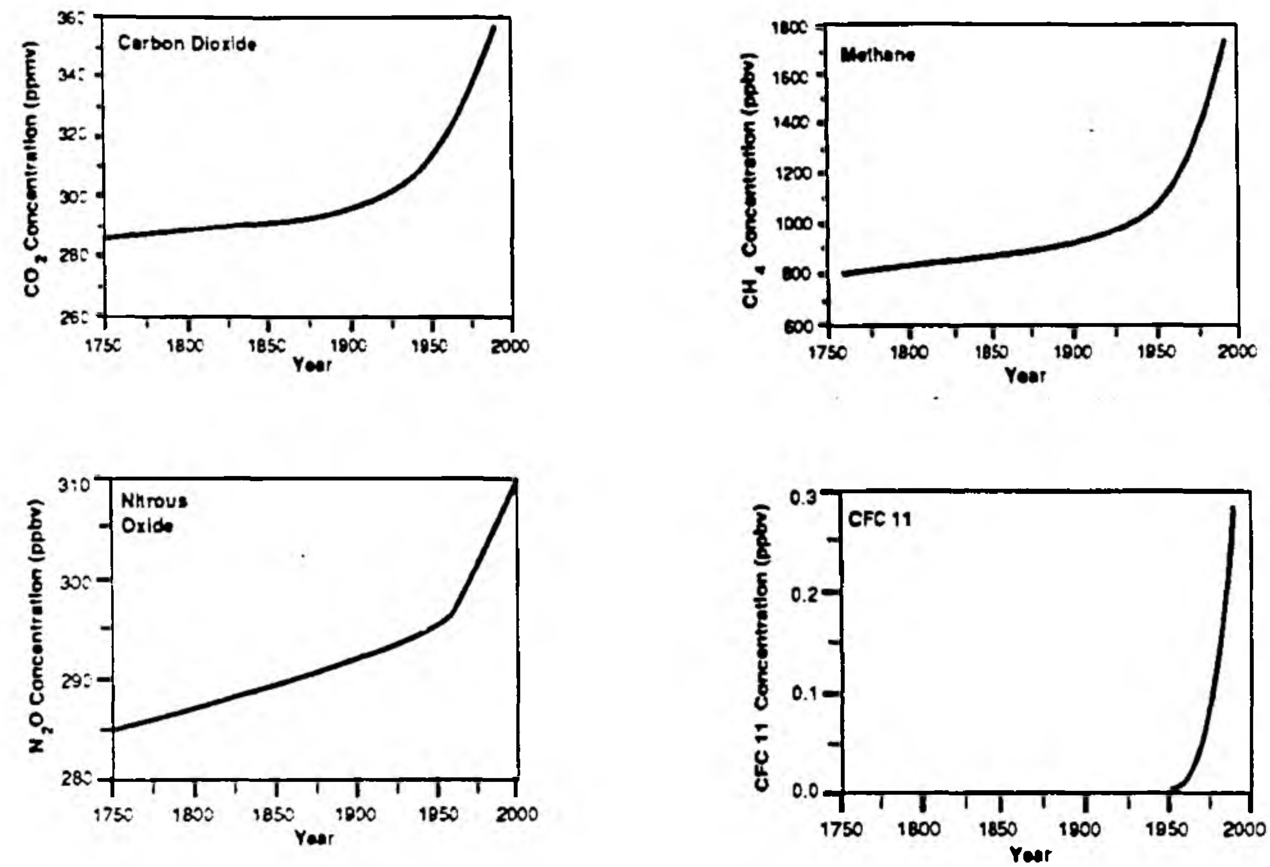


Fig 3 Concentrations of the Main Greenhouse Gases frompre-industrial times to the Present (Houghton et al, 1990).



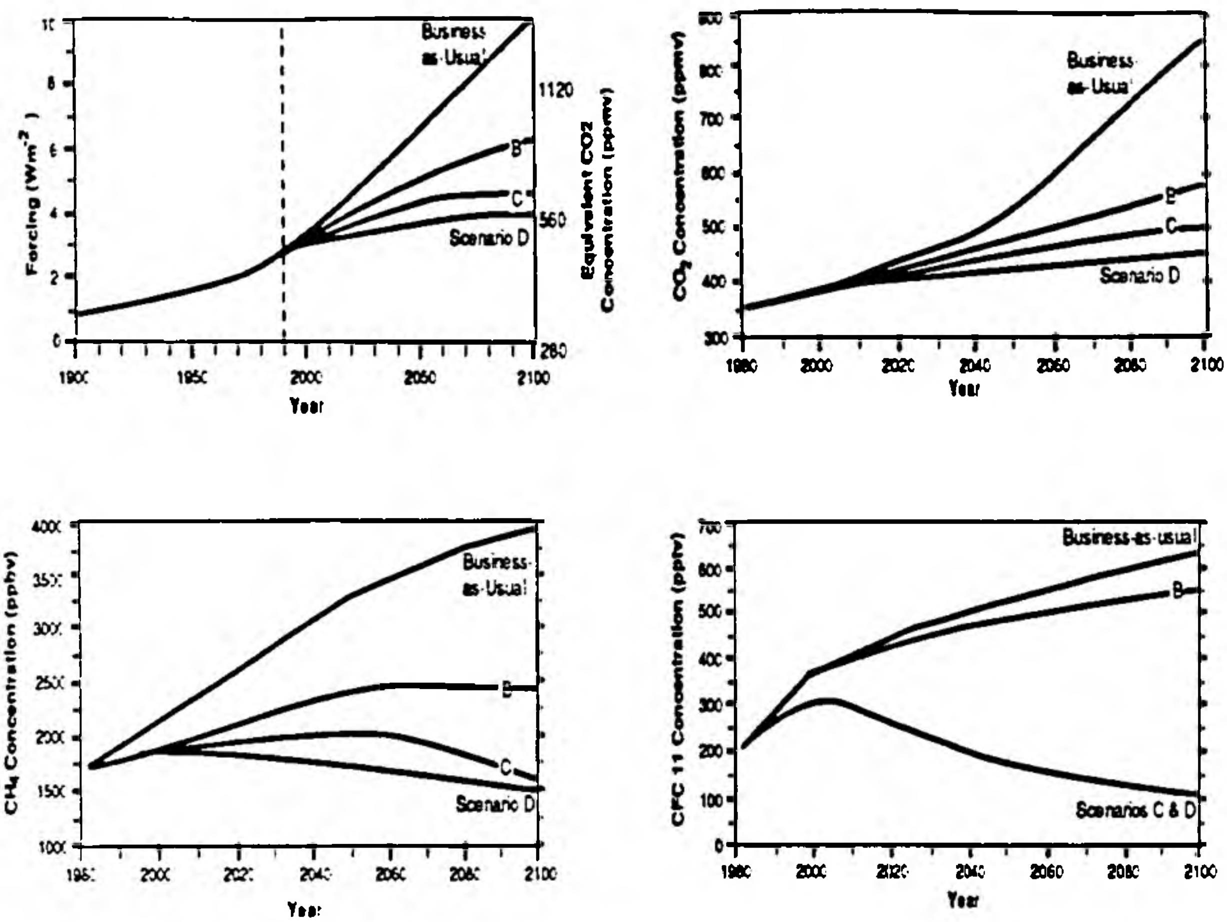
2.2.8 Even if CO_2 emissions stopped now atmospheric concentrations would still rise to 331 ppmv by 2050 and only reduce to 324 ppmv by 2100. A constant growth of CO_2 at a global figure of 2% p.a. would give concentrations of 575 ppmv by 2050, and 1330 ppmv by 2100.

2.2.9 Estimates of CO_2 concentrations by 2100 based on the four scenarios adopted by the IPCC (ranging from the worst Business-as-Usual scenario (BaU) to the best scenario, D - see Appendix A) are: BaU 800 - 850 ppmv; B 500 - 520 ppmv; C 500 ppmv; D 440 - 450 ppmv. This would give a range of radiative forcing estimates of between 10 WM^{-2} and 4 Wm^{-2} (Fig.4 and Fig.5).

2.2.10 Cycling of CO_2 in the future will be affected by a number of feedback processes which may be more or less enhanced by increased CO_2, but many of these processes are still poorly understood. Although they could be both positive (e.g. increased ocean water temperatures could mean less CO_2 uptake, ocean circulation changes would affect uptake) and negative (increased biotic productivity taking up more CO_2), the balance of these changes is considered more likely to lead to positive rather than negative feedback influences.

2.2.11 Even if fossil fuel burning was significantly reduced there is uncertainty as to whether this would reduce the potential warming. On combustion SO_2 is also released and these are a major source of aerosols in the atmosphere. Aerosols act to form nuclei for condensation and also act to reduce incoming radiation. SO_2 aerosols are an important emission from volcanic eruptions and their influence in the stratosphere has been argued as a cause of reduced temperatures, perhaps leading to significantly cooler climate, as in the 'Little Ice Age'. With a reduction in anthropogenic SO_2 aerosols this would make CO_2, even if reduced, more effective and could actually enhance warming (Hansen and Lacis, 1990).

Fig.4 IPCC Scenarios, greenhouse gas emissions and radiative forcing (Houghton et al 1990).



2.3 CH_4 (Methane)

2.3.1 CH_4 is produced by a wide variety of anaerobic processes and is a very active greenhouse gas both in direct terms of radiative absorption and indirectly through the creation of water vapour, particularly in the stratosphere. In the atmosphere the oxidation of CH_4 and CO leads to the creation of excess CO_2. The atmospheric lifetime of CH_4 is between 8 - 11.8 years and a figure of 10±2 years is normally adopted (Table 1). This figure may however be increasing as CH_4 is mainly removed from the atmosphere by reaction with OH, which has been decreasing in atmospheric concentration.

2.3.2 For the period 1965-90 CH_4 contributed 17% directly and 6% indirectly to radiative forcing, 11% and 4% respectively between 1980-1990 (Fig.5). Its contribution to the change in forcing is estimated from:

$$\delta F = 0.036 (\sqrt{M} - \sqrt{M_0}) - (f(M,N) - f(M_0,N_0))$$

where $M = CH_4$ in ppbv
$N = N_2O$ in ppbv
Valid for $M < 5$ ppmv

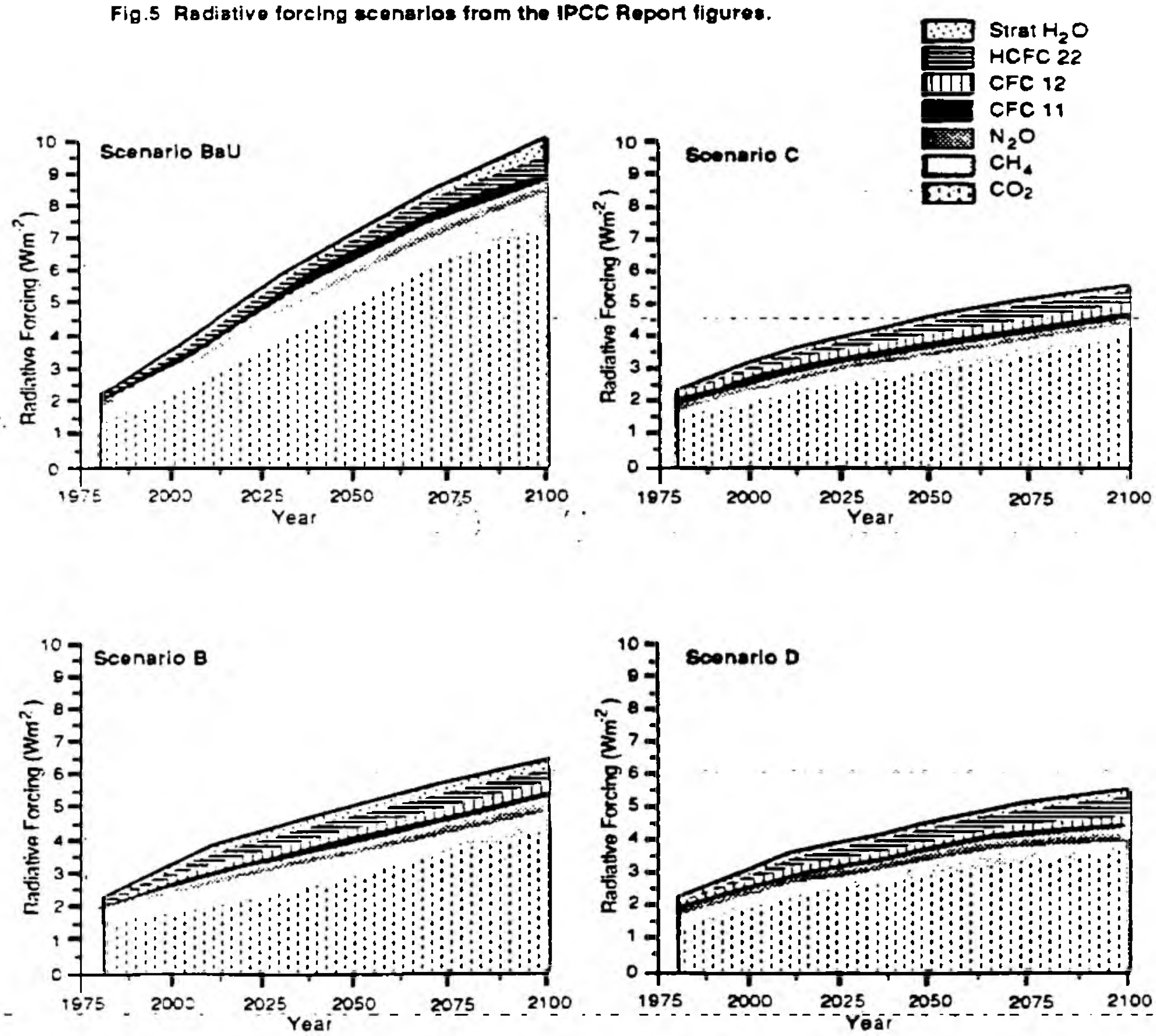
2.3.3 The main sources of CH_4 at present are from natural wetlands, rice paddies, animals and the burning of biomass, as well as from mining and gas drilling. Removal of CH_4 is almost totally through the atmospheric reaction with OH, with only a minor component in the form of removal by soils.

2.3.4 Ice core evidence suggests that pre-industrial levels were about 0.8 ppmv. Current figures are 1.72 ppmv increasing globally by 0.9%p.a., with higher atmospheric values in the northern hemisphere as this is where the major sources lie. As with CO_2 there is a close link between levels of CH_4 and temperature, with high values (0.65) in the previous interglacial and low values (0.35) during the last glacial maximum (Fig.2).

2.3.5 Estimates of future CH_4 levels by 2100 based on the four scenarios are: BaU 4 ppmv; B 2.4 ppmv; C 1.6 ppmv; and D 1.5 ppmv (Fig.4). Stabilisation of levels at present would require an immediate reduction by 15-20% or more.

2.3.6 Future emissions and atmospheric concentrations of CH_4 will be strongly influenced by human activity, both directly by changing agriculture and land use policies and indirectly through a possible change in the area of tundra as a consequence of warming. In general because of the close link to ecosystem processes, the influence of changing temperature could be noticeable over almost all vegetation types.

Fig.5 Radiative forcing scenarios from the IPCC Report figures.



2.4 CFCs (Halocarbons)

2.4.1 CFCs or halocarbons can be broadly separated into fully halogenated halocarbons which are entirely industrial in origin (especially from propellants and refrigerants) and non-fully halogenated halocarbons which have a hydrogen atom and which, although again mainly industrial, include the naturally occurring CH_3Cl (Methyl Chloride). There is no natural removal process for fully halogenated halocarbons hence they have long atmospheric lifetime; of the major CFCs 11 has a lifetime of 65 years, 12 - 130 yrs, 113 - 90 yrs, 114 - 200 yrs and 115 - 400 yrs (Table 1). In the stratosphere bromine and chlorine in the CFCs remove O_3 creating the so-called ozone hole, and in the troposphere they act as a greenhouse gas. Non-fully halogenated halocarbons can be removed from the atmosphere by OH hence their lifetime is shorter (for CH_3Cl - 1.5 yrs).

2.4.2 The atmospheric concentration of CFCs has only recently become a problem due to the expansion of use of propellants and refrigerants with noticeable concentrations only since the 1950s; and pre-industrial values of 0 ppbv. For 1990 concentrations of CFC-11 were 280 pptv, and of CFC-12 were 484 pptv, increasing at respective rates of 9.5% p.a. and 17% p.a. For the period 1765-1990 the contribution of CFCs to radioactive forcing was 12%, but this rose to 24% for the decade 1980-1990 (Figs 3 and 4). The contributions of CFC-11 and CFC-12 to changes in forcing are estimated from:

$$\delta F = 0.22\,(X - X_0)$$

where X = CFC-11 in ppbv, valid for <2 ppbv

and

$$\delta F = 0.28\,(Y - Y_0)$$

where Y = CFC-12 in ppbv, valid for <2 ppbv

Relative to CO_2 CFCs have very high GWP, with values between 3500-7300 over the 100 year time scale i.e. 3500-7300 times more effect ive than CO_2.

2.4.3 Because of the concern over the effect on the ozone layer CFCs are the one type of greenhouse gas for which international restrictions in the form of a protocol exist. The Montreal Protocol of 1987 agreed to the following limitations on the use of CFC-11,12,113,114 and 115:

- Standstill on production and consumption in developed countries at 1986 level by 1990
- Reduction in developed countries to 80% of 1986 level by 1993
- Reduction in developed countries to 50% of 1986 level by 1998

For developing countries it was agreed to allow increases in CFC use to the 1986 figure but reduction then had to start by 1997. This overall agreement is now being developed to try and prevent any further emissions by 2000.

2.4.4 Because of the protocol all the scenarios assume considerable reduction, abandonment or substitution of CFCs. Nevertheless, because of their long lifetime they will affect the atmosphere for at least the next 100 years. For CFC-11, for example, estimates for 2100 are BaU - 630 pptv, B - 555 pptv, C and D - 100 pptv (1990 figure - 280 pptv) (Figs. 4 and 5).

2.5 NO_x (Nitrous oxides)

2.5.1 Nitrous oxides (mainly N_2O) derive from a range of sources, by exchange with the ocean, denitrification in aerobic soils, and , to a lesser extent, the burning of biomass. Once in the atmosphere N_2O acts both directly to absorb radiation and indirectly in the stratosphere to deplete O_3. Because most of the removal of N_2O occurs through stratospheric photochemical decomposition it has a long lifetime of 150 years (Table 1).

2.5.2 Pre-industrial levels of NO_x were stable at around 285 ppbv but had reached 310 ppbv by 1990, increasing at a rate of 0.2 - 0 .3% p.a (Fig.3). Although values are clearly increasing and atmospheric removal cannot compete, leading to the present imbalance, the main sources and sinks of NO_x are not well understood. Removal of Tropical Rain Forest has for instance been estimated to both enhance and deplete atmospheric NO_x. Estimates of δF for N_2O are based on a square root relationship which includes methane because there is an overlap in their atmospheric chemistry. For the period 1765 - 1990 N_2O contributed 4% to radioactive forcing, 6% for the decade 1980 - 1990 (Fig.5).

2.5.3 Because of its long lifetime the influence of N_2O will be felt throughout the next century and all scenarios assume increased concentrations BaU - 418 ppbv; B - 375 ppbv; C and D - 357/356 ppbv (present 310 ppbv) (Fig.4). In view of the range of uncertainties concerning sinks and sources it is difficult to ascertain at present how emissions of N_2O can be reduced.

2.6 Other Greenhouse Gases

2.6.1 Other trace gases believed to act as greenhouse gases include stratospheric O_3, tropospheric O_3. CO and aerosols.

2.6.2 Stratospheric O_3 (ozone) acts in the form of a greenhouse gas to regulate temperature in the stratosphere. A reduction in stratospheric O_3 increases incoming solar ultra violet radiation but also increases outgoing terrestrial radiation. Despite the Montreal Protocol which was designed to protect the layers of O_3 in the stratosphere by reducing CFCs, it is likely that depletion willtake place. This will vary over the globe with the most intense removal over the poles. It is thought that depletion of upper stratospheric ozone will lead to slight warming whilst decrease in lower stratospheric ozone could lead to slight cooling. Overall this is an area of considerable uncertainty.

2.6.3 Tropospheric ozone (O_3) has a very short atmospheric lifetime, a matter of a few weeks. As its concentration is closely linked to CH_4 and NO_x its influence depends largely on their concentrations. Concentrations of tropospheric O_3 are increasing, largely from northern latitude sources at about 1% p.a. but future predictions are made difficult due to the complexities of the interaction s and the feedbacks involved.

2.6.4 Carbon monoxide (CO), although increasing at a rate of 1% p.a., again largely from northern latitude sources related to fossil fuel combustion, has an atmospheric lifetime of 2 - 3 months and its contribution as a greenhouse gas is still poorly understood.

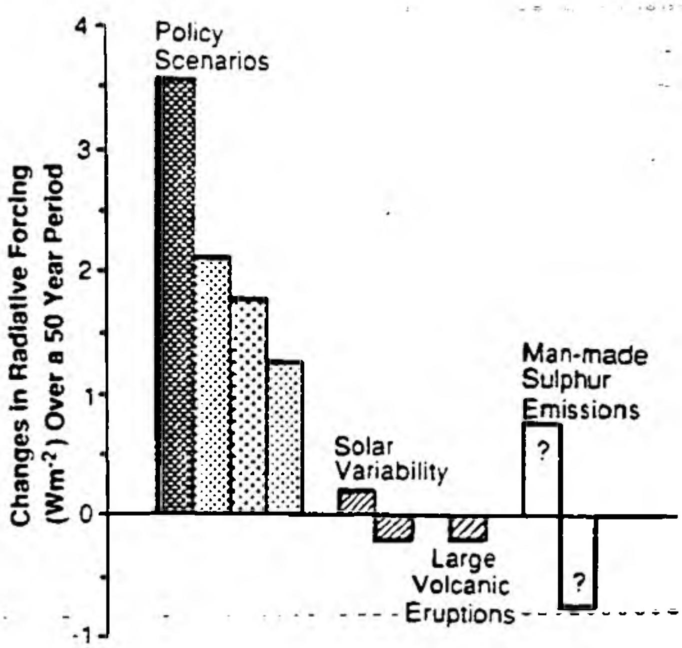
2.6.5 Aerosol particles, solids or liquids between 0.001 - 10µm radius, occur in the atmosphere as a result of both natural and human influences. They play an important role in the regulation of climate through scattering and absorption of radiation, and also through the modification of clouds. In the past increased concentration of aerosols from e.g. volcanic eruptions, have been thought to have reduced incoming solar radiation, normally by their increased stratospheric concentration. Increases in cloud concentration nuclei (CCNs) have been ascribed to aerosol effects, particularly sulphates, and this increase in cloud cover with subsequent increased albedo will also lead to negative radioactive forcing. Human sources of increased aerosol concentration are principally industrial and from the burning of biomass, and as such global impacts vary considerably between 'polluted' and 'unpolluted' areas. Overall the complexity of the role of aerosols is still such that neither the sign nor the degree of effect can be adequately determined for the future.

2.7 Summary

2.7.1 The role of greenhouse gases in climate change is principally through postulated increases in radioactive forcing as measured at the tropopause. The estimated future contributions of the various gases varies according to the different scenarios (Fig.5). Radiative forcing is increasing at between 0.4 - 0.6 Wm^{-2} per decade due to greenhouse gases but this figure will also vary with natural influences such as changes in solar irradiancy or volcanic eruptions. Changes in radiative forcing for the different scenarios are presented in Fig 6. for both the next decade and the next 50 years. The figures demonstrate that anthropogenic influences outweigh natural factors, and that there will continue to be a general state of disequilibrium.

2.7.2 Although it is possible to estimate changes in radiative forcing based on the simple models outlined above, the link between forcing and climate change is more complex and it is the nature of this link and our ability to model it successfully which is the key to accurate predictions. This is the subject of the next section.

Fig.6 Comparative Radiative Forcing Mechanisms Over a 50 year Period (Houghton et al, 1990)



3. Greenhouse Gas - Climate Links : Climate Models and Predictions

3.1 Introduction

3.1.1 Predicting future variations in climate as a result of increases in the atmospheric concentration of greenhouse gases is based on the incorporation of data on greenhouse gas emisions into various kinds of mathematical models. A wide range of mathematical models generally known as General Climate Models (GCMs) exist and the 1990 IPCC Report produced a synthesis of their results as a principal part of its brief. The aim of the synthesis was not only to provide 'best estimates' of future changes for the main climatic parameters, e.g. temperature, precipitation, soil moisture, but also to highlight areas of weakness in the modelling that has so far been undertaken as a means of structuring the future integrated research programme (see Appendix B).

3.1.2 Successful modelling requires the ability to adequately understand and 'parameterise' (i.e. provide a suitable mathematical expression of the processes and elements involved) all the major components of the world's climatic system - the atmosphere, oceans, cryosphere (areas of snow and ice), biosphere and geosphere. Whilst modelling of the individual components has been carried out for some time, the integration of all the components, especially the coupling of the atmosphere and the ocean has only recently been attempted.

3.1.3 It is perhaps in the area of modelling and deriving predictions from models that the greatest uncertainties lie in terms of estimating the effects of greenhouse gases on future climate, largely as a function of the inherent problems of producing and validating models of extremely complex systems. For those involved in modelling the weaknesses manifest themselves in the error terms associated with prediction, but for sceptics about the likelihood of future global warming such as Idso (1989) they are the central weak element, the results of which have no validity at all.

3.2 In a broad sense there are two general types of models that have so far been used. By far the most important type are the GCMs but also of value are Palaeo-anologue models whereby models of past climatic conditions are used as analogues for possible climatic states. Because of the importance of GCMs they will be considered in some depth here but reference will also be made to the use of palaeoclimatic analogues. It should be emphasised that all the models are run at the global scale.

3.2.1 GCMs

3.2.1.1 GCMs are mathematical expressions of those processes which comprise the fundamental elements of the climatic system. They utilise classic physical principles but are based on 'primitive' equations i.e. the mathematical expressions of the processes and their interaction are relatively simple.

3.2.1.2 Most models are termed equilibrium models in that they work on the basis of climate returning to an equilibrium with changes in the forcing functions, i.e. changes in radiative forcing. Typically they generate equilibrium conditions for a doubling of CO_2 (CO_2x2) and equivalent changes for other greenhouse gases. Because of the lifetime of greenhouse gases and the slow response rate of the oceans, the time taken to reach equilibrium is beyond the timescale which is of interest, with conditions over, say, the next 50 - 100 years representing a transient state between equilibria. Modelling of transient conditions is extremely difficult so most predictions assume that the equilibrium models provide a reasonable approximation of the time transient state. Furthermore, such equilibrium models allow for more detailed parameterisation within the general constraints of computer time and technology.

3.2.1.3 In their synthesis the IPCC working group consider the results from 20 equilibrium models which are coupled atmosphere-ocean models run by 9 groups, and 4 which incorporate time-dependency. These latter models are a significant advance but have only been available since 1989.

3.2.1.4 All the models input global data for the parameters included on a grid square point basis. The horizontal scale obviously has a significant effect on the ability of the models to represent processes, as sub-grid scale processes are often significant in climatic terms. The range of horizontal scales is from 300-1000 km and the level of resolution in the vertical axis varies from 2 - 19 levels. For the time-dependent models a range of time scales have been tried from 25-100 years.

3.2.1.5 Models are run for present conditions as a control which can be verified from present observations and then run repeatedly with changes in the main parameters. For non-time dependent models the results are then integrated over varying time periods from 5 -100 years.

3.2.1.6 The adequate parameterisation of the key ocean-atmosphere-land surface elements of the climatic system plays an important part in the likely value of the model predictions. The parameters used derive originally from those used on simpler models of the individual elements. As the models become more complex then they need to incorporate several important feedback processes:

i) Water vapour feedback - this tends to be positive, for as temperature rises so will evaporation and the concentration of water vapour in the atmosphere.

ii) Snow-ice albedo feedback - with less snow/ice cover less radiation is directly reflected and more is absorbed. The effect of this is however uncertain as to sign or quantity.

iii) Cloud feedback - this is by far the most complex and uncertain area and is one which is the centre of a lot of current study. Increased evaporation should lead to more cloud concentration nuclei (CCNs) and hence more cloud and a net cooling effect. Most of the GCMs however tend to predict less cloud cover for CO_2x2. Also of importance are the altitudinal distribution of clouds and their water/ice content. Running the Meteorological Office High Resolution Model for different, and increasingly sophisticated, cloud parameters changes the net result in terms of increased temperature for CO_2x2 from 5.2°C for a simple model to 1.9°C for a more complex model. Although originally considered a likely negative feedback process the nature of cloud feedback processes are increasingly seen as possibly enhancing warming, albeit by an uncertain amount. Original estimates of δT (change in global mean temperature) for CO_2x2 without feedbacks were + 1.2°C, but accounting for the feedbacks, especially i), estimates of increased temperature of up to 3.1°C have been derived.

3.2.1.7 The problem of the sub-gridscale processes which have to be generalised to a specific grid point value, occurs within all the elements of the climate system but especially in the ocean and over the land surface. In the oceans small scale eddies <50 kms, and in some cases <20 kms, affect circulation and transference of heat and energy. On land, soil moisture varies considerably within the grid scales. Future models aim to both improve the horizontal/vertical resolutions adopted and to improve parameterisation. A general review of the major uncertainties facing prediction as a whole may be found in Dickinson (1989).

3.2.2 Palaeo-Analogue Models

There are two approaches which utilise an analogue model based on palaeoclimatic information.

3.2.2.1 In the first the past relationship between levels of CO_2 and global mean temperature is estimated from geological data. Allowing for changes in albedo and solar irradiance over such geological timescales estimates are then made of the sensitivity of temperature to changing CO_2 levels. For CO_2x2 the best estimate is 3±1°C.

3.2.2.2 A second approach examines climatic conditions at a series of more recent time periods over regions for which there is adequate palaeoclimatic data and seeks to use them as possible future analogues. Here there is no attempt to directly link CO_2 and climate, the aim is to examine regional climatic characteristics under warmer conditions. The 3 chosen periods are:

i) Mid-Holocene 5-6,000 B.P. when temperatures were +1°C;
ii) Last Interglacial (Eemian) 125,000 B.P., +2°C;
iii) Pliocene 3-4 m B.P., +3 - 4°C.

Although there are significant differences in the causes of these higher temperatures it is the general pattern of the effects that is of interest.

3.2.2.3 The value of the Palaeo-analogue approach lies in the availability of different baseline conditions so that predicted GCM results can be evaluated against known past conditions.

3.3 Model Validation

3.3.1 To be of value for future prediction it is necessary to be able to validate GCMs for present day conditions. Such validation also has the effect of identifying systematic errors in the models. Apart from problems over the choice of variables (parameters) discussed earlier, two other problems are important: the availability of observational data for all the parameters, and the lack of a single statistical approach to test the way the models fit the present position.

3.3.2 The range of variables which can be used for validation are presented below with comments on the reliability of the models to reproduce current conditions:

i) Sea-level pressure - good fit.
ii) Temperature - the zonal pattern is reproduced but polar estimates are weak.
iii) Zonal wind patterns - there is some improvement within newer models but this is still inadequate outside the global level.
iv) Eddy kinetic energy - this complication of air flow is as yet poorly modelled but of great climatic importance.
v) Surface air temperature - adequate but some consistent errors.
vi) Precipitation - becomes weaker at the regional level, in W. Europe the number of raindays is overestimated and heavy rain underestimated.
vii) Soil moisture - results are described as 'relatively crude' if reasonable at a large scale, but part of that is a function of poor data on present day conditions.
viii) Snow cover - acceptable but only above the regional scale.
ix) Sea ice - this requires improvement, especially for high latitudes.
x) Clouds and radiation - although the data is improving due to satellite observations - there are still problems in this area.

xi) Seasonal cyles - varying at regional scales this is another area which shows a lot of variation between models.

3.3.3 There are other areas of climate that present difficulties for global models but which are significant, especially at the regional level:

i) Regional anomalies - these are mostly outside the area of western Europe, comprising the El Niño effect (a 3-5 year irregular sea surface temperature anomaly off E. Peru), Sahelian drought and areas of summer monsoon.

ii) Extreme events - tropical storms are difficult to incorporate in global models as are any disturbances at the sub 300 km scale, hence some of the difficulties in predictions concerning Atlantic storm tracks.

3.4 Regional models

3.4.1 All the models so far discussed are simulated at the global scale and regional inferences made from the global scale results. This inevitably means a very poor resolution level for prediction at the regional scale.

3.4.2 For the IPCC Report (Houghton et al, 1990) 5 regions were examined in more detail for changes to 2030 under the BaU scenario (with some estimates based on scenario B). The areas were chosen to cover a wide range of critical climates in C.N. America, S.E. Asia, Sahel, S. Europe and E. Australia. For the nearest to the UK, S. Europe, predictions for 2030 suggested: +2°C for winter, +3°C for summer, ?increased precipitation in winter, 5 - 15% decrease in precipitation in summer, and a similar reduction in summer soil moisture.

3.4.3 A more detailed model assessment for the area between 30°N-70°N and 20°W-40°E has been made in Hamburg (Santer et al, 1990), where by mapping the distribution of signal-to-noise ratio it has been possible to isolate those areas of Europe with more reliable estimates of change. The UK is reasonable with most uncertainty in winter in the central Mediterranean and Denmark/N.Germany, and in the summer also in the Mediterranean.

3.4.4 For the UK the Hadley Centre at the Meteorological Office is planning the development of a regional model so as to improve predictions at the regional level. Their programme is for model development between 1991-93, and evaluation between 1993-95, with predictions being produced between 1995-99. By 2000 smaller scale sub-regional models are planned. Selected models used by the UK group for the DOE Report in 1991 are discussed later.

3.4.5 At present it should therefore be reiterated that there is as yet no model capable of producing regional climatic predictions for the UK from a regional model basis. No such predictions will be available until 1995 at the very earliest and any change in predictions between 1991-95 will derive from improved global modelling.

3.5 Predictions

3.5.1 The predictions which are made by the IPCC 1990 Report are based on a comparison of all the available CO_2x2 model runs. The authors emphasise that what are accepted as valid predictions are those common to all models and which are 'physically plausible' (their emphasis). They also further make the point that they are made in the 'light of current knowleldge' (again their emphasis), and are likely to change with the development of ever more powerful models, particularly those which can deal with the complex feedback processes and more accurately define transient systems. In terms of the confidence which should be placed in individual predictions they are assigned *s, ranging from 5, virtual certainty, to 1, low confidence.

3.5.2 **Global Mean Temperature** - the lower atmosphere and the surface of the earth will warm (*****) with an associated cooling of the stratosphere (*****). Estimates of the overall rise are still within the range accepted in 1979 by the United States Academy of Science of +1.5 - 5°C. The most recent models have narrowed this to 1.9 - 4.4°C but a 'best guess' of 2.5°C is still the accepted single figure to work from (***). For the globe this will mean an increase in general evaporation of 3 - 15 % (***).

3.5.3 **Regional Temperature Changes** - there are a number of regional variations within the overall warming trend:

i) There will be enhanced late autumn/winter warming in higher latitudes. In Central N. America this is estimated as a winter rise of 4°C, increasing to 8°C to the east. In Europe and N. Asia this will be 4°C (***). At the highest latitudes e.g. over sea ice in the Arctic, the level of warming will be less than the global figure.

ii) Over tropical latitudes warming will be below the mean (***).

iii) Summer warming over northern mid-latitude continents will be greater than the mean e.g. 5 - 6°C over C. Asia. This is thought to be largely a function of reduced cloud cover and soil moisture.

3.5.4 **Precipitation** - there is less certainty over precipitation changes than temperature but overall the models suggest:

i) Enhanced annual precipitation in high latitudes and the tropics (***).

ii) Enhanced winter precipitation in mid-latitudes between 35 - 55°N (***), possibly in the order of 10 - 20%. It should be noted that there will be considerable discrepancies in precipation variation at the sub-continental scale, and that these are far from being understood at present.

3.5.5 **Soil moisture** - soil moisture is considered as a key variable especially in the influence of climatic change on human activities. It has however been more difficult to model and predict, thus the estimates have a low confidence:

i) Increase in winter soil moisture in northern high latitudes (***).

ii) Enhanced summer drying in northern mid-latitudes, possibly 17 - 23% between 35 - 55°N (**). Although at a low level of confidence there are good physical reasons for such a change and this particular prediction is a logical outcome of the temperature/precipitation changes.

3.5.6 **Sea-ice** - the global extent will be reduced (****) but by uncertain amounts.

3.5.7 **Mean Sea-Level Pressure** - the warming process will eventually lead to a weakening of the N - S gradient in pressure. In mid- latitudes this would reduce the strength of mid-latitude westerlies.

3.5.8 **Climatic Variability** - the degree to which global change will be reflected in the variability of climate is still difficult to predict using present models. There are a number of fundamental problems hindering progress - the short data set of current climatic variables, regional variations, lack of understanding of influence of small scale variations such as the El Niño effect. Nevertheless it is suggested that:

i) If temperature increases there should be more 'hot' days and fewer 'cold' days.

ii) There may be greater variability in precipitation; for 60 - 70% of the model data points where mean precipitation increases so does variability.

iii) All models show a consistent increase in frequency of convective precipitation which would lead to more intense events and higher run off. This is however largely at the sub-grid scale level and difficult to model.

iv) It is possible that there will be a reduction in variability in mid-latitude winter storm events, both in frequency and intensity, but this is only at the <1000 km grid scale. Although of obvious importance the scale is coarse and implications for smaller scale disturbances are uncertain.

Variability of climate is an extremely difficult area and it is not known whether future patterns will reproduce a general shift of the present distribution patterns for events e.g. precipitation, or a change in the nature of the distributions themselves.

4. Natural Climatic Variability - Detecting the Influence of Greenhouse Gases

4.1 Timescales of Climatic Variability

4.1.1 Over recent geological time climate has changed markedly. Prior to the present geological epoch (Pleistocene) which began ca 2.4m years ago, the latter part of the Tertiary, the Pliocene, saw Northern Hemisphere mean temperatures 3 - 4°C higher than the pre-industrial mean.

4.1.2 Within the most recent geological epoch, the Pleistocene, there have been a series of glacial/interglacial cycles broadly on a 100,000 year timescale and driven by orbital changes. During these oscillations, global mean temperatures have varied by up to 7°C,with estimates of variation as high as 10 - 15°C in Northern hemisphere mid- and high latitudes.

4.1.3 Over the last 10,000 years, the Holocene, climatic variability has been much less, with temperatures at a maximum 5-6000 years ago (probably +1°C), and at a minimum in the 'Little Ice Age', roughly between A.D. 1500-1850, when temperatures may have been as much as 1.5 - 2.0°C less than today. Thus within the context of variability that could be expected from data for the very recent timescale it will prove difficult to identify any possible greenhouse gas effect. Natural variability at the 10-100 year timescale is by far the least well understood area of climatic change over time.

4.2 Methods of Detection

4.2.1 Detection requires the concept of 'attribution', that a detailed change can be attributed to a specific cause i.e. greenhouse gas forcing. This concept is difficult to apply because the signal to be detected is lost in a great deal of noise. This noise derives from the following factors:

- i) Inherent climatic variability at the annual, decadal and century timescale.
- ii) Lack of regional models which can adequately define the specific signal to be detected.
- iii) Weakness of global time-dependent models to use experimentally.
- iv) Noise from other anthropogenic effects.
- v) Short timescale and uncertainties of observational instrumental data.

4.2.2 The main approach to detection has been by the Fingerprint Method which seeks to define and observe a 'multivariate signal with a structure unique to a predicted enhanced greenhouse effect'. Such a sign is difficult to define and observe, and identification of simple univariate signals is not adequate. So far although a number of different methods have been tried none have convincing evidence for an 'attributable' greenhouse effect.

4.3 Model Predictions and the Observational Record

4.3.1 A number of predictions have been made from the GCMs concerning probable responses of climate parameters to enhanced greenhouse gas concentrations since pre-industrial (i.e. AD 1765) times. Individually whilst not providing the 'fingerprints' they may be able to indicate the likelihood of a greenhouse gas influence.

4.3.2 **Global mean temperatures** - global mean surface temperatures have been rising in the 20th century. The pattern of warming has not been monotonic but has been generalised to between 0.3 - 0.6°C over the last 100 years, and the last decade has seen higher temperatures than any in the instrumental record, the last 140 years (Fig.7). The combined rise for land and sea temperatures is also comparable (Fig.8). Temperature changes have shown variations between the hemispheres, and the variabilities from year to year, and decade to decade are consistent with natural variability. It is not yet possible to attribute all the warming, partly because the changes lie within estimates of temperature variability experienced over the last 1000 years, and partly because of instrumental variations, especially the influence of increasing urbanisation and 'heat island' effects around instrumental stations (estimated at between 0.05 - 0.1°C). Nevertheless the averaged increase over the last century is consistent with model predictions.

Fig.7 Smoothed Land Temperatures Relative to 1951 - 1980
(a) Northern Hemisphere; (b) Southern Hemisphere
(Houghton et al, 1990)

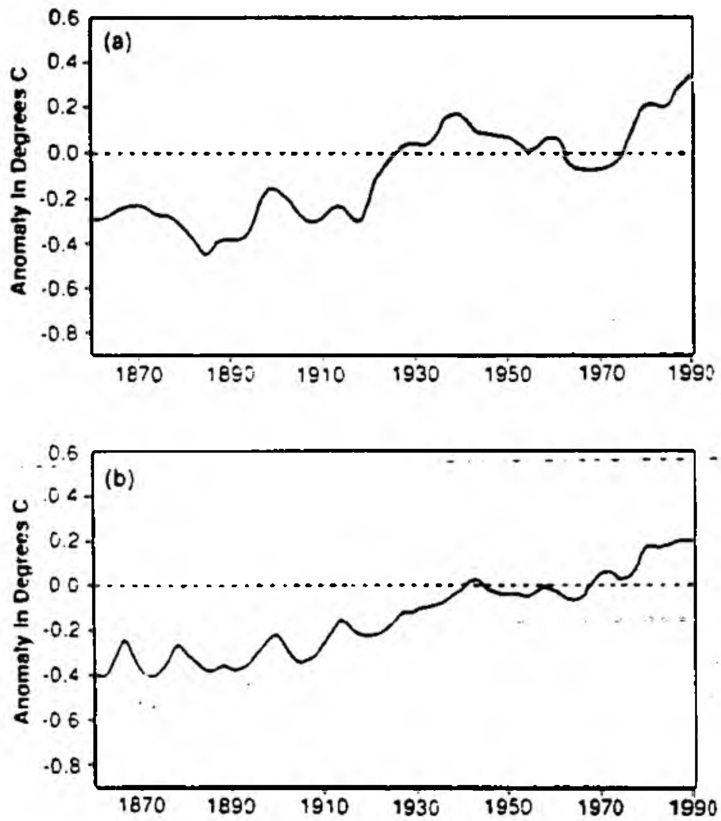
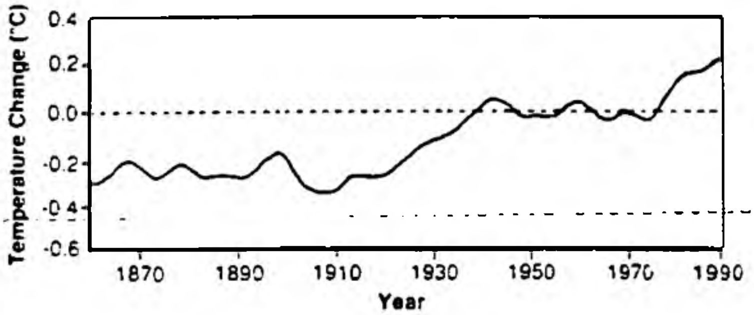


Fig.8 Global Mean Combined Land - Air and Sea-surface Temperatures, 1861 - 1989 (average = 1952 - 80) (Houghton et al, 1990)



4.3.3 **Estimated high latitude warming** - variability in temperature series is greater in high latitudes, thus making signal detection more difficult. Although there has been some warming north of 50°N over the last century there has been no consistent rise since the 1920s. Furthermore a recent very detailed study of N.Fennoscandia using dendrochronological evidence for the last 1400 years finds no evidence for any greenhouse warming at all and suggests that it is unlikely to be ascertained in such areas until after 2030 ((Briffa et al, 1990).

4.3.4 **Tropospheric warming and stratospheric cooling** - a consistent feature of model predictions is a pattern of tropospheric warming and associated stratospheric (above 50 mb) cooling. This has been seen as the most distinctive fingerprint and there is some evidence to support such a pattern. It is not yet 'attributable' to greenhouse gas emissions for there are possible natural explanations, and stratospheric data is still very limited. Good data on the vertical distribution of temperature through the atmosphere has only been available since 1958.

4.3.5 **Increased global precipitation** - due to sampling problems and the inherent variability of precipitation it is unlikely that a clear 'attributable' signal will be available. There has been some enhancement of precipitation in mid-latitudes in the last few decades but such a phenomenon is not an adequate 'fingerprint'.

4.3.6 **Sea level rise** - this will be dealt with in section 5. Although there is a rise consistent with warming, it will only be acceptable as an indicator if the warming itself can be shown to be greenhouse gas related.

4.3.7 **Increase in tropospheric water vapour** - increases in the key greenhouse gas, water vapour, are predicted and have been observed in the tropics at levels up to 20% over the Pacific. Observations are above expected levels but may have a natural cause.

4.3.8 Because of the difficulty of detection using observational climatic parameters it has been suggested that indirect indicators could be more sensitive and identifiable. Such a claim has been made for microbial activity in soils which is temperature dependent and may therefore provide an alternative 'fingerprint' (Harriss, 1989).

4.3.9 By 1990 it was not possible to say that global warming as a result of greenhouse gas emissions had yet been detected. Although trenc in som climatic parameters approximated those predicted by GCMs the degree of change experienced was not considered 'attributable' solely to greenhouse gas related warming.

4.3.10 Addressing the question of when will the greenhouse effect be detectable, the IPCC Report in 1990 suggested that if it is accepted that the critical threshold for 'attributable' change is a further 0.5°C increase in global mean temperature, then the GCM data could be used to provide an answer. For the BaU scenario this could be as early as the end of the 20th century; for scenario D as late as 2047. As the BaU scenario is likely to be the best estimate over the next decade it should therefore be possible to detect the greenhouse signal with reasonable confidence by the year 2000. The noise in the system will however still be there as will the inherent variability in the climate system which will mask any monotonic trend.

5. Sea-Level Change

5.1 Introduction

5.1.1 Sea-levels vary according to two major factors, eustatic factors, which are changes in the volume of the oceans, and isostatic factors, which are changes in the land surface relative to the oceans. Over the timescale of the next century the principal cause for concern lies in the eustatic changes which could occur as a result of global warming. Isostatic factors and other influences on sea levels which are not attributable to the influence of greenhouse gases do however need to be considered, if only on a local scale as they may affect relative sea level. It is the accurate separation of eustatic and isostatic effects upon recent sea-level change that has also presented difficulties in evaluating the direction and rate of sea-level change over the last century.

5.2 Measurement of relative sea-level

5.2.1 Measurement of the height of relative sea level needs to be accurate in order to identify rates of change that are likely to be in the order of mms century^{-1}. Currently the height of sea level is measured by tide gauges relative to fixed bench marks (Pugh, 1987) and for global sea level figures are recorded in the UK at the Permanent Service for Mean Sea Level (PSMSL). This database holds records for over 1300 stations but only two-thirds are considered suitably accurate for analysis, and of those only 420 span more than 20 years.

5.2.2 The available database for estimating the current state of world sea level and to predict likely responses to global warming is therefore relatively short, and also biased in favour of the developed world, especially in the northern hemisphere. The recently developed GLOSS (Global Level of the Sea Surface) programme is designed to provide a comprehensive cover of the globe but it will be decades before this provides a good time series of global sea-level data.

5.3 Recent sea-level change

5.3.1 Much attention has been placed on whether, given current records, it is possible to detect any rise in global sea level over the last century. Although sea level has varied over the last 10,000 years it has been thought to be relatively stable over recent millennia. Using a variety of data bases several studies have derived estimates of trends in sea level over the last 100-200 years.

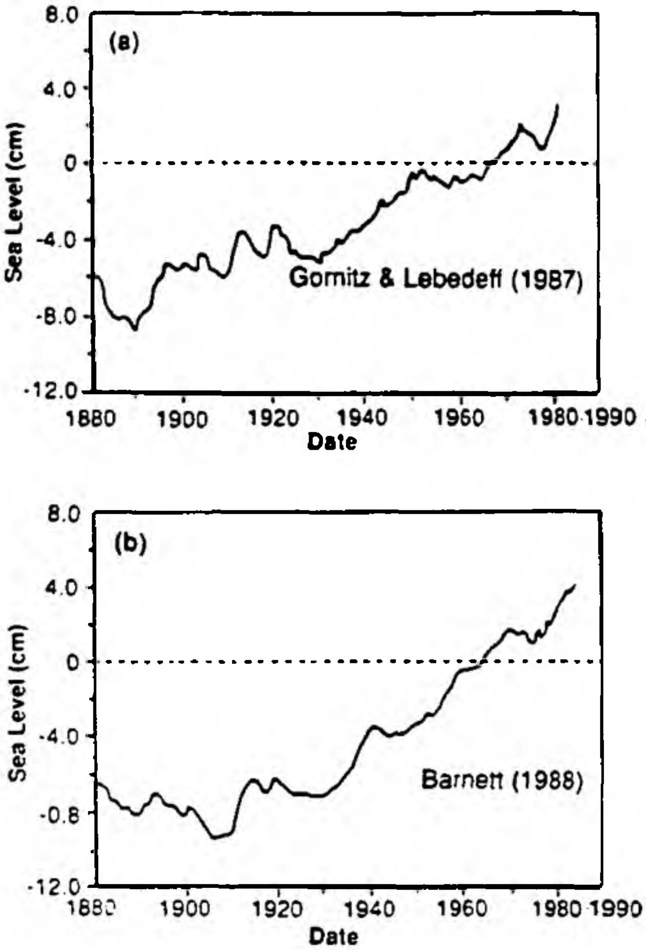
5.3.2 All the studies show a rise in world sea level at rates of between 0.5-3.0mm year^{-1}; thus the SCOPE Report accepted a figure of a rise of 12.5cm since 1900 and the US Department of the Environment (1985) 10-25cm. The three principal studies since both the SCOPE Report and the USDOE report have provided the following estimates:

i) Gornitz (1990) and Gornitz and Lebedeff (1989) - rates of either 1.0±0.1mm year^{-1} or 1.2±0.3 mm year^{-1}. This was based on 130 stations of minimum 20 year records (Fig.9).

ii) Barnett (1988) - 1.15mm year^{-1} (with a steeper rise of 1.7mm year^{-1} between 1910-80). This was based on 155 stations (Fig.9).

iii) Peltier and Tushingham (1989, 1990) - 2.4±0.9mm year^{-1}. This higher figure was based not on a century of observations but on observations between 1920-1970 at 40 stations. Despite the differences the IPCC Report considers the results a 'robust finding of a positive trend'.

Fig.9 Global Mean Sea-level Change Since 1880
(a) Gornitz & Lebedeff, 1987; (b) Barnett, 1988



5.3.3 The IPCC Report concludes that global sea level has been rising over the last century at an average rate between 1.0-2.0mm $year^{-1}$, but that there is no consistent conclusive proof of any acceleration in the rate of sea-level rise.

5.4 Contributors to sea-level rise

5.4.1 Thermal expansion of the oceans - as the density of ocean water hanges in inverse relation to temperature so its volume also changes; what is known as a steric change in sea level. Evaluation of the role of thermal expansion in recent sea-level change is hampered by a paucity of observational data on the temperature, density and volume of oceans. This too is now the subject of an international project to improve the database. Assessment of this factor has therefore been made by modelling, utilising a simple ocean-atmosphere model, the upwelling-diffusion energy-balance model which has also been used in general climatic modelling (Wigley and Raper, 1988,1990). Running this model for the last century, assuming a global warming between 0.3-0.6°C gives a range of values for sea- level rise of 2-6cm, i.e. probably 40% of the total observed changed according to 'best estimates' (Table 2).

5.4.2 Glaciers and small ice caps - for all ice masses except Antarctica (and possibly Greenland). increases in temperature will lead to a reduction in ice extent. In an early study Meier (1984) estimated a contribution of 0.46±0.26mm $year^{-1}$ to sea-level change from this source. Later use of models based on mass balance assumptions for glaciers suggested a range between 0.45-0.70 mm $year^{-1}$, from dry to moist regions. Thus overall a global mean contribution of ca 40% is a reasonable estimate for this source to change over the last century (Table 2).

Table 2. Estimated contribution to sea level rise over the last 100 years (in cm)

	Low	Best Estimate	High
Thermal expansion	1	4	6
Glaciers / small ice caps	2	4	7
Greenland ice sheet	1.5	2.5	4
Antarctic ice sheet	-5	0	5
Total	-0.5	10.5	22
Observed	10	15	20

5.4.3 Greenland - estimation of the role of the Greenland ice cap is made difficult by a very limited run of mass balance data. As Greenland does have a large ablation area around the ice cap where a rise in temperature will lead to increased ice loss it should be a net contributor to sea level rise but the increased precipitation which occurs with higher evaporation may have offset this to some extent. Warming over Greenland has been ca 0.5°C since 1866, but there was exceptional warming of 2°C between 1930-1935. A reasonable estimate of the contribution of Greenland over the last century is considered to be a rate of 0.23 ±0.16mm $year^{1}$, approximately 20-25% of total rise (Table 2).

5.4.4 Antarctica - because Antarctica has no area of ablation and temperatures are so cold, the net effect of rising temperatures is likely to be an increase in mass balance through higher precipitation. Observational data is poor for the continent and modelling is made difficult by the long response time to changes in input; it is thought for instance that the ice cap is still responding to the termination of the last glacial period 10,000 years ago. Various estimates have been made, largely model based, of responses to w arming, with a sea-level effect of between -0.2 to -0.38mm $year^{-1}$. Using the best estimate figures Antarctica is thought to have had nei ·er a po ·i-tive nor negative influence over the last century (Table 2). As the West Antarctic ice sheet is a grounded ice sheet within ocean water it is potentially unstable. This instability may worsen if ocean temperatures rise and detatch the ice from the sea bed as a result of ice thinning. Were the ice sheet to collapse this would have a significant effect on world sea level but such an event is not likely to occur within the short timescales considered here.

5.4.5 Other factors - changes in groundwater and water storage may affect global sea level but accurate figures are not available and it is not considered that they have been or are likely to be significant when seen alongside the above factors.

5.4.6 In summary, for the last 100 years using 'best estimates', there has probably been a global sea-level rise of 10.5cm, 4.0cm from thermal expansion, 4.0cm from glacier/small ice cap ablation, 2.5cm from Greenland ablation and 0.0cm from Antarctica.

5.5 Predicted future sea-level change

5.5.1 There have been at least 11 estimates of future sea-level rise for a range of timescales and based on a range of different methods. With two exceptions they all predict a further rise, with maximum figures by A.D.2100 of between 160-367cm. The likelihood of a continuation of the trend of rising sea level is strong because of the 'commitment' to rise already in the global climatic system. For the immediate future, to A.D.2030, all estimates fall within +10-30cm.

5.5.2 Using the upwelling-diffusion model and running it for the four scenarios gives figures of between +8-29cm by A.D.2030, +21-71 cm by A.D.2070, and +31-110cm by A.D.2100 (Fig.10). Because of the great uncertainties after A.D.2030, although sea level will still rise the rate is considered very uncertain and it is expected that scenarios B-D will be more apposite as the world can see and recognise the greenhouse effects. For A.D. 2030 however the figures are thought to be more applicable with a 'best estimate' of +18.3cm (thermal expansion 10.1cm; small glaciers/ice caps 7.0cm; Greenland 1.8cm; Antarctica -0.6cm) (Table 3). If all forcing were to cease after A. D.2030 sea-level would still probably rise by 41cm over the present (Fig. 11).

Fig. 10 Global sea-level rise to the year 2100 assuming Business-as-Usual scenario.

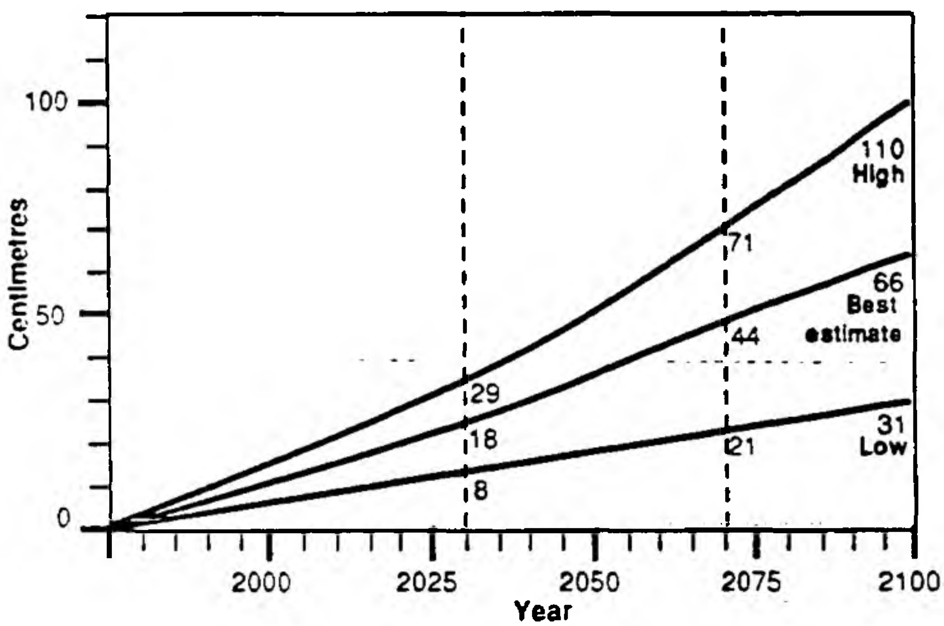
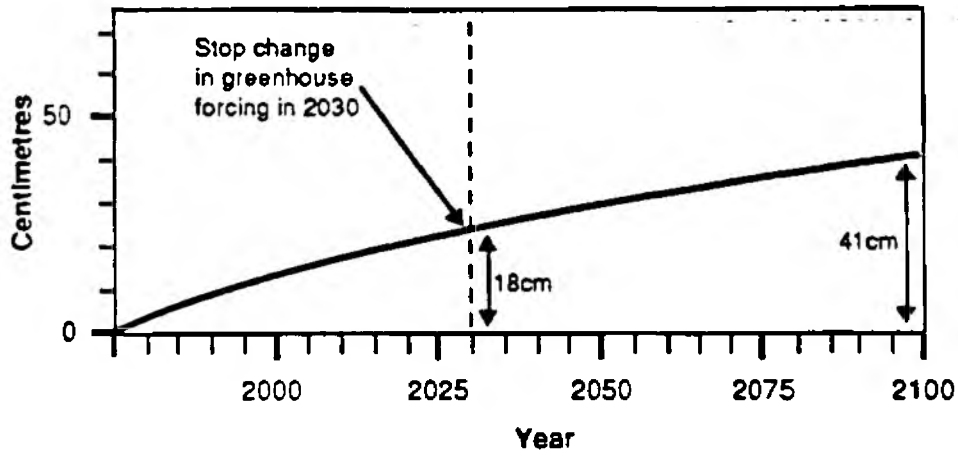


Table 3 Factors contributing to sea level rise (cm),1985-2030. "Business-as-usual" scenario. Best Estimate for 2030.

	Thermal Expansion	Mountain Glaciers	Greenland	Antarctica	*Total*
High	14.9	10.3	3.7	0.0	28.9
Best Estimate	10.1	7.0	1.8	-0.6	18.3
Low	6.8	2.3	0.5	-0.8	8.7

5.5.3 In terms of sea-level experienced at any one point over the globe this would still be affected by local conditions, such as land movements (isostatic recovery, subsidence etc.), but also by changes in air and ocean circulation. These are very uncertain and their effect is therefore unclear. Similarly changes in the frequency of extreme high sea-level events are largely a function of regional patterns of change and cannot be estimated from the sea-level data. Because of the weakness of such models at present this is not an area in which good predictions can be made.

Fig. 11 Sea Level Rise Commitment to 2030, with Further Committed Rise to 2100 Assuming Stabilised Forcing in 2030.



6. Ecosystem Change

6.1 Introduction

6.1.1 It is inevitable that increased global temperatures will have an effect on ecosystems. Evidence from palaeoecological studies has shown significant changes in the spatial arrangement and composition of ecosystems concomitant with the climatic shifts both of glacial/interglacial cycles and over the millennia of the present interglacial. This is true for both terrestrial and marine ecosystems, in the latter case there were considerable variations in the spatial arrangement and productivity of marine plankton communities over the cycle.

6.1.2 The timescales of response to climatic change within ecosystems are likely to vary considerably. At some levels responses will be almost immediate whereas at other levels change could still take tens or hundreds of years. A lack of understanding of the degree of equilibrium that exists at present between ecosystems and climate also makes determination of response time difficult, as does the strong influence of human interference with most, if not all global ecosystems.

6.1.3 Unlike climatic and sea-level modelling there is a relatively poor observational basis for establishing links between climate change and ecosystem change. Furthermore, as the significant processes often manifest themselves at a very wide range of spatial and temporal scales, choosing modelling strategies is not straightforward. This is further complicated by uncertain baseline data and its relation to climate rather than to human interference. ITE uses data for the period 1941-1970 as their baseline material but this is a function of availability as much as relevance for the problem.

6.1.4 It is noticeable that despite the detail afforded to ecosystem responses in the 1986 SCOPE Report (Bolin et al, 1986) the IPCC Report presents very little new evidence that goes beyond speculation about the probable important links with no firm predictions for change. At a more detailed level there is a good review of the potential impact of climate change on freshwater ecosystems in George (1988). A major weakness of this document for current thinking is that the scenarios chosen for evaluation are based on a model from 1980 and tend to overestimate climate changes, as well as considering regional changes that are as yet very uncertain.

6.2 Impact of increased CO_2

6.2.1 The impact of increased CO_2 will vary between C3 plants (which comprise 95% of the global total) and C4 plants. In the former the enhanced levels of CO_2 will increase the rate of photosynthesis and reduce photorespiration, and biomass accumulation will increase, although variably between species and environments. Increased CO_2 also causes some closure of stomatal pores which leads to more efficient use of water in plants. Where there are C3 and C4 plants in competition then C3 plants are likely to be favoured. Overall there should be an increase in Net Primary Productivity (NPP), and increased storage of C, except perhaps in woody plants. There should also be less detrimental effects from water stress, low light and poor nutrition.

6.2.2 It is also likely that there could be changes in tissue quality which will, in particular, affect susceptibility to pathogens.

6.2.3 As a result of increased CO_2 it is probable that the period of active growth will increase with an earlier start to growth and later senesence.

6.2.4 Increased CO_2 may also encourage growth of mycchorizal fungi and enhance the rate of nitrogen fixation.

6.2.5 In freshwater ecosystems the direct effect of CO_2 will not be great. George (1988) estimated that the pH of acid waters could become more acid by 0.02, and neutral waters by 0.2 for CO_2x2. Increased concentration of CO_2 in the water would still leave concentrations well below those that would be toxic, possibly 0.9 mg l^{-1}, against the lowest estimate of 20 which would be toxic for trout. There may however be some increase in the transfer rate of other toxicants with higher CO_2.

6.3 Impact of increased temperature and precipitation

6.3.1 Increased temperature and moisture lead to increases in the rate of photosynthesis and respiration. Although increased moisture can lead to reduced photosynthesis this would probably be offset by the direct CO_2 effect; there would be considerable variations according to environment and scale.

6.3.2 At a community level it is likely that composition would change, especially at present community margins (ecotones) and there would be greater susceptibility to stress (e.g. drought) and disease. In some communities changes could be dramatic e.g. changes in tundra with accelerated decomposition and release of C to the atmosphere.

6.3.3 Modelling of changes at the community and regional levels is underway but still very preliminary. At a simple level it is clear from palaeo-analogues that where a change of 1°C leads to a latitudinal shift in isotherms of 100-125km, predictions of more than +1°C will lead to significant alterations in limits to vegetation growth and displacement of communities and individual species. For models based on CO_2x2, estimates of a 37% reduction in tundra and a 32% reduction in boreal forests have been made.

6.3.4 Where there is a combination of enhanced overwintering of pests and pathogens and increased stress this could lead to greater susceptibility to epidemics, especially from aphid species.

6.3.5 In freshwater systems there is a strong and direct relationship between air temperature and water temperature so there would be a noticeable and measureable change in water temperature. This could however vary from catchment to catchment as demonstrated by Walling and Carter (1980) for catchments in the Exe system. Higher temperatures would affect the way pollutants could be handled within a catchment and most bacteria mediated environmental processes would be affected, especially those cold sensitive processes which would be more effective e.g. methane production. Phytoplankton and zooplankton productivity and succesion would also be affected with earlier development and probably higher productivity, although the latter are also environmentally dependent.

6.4 Climate Feedbacks

6.4.1 Changes in vegetation and soils can affect the rate of transfer of CO_2 and other gases such as CH_4 and N_2O to the atmosphere. 30% of CO_2 derives from biotic sources, 70% of CH_4 and 90% of N_2O. It has even been suggested that reforestation could be used to try and offset the rise in CO_2. The figures required are very large and probably unrealistic politically and socially but also serve to emphasise the role of non-greenhouse based climatic interference such as tropical rainforest removal and soil fertilisation. Some researchers have seen biogeochemical feedbacks as potentially of great importance although little understood..'a better quantitative assessment of both the impact of climate change on biogeochemical cycles and the associated feedbacks is urgently needed' (Lashof, 1989).

7. Climate and Sea-Level Change in the UK

7.1 Basis for predictions

7.1.1 The IPCC scientific assessment provides the basis for making predictions or ascertaining scenarios (what would happen if..) for climate and sea-level change. Because all the models are essentially global the results are at a general level and should be seen as extrapolations from global scale results. Nevertheless as a basis for assessment the UK Climate Change Impacts Review Group selected 5 GCMs which have been published (the rationale for the choice is in as yet unpublished form) as a means to derive data for the UK from this selection, and ran the models for a BaU scenario and for CO_2x2 (the basis for the BaU scenario was essentially the same as that used by the IPCC - see Appendix 1). These results therefore differ at times from the IPCC results discussed above although the differences are not very great. One other reason for the differences are changes in the assumptions; the IPCC assumed CO_2x2 by 2020, but the UK exercise assumed 2030; the IPCC utilised change in temperature as model-predicted by 1990, whereas for the UK an increase of 0.5°C by 1990 was assumed (a figure that has been observed but may not represent just greenhouse gas forcing).

7.1.2 For predicting future temperature and precipitation characteristics, especially for purposes of illustration, the UK group assume that both temperature and precipitation can be modelled by a simple normal distribution, which on the observational data is a fair assumption. Thus to illustrate likely future conditions they assume constancy of form i.e. still a normal distribution with similar standard deviation, and just change the mean values. It is then possible to derive an estimated probability of e.g. a repeat of the summer of 1976, or the dry winter of 1975/76 (see Fig.13).

7.2 Predictions and Scenarios

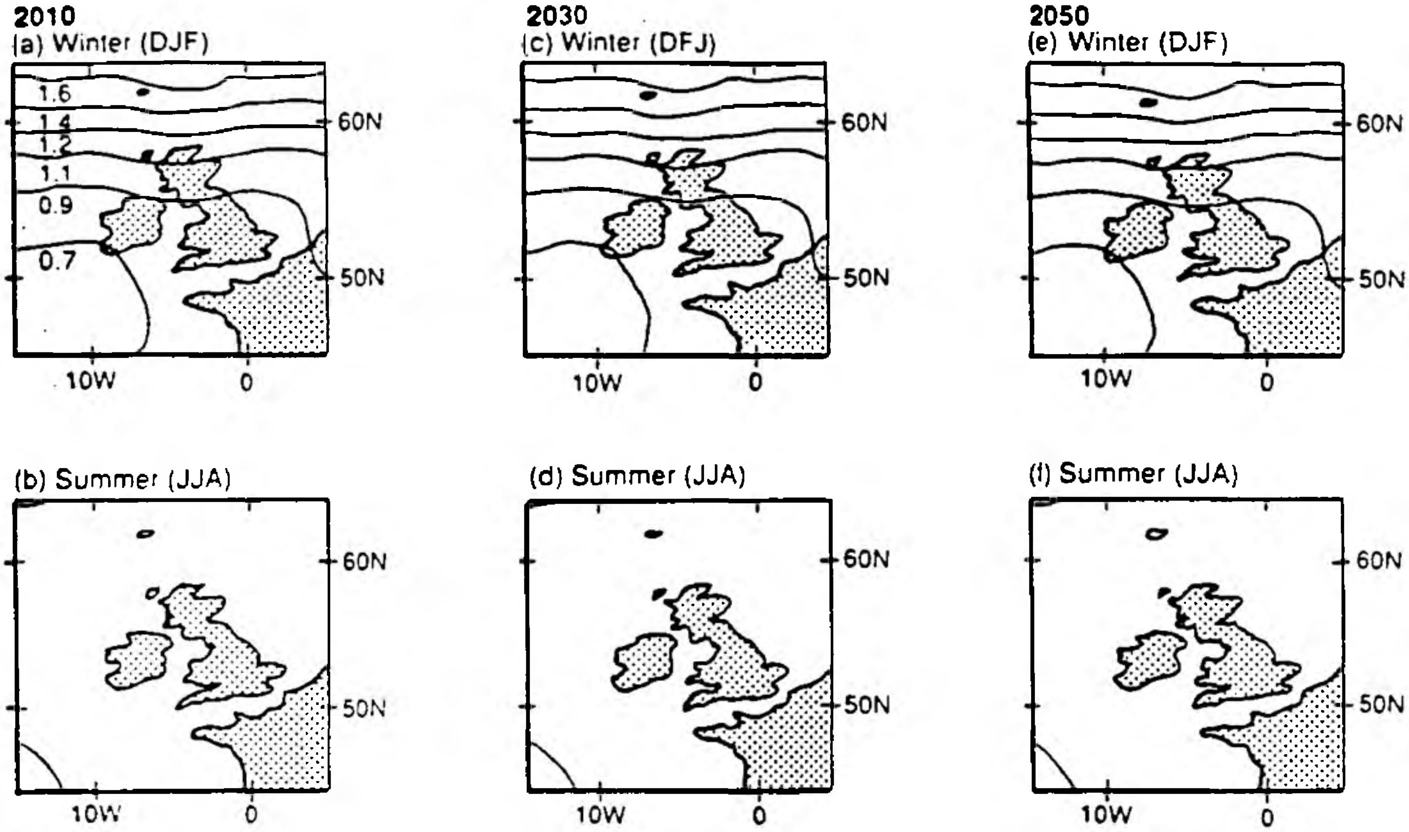
7.2.1 It should be emphasised that all the figures are essentially scenarios, but given the strength of some of the IPCC conclusions, figures for temperature and sea level are probably quite reasonable predictions.

7.2.2 **Global temperature** - because of the differences in the models there are variations from IPCC figures, by 2010 +0.7°C; by 2030 the range is a rise of between 0.7-2.0°C, best estimate 1.4°C; for 2050 2.1°C. These compare with best estimates of 0.5°C, 1.1°C and 1.7°C from the IPCC.

7.2.3 **Summer temperature** - temperature change would be uniform across the UK (Fig.12) and approximate the global mean, thus +0.7°C for 2010, +1.4°C for 2030 and +2.1°C for 2050. By 2030 the mean summer temperature for southern England would be 16.7°C. Using the normal distribution basis discussed earlier the probability of a summer with a mean as high as 1976 changes from 0.1% to 10% by 2030 (Fig.13).

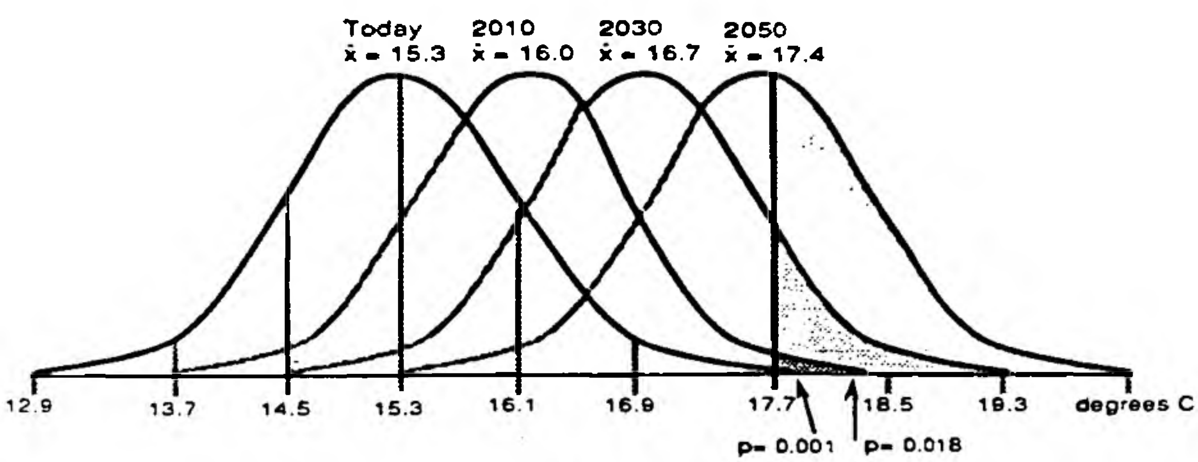
7.2.4 **Winter temperature** - winter temperature change would show a southwest/northeast variation with greater warming towards the north (Fig.12). By 2030 winters would be warmer by between 1.5-2.1°C, by 2050 2.3-3.5°C. The probability of winters as severe as either 1946/47 or 1962/63 would be less than 0.001%.

Fig.12 Estimated Seasonal Mean Temperature for the U.K. 2010, 2030, 2050. Changes from 1990 (U.K. group 1991)



7.2.5 Precipitation - both summer and winter precipitation are extremely difficult to predict from the models. The mean annual precipitation for the 5 models shows a change of +33%, but this is mainly in the winter, and summer estimates vary from both positive to negative. Because of the uncertainties neither increased convective rainfall nor a reduction in the effect of mid-latitude storm tracks are considered likely scenarios at present. As a general scenario the UK group assume a 0 change in precipitation but with high variability. It is worth noting that the group does not take account of the findings of the UEA study which examined the variability of precipitation and believed there had been increased variability in the 15 years up to the mid-1980's (Wigley and Jones, 198[illegible]). This study is however now being extended in view of the critical importance of precipitation variability.

Fig.13 Use of the normal distribution to predict the likelihood of climatic 'events' (UK Group). Example of the 1976 temperatures.



7.2.6 **Summer precipitation** - estimates are 0±5% for 2010, 0±11% for 2030 and 0±16% for 2050. Using these figures a range of probabilities can be derived for recurrences of major anomalies such as the drought of 1976 (Table 4). Thus for a '1976 event' by 2030 the probability could be as high as 0.02 or as low as 0.0022. This is however only in terms of precipitation and does not for instance take into account changes in evaporation. The likelihood of a sequence of events can also be estimated by assuming a normal distribution; the 1975-1976 sequence would have a probability between 0.0032 - 0.0000 by 2030. Santer et al. (1989) from their synthesis of models for Europe suggest a decrease for summer but the amount is expressed as the probability of a decrease rather than an actual figure.

Table 4 Exceedance Probabilities for Dry Summers Based on Baseline Probability from 1873 - 1987 Data . BaU Scenario: Year and Change In P (%).

Analogue Years	Baseline Probability (P)	2010 -5 %	2010 +5 %	2030 -11 %	2030 +11 %	2030 -16 %	2030 +16 %
1976	0.0071	0.0119	0.0043	0.0207	0.0022	0.0314	0.0012
1975 - 76	0.0005	0.0013	0.0000	0.0032	0.0000	0.0063	0.0000

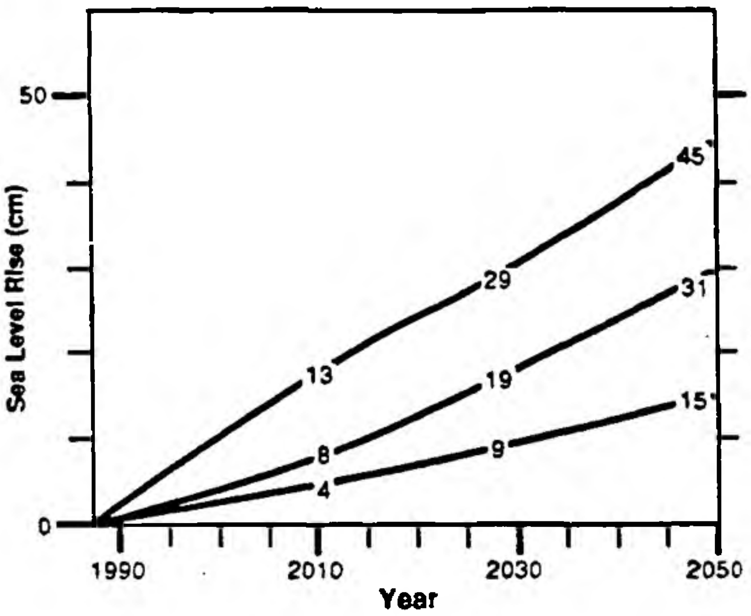
7.2.7 **Winter precipitation** - all models predict an increase in winter precipitation but also with high variability. Estimates are increases of 3±3% (2010), 5±5% (2030) and 8±8% (2050). The likelihood of extremely dry winters will be reduced and despite increased temperatures there should be little effect on available moisture during the winter months. Santer et al. (1989) suggest a probability of 0 change for December, January, February.

7.2.8 **Soil moisture** - the UK group make no specific predictions regarding soil moisture but map maximum potential summer soil moisture deficits for current climate and by use of adding standard deviation results demonstrate those areas most at risk for enhanced deficits. Even for the South West an extreme scenario of enhanced deficits equivalent to the present mean + one standard deviation would affect most of the lower areas.

7.2.9 **Other climatic parameters** the UK group make no estimates concerning other climatic variables emphasising the difficulty of predicting phenomena that are strongly related to regional patterns and circulation effects that are below the grid scale of the models.

7.2.10 **Sea level** - the results for global sea level from the chosen models are virtually identical to the IPCC figures despite the differences in the modelling processes. The estimated rises are for 2010 +8cm (range 4-13cm), 2030 +19 (19-29cm) and 2050 +31 (15-45c m) (Fig.14). These will vary according to local conditions of land stability but as far as South West England is concerned, unless there are specific areas prone to land movement it is reasonable to assume a relative stability of the land surface as demonstrated by Shennan (1989)(App. C). Limited data quoted in the UK group report show that at certain stations in the South West there is measurable downward movement of the land, for Newlyn -0.3mm year^{-1}, and a probable net downward movement at Devonport, but there are few sites with sufficient reliable data to establish detailed patterns. The impact of higher sea levels will also be felt if they are associated with greater storm frequency or a greater likelihood of surges, but given the uncertainties over the probabilities of more extreme events it is not possible to accurately estimate potential impacts in South West England. Potential overall effects in the UK have been discussed in Doornkamp (1990).

Fig. 14 Estimated sea-level rise figures used by the UK Climate Impacts Group.



7.2.11 General comments - the UK group make the point that because of the latitude of the UK it would be unwise to extraploate a general climatic regime for the UK in the 21st century. Although mean values for temperature may be similar to the Mediterranean there would be no wet/ dry season pattern. They also point to the 'climate change commitments', those changes to which the world is already committed due to the level of past and present greenhouse gas concentrations, especially the effect on world sea levels.

7.3 Potential impacts of significance for the NRA

7.3.1 For the NRA with responsibilities 'to conserve, redistribute, augment and secure proper use of water resources' there are a number of areas within which potential impacts can be defined associated with the parameters outlined above, and these are defined in the following section.

7.3.2 Temperature changes

7.3.2.1 With warmer temperatures, particularly in the summer, there is likely to be an increase in demand, especially for domestic and agricultural use. The planned general rise in demand for the UK of 1% pa would therefore be likely to be exceeded in the South West, particularly if tourism expanded in the coming decades. This demand would be most noticeable at peak times. Demand in the winter is unlikely to change by such an amount but an increase in the length of the growing season could spread agricultural and horticultural demand.

7.3.2.2 Higher summer temperatures and lower or equivalent summer precipitation would lead to a deterioration in water quality with greater problems of pollution control and hence increased treatment costs. Such costs would be extra to those already planned for improvement of water quality to meet EC standards. A greater incidence and longer extent of low flows could cause problems similar to those of 1990 when the overall length of polluted stretches increased and lead to algal blooms on a more regular basis. The latter problem could become especially acute in reservoirs with more stable thermal stratification.

7.3.2.3 Disease would become a greater problem in fish stocks with warmer winter conditions and lower summer flows. It has also been suggested that if the full impacts of warming are felt there will be changes in the range of species, and in the south salmonids, especially trout, would find conditions less encouraging. The general thermal requirements of different fish species at different stages of their life cycle are well known so it will be possible to evaluate likely effects. What will be more difficult to estimate will be the potential changes in food sources e.g. invertebrates, as a result of warming.

7.3.2.4 Warmer summers and greater soil moisture deficits would enhance structural problems and cause a greater incidence of summer bursts. To some extent this would be offset by reduced winter bursts as the probability of very low temperatures was reduced.

7.3.2.5 Over the longer timescale a significant shift in temperatures could lead to changes in agricultural and forestry practices which might have knock-on effects on demands for water and water quality. It is unlikely that such major shifts would happen this century but given changing economic circumstances, especially in the light of EC agricultural policy there may be some temptation at diversification in expectation of improved climate.

7.3.3 Precipitation changes

7.3.3.1 The potential demand and resource problems associated with equal summer rainfall but higher temperatures have been dealt with in 7.3.2.1 above.

7.3.3.2 The increase in winter rainfall could have a beneficial effect on resources but if reservoirs are at capacity then much will be lost as runoff. There is obviously a need to understand the particular characteristics of individual storage catchments to decide whether there is likely to be a problem.

7.3.3.3 The problem of greater intensity of rainfall events is one which remains. There are no grounds for expecting an increase in winter intensities but neither is there any indication of how additional winter rainfall will be distributed, this must await more detailed modelling over the next decade. Nevertheless it would be prudent to assume that there could be an increase in winter intensities but not of a significant order. Ironically the UK group also consider the potential problems of the added probability of very dry winters; this too is speculative on the basis of present models but if the distribution of precipitation was to be affected by changes in mean values, greater year-to-year variability would become a problem.

7.3.3.4 Drier summers or summers with equivalent rainfall but higher temperatures could lead to less summer flood events but it is also possible that extreme summer events could increase. Again there is no model evidence for this but an increase in 'hot' days could lead to added convection and associated storm events. Similarly, a variation in summer circulation could lead to more days with hot unstable air being drawn in from the south. At the moment these are major uncertainties but should be considered as possible outcomes. More intense events with high runoff both in summer and winter could involve higher pollution loads and lead to associated problems for quality. The possible effect of higher precipitation leading to amplified runoff (daCunha, 1989) requires some evaluation.

7.3.4 Higher sea levels

7.3.4.1 Higher sea levels would affect any water extraction direct from sources near the coast and also from groundwater close to the coast but this effect would soon disappear upstream.

7.3.4.2 The impact of higher sea levels would be felt most in those areas prone to sea flooding during extreme storm events. There is still no evidence for increased frequency of either extreme storms or surges (mainly a North Sea phenomenon) but with sea level increases as a 'commitment' which cannot be avoided, at least over the next century, there would inevitably be an added threat at some locations. This is not as apparent in the South West as in other areas of the UK but given the cost involved still represents a significant potential problem. Further problems could occur if changes in sea level lead to offshore changes and shifts in deposition and erosion along coasts. It is uncertain whether the amount of rise would lead to such results but areas of coast which are prone to change would require monitoring.

7.3.5. General comments

7.3.5.1 As far as the South West is concerned it will not be until the end of the decade that sufficient regional models are available to validate and compare the results which they provide. In the intervening time it is therefore necessary to work on the basis of the scenarios outlined above. Some of the potential priorities for action have been outlined by Parry and Read (1988) and are summarised in Table 5.

7.3.5.2 The single weakest area of climatic prediction as it is related to the NRA is the lack of ability to estimate variability rather than mean conditions. It is therefore not possible to accurately estimate future total effective precipitation nor to evaluate the probability of serious extreme events.

Table 5 Impacts and Sensitivities of Climatic Variability on the Water Industry (adapted from Parry and Read, 1988). Key: Importance / cost; H - High, m - medium, L - Low.

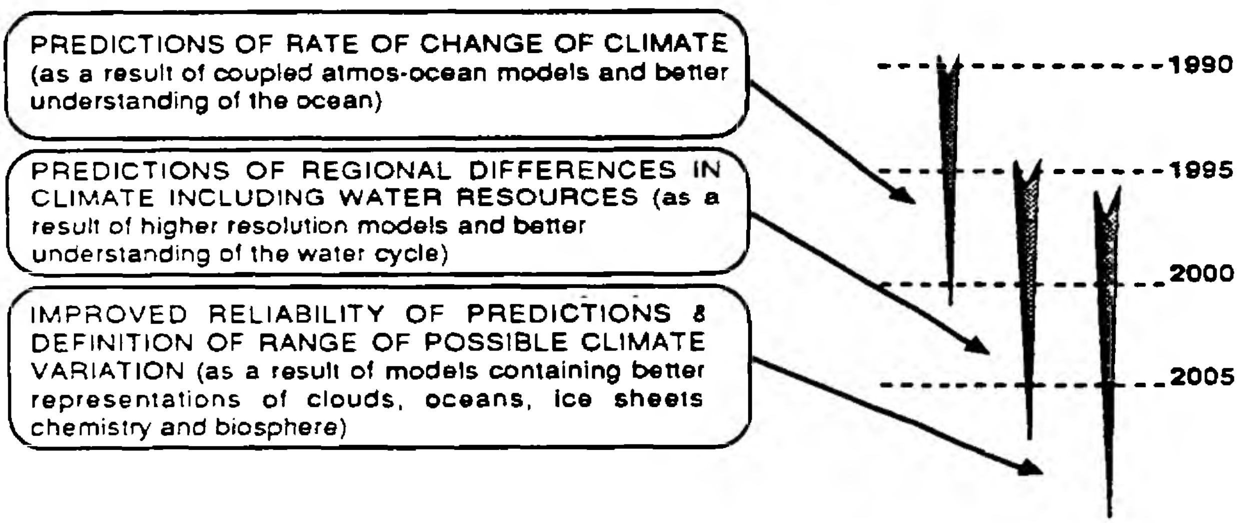
Climatic Effect	Water resources	Water treatment & supply	Sewerage treatment & dispersal	Pollution control	Land drainage	Sea defences	Fishing / conservation / recreation
Higher Rainfall	L/L	H-M/H-M	H/H	H-M/H-M	H/H		
Drought	H/H	H/H	M/M	H-M/H-M			H/L
Higher Temperature	M/M	L/L		M/M			H/M
Higher Sea Level	H-M/H-M	H-M/H-M				H/H	

8. Points For Consideration by the NRA

8.1 General points

8.1.1 It is of critical importance that the NRA recognises the timescales involved, not only in terms of future climatic changes but also in improvement of understanding of the problem. For the period until 2030 the scenarios are reasonable and where 'commitments to climate change' are concerned they should be taken seriously. Beyond 2030 estimates are highly uncertain and the nature of changes will very much demand on global responses, especially once genuine greenhouse gas effects are detected around the end of this century. On the shorter timescale i.e. up to 2010 it is likely that any changes will be broadly within current experience. In planning major expenditure it would be wise to limit the timescale to 2030 and accept the 'best estimate' figures as a guide. If possible very expensive areas should be held in check until the end of the century by which time a combination of possible warming detection and improved UK models will provide a much clearer picture of probable conditions in the next century (Fig. 16). Planning based on the concept of return periods derived from historical data cannot yet be supplemented by any improved predictive form but if gross climatic conditions do alter it will be necessary to re-evaluate the approach.

Fig. 16 Timescales for Narrowing Uncertainties



8.1.2 Because of the many uncertainties it will be necessary to develop a series of priorities in dealing with areas which could be affected by global warming and some suggestions along these lines are made below under more specific comments. In the Executive Summary of the IPCC Report the conclusions are detailed under a series of headings indicating the status of current (1990) knowledge: We are certain of the following....[this defines only increased emission levels]: We calculate with confidence that....[again still on the gases themselves]; Based on current models we predict....[covering only temperature and sea level];and..Our judgement is that.... [includes detection and variability uncertainties]. From this is it is clear that at present priority can only be given with confidence to those areas for which there is a reasonable consensus of scientific opinion, mainly relating to global temperature and sea-level change. Determination of priorities should therefore be made on the basis of agreed probable scenarios and the cost implications i.e. whether it would be more prudent to await clearer scientific evidence. To some extent such advice goes against the findings of the WCP (1988) who advocate a more prepared stance but seems rational where there are competing requirements for resources.

8.1.3 There is a need for an informed watching brief on developments. The area of global warming is one in which there a lot of current activity and this will only increase. Despite the programme of international research stretching out into the 21st century (Appendix B) there are constant developments taking place. In the US there is now a regular monthly Greenhouse Effect Report available for business subscribers providing a policy update on global warming and world climate. Because it is a popular issue with the press it is necessary to be aware of the significance of any relevant items published either nationally or locally. The selective items printed from the UK Climate Change Impacts Review Group Report to the DOE in January 1991 provides a case in point, as does the report in early January of work from Edinburgh on the role of the Greenland ice cap in sea-level change. The final recommendation of the Report of the U K group to the DOE in the section on the water industry was, 'In view of the long lead time required to plan, agree and develop water resources, the industry and the NRA require guidance on climate change at the earliest opportunity so that the implications can be assessed'.

8.1.4 There is an important role for PR in responding to the potential problems of global warming, not only in providing informed responses to the public but also in informing all those making decisions or affected by decisions within the organisation. Over the next decade until it is possible to demonstrate more clearly that the Greenhouse Effect is real, it will be difficult to persuade many people that it is worth taking seriously. There is no reason to believe that we are not likely to experience typical climatic variability, despite warming, and hence have a wet, cold summer or even two by 2000. In the light of such events persuading the public that it is worth spending money on global warming problems will need well-informed communication. Similarly, if there are further dry summers, it will be difficult not to be pressured by public opinion into 'panic measures'.

8.2 Specific points

8.2.1 Highest priority will probably need to be given to planning water resources to cover possible climatic developments over at least the next two decades, and more valuably to 2030. For this purpose it would be sensible to run any model of future resource availability and allocation to incorporate the worst estimates of the BaU scenario to 2030, and to account for possible increases in demand outside those postulated as a result of global warming. For the South West this could involve expansion of tourist demand, which itself could increase if summers were noticeably warmer. There are inevitable difficulties in developing good integrated models of resource availability and demand, especially where the physical model relies of extrapolating down from global to regional and finally to drainage basin scale, but relatively coarse results to cover the immediate time scale could be obtained.

8.2.2 Priority should also be given to evaluating the effect of warmer temperatures throughout the year on river systems with respect to pollution problems, the response of aquatic flora and fauna and general water quality. This will require evaluation of the relationship between air temperature and water temperature and its variability across catchments. It may be necessary to reconsider levels of maximum permitted loads of chemicals to be discharged into rivers.

8.2.3 As far as sea level is concerned it will be necessary to identify those areas most at risk at the predicted levels and plan defences or response strategies accordingly. Here again it would wise to use the extreme BaU scenarios for planning to 2030 but it would also be necessary to look at local rates of land subsidence evidence which might also affect theamount of rise, if the data is available. Because of the 'commitment' to a rise but the uncertainty of the amount involved it may in some cases be financially preferable to consider soft defences over the immediate timescale, i.e. 10-20 years, with more expensive long-term schemes put off until trends are clearer and estimates more accurate.

8.2.4 There may be more small scale problems of relevance to different areas of NRA activity which could be identified at an early stage and kept under review. This could include biotic changes such as possible stress on Sitka Spruce which might affect reservoir behaviour, or general changes in soil structure as a result of changes in the regime of soil moisture. In the future these could cause problems but do not need immediate action at present.

9. Conclusion

9.1 There is a strong body of theory behind the idea of a Greenhouse Effect which will lead to global warming but the whole area remains one which is 'theory-rich and data-poor' (Harriss, 1989). Many would argue that the first signs of warming are apparent in various climatic records but such a view cannot be adequately validated at present, and it is likely to be at least into the next century before a genuine signal can be isolated from all the other climatic noise. The view of the George C. Marshall Institute in the USA two years ago that 'It is our judgment that if a prudent investment is made in computing power, observing programs and added manpower, answers that have a usable degree of reliability can be provided for policy makers within 3 to 5 years', is a gross simplification of a highly complex problem, and this view has been rejected several recent meetings (e.g. Andreae and Schimel, 1989).

9.2 Options for responses to the potential changes have been discussed at all levels and Working Group II of the IPCC has specifically evaluated the impacts to assess the sort of responses possible, and prepare material for Working Group III where governments and policy makers are represented. Thus although individual institutions will have to cope with whatever the nature of the changes are, there will also be national and international policies and guidelines. If the change in climate is near to the worst scenarios then it is likely that there will be quite a strong legal input into coping with the changes. There are essentially two possible types of responses to global warming, limitation or adaptation (WCP, 1988). Most of the international attention tends to focus on the former whereas at the national and institutional level adaptation is more likely to be needed. As far as the NRA is concerned both strategies are likely to be required. Indirectly limitation will be required e.g. to reduce the input of chemical or organic pollutants into warmer, low-flow rivers, but mostly the NRA will be dealing with how to adapt its various responsibilities to sytems that may, in the worst cases be very different from those peviously experienced.

9.3 With a problem as complex as global warming, for which there are extremely contrasting opinions amongst scientists, and a high level of ignorance and misunderstanding even among informed public opinion, the response of any institution likely to be affected needs to be measured, well informed and flexible. There will inevitably be the danger of a 'British Rail' form of response, to be very well prepared, but for a manifestation of the problem in a slightly different form to that expected. By careful monitoring and wise use of resources it should be possible to avoid such a course and the inevitable lack of government and public confidence that would ensue.

10. Summary

1.Greenhouse Effect: Definition, History and Recent Developments. The term Greenhouse Effect refers to a natural process whereby warming of the lower atmosphere is enhanced by the ability of certain trace (greenhouse) gases to absorb and re-radiate long wave radiation emitted from the earths surface. Although recognised for over 150 years the potential impact of these gases, especially CO_2, CH_4 (methane), N_2O (nitrous oxide) and CFCs, has only excited world interest over the last two decades. In this time a variety of scientists have modelled the possible climatic impacts and produced a variety of estimates of likely climatic change. International co-operation has seen the establishment of the Intergovernmental Panel on Climate Change (IPCC) which met in 1990 in Geneva, and has also published the most up-to-date scientific assessment of the problem (Houghton, 1990). In the UK this formed part of the basis for Report to the DOE by the UK Climate Change Impacts Research Group in January 1991, The Potential Effects of Climate Change in the UK.

2. Greenhouse Gas Emissions - Predicted Changes and Their Role in the Climate System. Measurement of the concentration of greenhouse gases is made from ice core evidence and current monitoring programmes. CO_2, which is mainly released due to burning of fossil fuels, has risen from pre-industrial (pre-1765) levels of 280ppmv to 353ppmv in 1990, and accounted for 61% of total radiatve forcing (the amount of extra radiation trapped) for the same period. For the most extreme scenario adopted by the IPCC, the Business-as-Usual scenario, this value would rise to between 800-850ppmv by 2100. Because of the long atmospheric lifetime of CO_2 of 50-200 years, the time it is retained in the atmosphere and hence is 'active', concentrations are certain to continue to rise, and will be at 575ppmv in 2050. CH_4, although it has a shorter lifetime of 10±2 years, has a greater Global Warming Potential (GWP) relative to CO_2 and is increasing at 0.9% pa, mainly due to agriculture, especially rice paddies. CFCs which derive from propellants and refrigerants have an even higher GWP, up to 7300 times that of CO_2, and have lifetimes up to 400 years. Thus despite the limitations on use as a result of the 1987 Montreal Protocol the effects will be long lasting. For CFC-11 estimates are for concentrations of 630pptv by 2100 under BaU (1990 - 280pptv). For N_2O which has a range of sources and a lifetime of 150 years concentrations have risen from pre-industrial levels of 285ppbv to 310ppbv in 1990, and estimates of 418ppbv in 2100. Other trace gases such as stratospheric and tropospheric ozone (O_3), and CO, also increase radiative forcing, but to much lesser extents.

3. Greenhouse Gas - Climate Links: Climate Models and Predictions. The influence on climate due to radiative forcing from greenhouse gases is inferred through modelling. Although there is some use of Palaeo-analogue models utilising past climatic evidence, most modelling is numerical using Global Climate Models (GCMs) which attempt to model various aspects of the climate system. The IPCC assessment synthesises the results of 20 models run for a doubling of CO_2 (CO_2x2) to ascertain common trends and results. The recent development of coupled atmosphere-ocean-terrestrial models which require extensive computer time but are more 'realistic' promises to provide a better model base. There are many problems with GCMs, both due to the need to represent the global scale and due to uncertainties over major feedback processes in the atmosphere which are poorly understood, the effect of water vapour, of clouds and of the albedo effect of snow and ice. Validation of the model results is achieved by running for current conditions and comparing with observational evidence but this too is made difficult by limitations of the observational data. At the regional scale there are as yet no models available for the UK; a Meteorological Office model is being developed but is not expected to produce acceptable results until the end of the decade. At the global level the following general predictions derive from the GCMs: temperature - a general global rise between 1.9-4.4°C with a best estimate of 2.5°C, and greater warming at higher latitudes; precipitation - more difficult to estimate, but probably a net increase with greater winter precipitation between 35-55°N; variability - there is no evidence for any change in the nature of climatic variability, but again this is an area of uncertainty.

4. Natural Climatic Variability - **Detecting the Influence of Greenhouse Gases.** Detection of change which can be 'attributed' to greenhouse warming is made difficult by the natural variability of climate. Observational data to 1990 shows changes which are consistent with some of the model predictions but which are also well within historical varaiability. Over the last 100 years there has been a rise in global mean temperature between 0.3-0.6°C, but there has been no enhanced warming in higher latitudes. The use of 'finger prints' for detection, changes that are specific to model predictions e.g. troposheric warming/stratospheric cooling, has been suggested but these are still too difficult to detect in a system with a high signal-to-noise ratio. Assuming that it will be necessary to see at least another 0.5°C rise in global temperature to be able to detect greenhouse warming, this may be seen by the early 21st century under the BaU scenario. Before then there will be no possibility of confirming any of the predictions of the GCMs.

5. Sea-Level Change. As a result of warming a major area of concern will be possible sea-level rise. Over the last 100 years, despite a very limited global data base, it has been estimated that global sea level has risen at rates of between 0.5-3.0mm $year^{-1}$. 40% of this rise has been accounted for by thermal expansion of the oceans, a similar figure to that for the melting of mountain glaciers and ice caps. Limited data for Greenland suggest a contribution of 20-25% whilst the net contribution of Antarctica has been to remove moisture as the higher temperatures allow greater accumulation of snow, -0.2 to -0.38mm $year^{-1}$. Because of the lags in the response of oceans to climate future sea-level rise is highly probable as it is an area where there is a 'commitment' to change. By 2030 a 'best estimate' of +18.3cm is predicted (10.1cm - thermal, 7cm from glaciers, 1.8cm from Greenland and -0.6cm from Antarctica). By 2100 sea level could be anywhere between +31-110cm; even if all forcing were to cease by 2030 there would still be a rise of 41cm over present by 2100.

6. Ecosystem Change. The impact of global warming on ecosystems has received less attention han mo: -other areas, although a number of potential changes have been identified - possible increases in productivity and storage of carbon, changes in the distributions of species and communities, and a greater overwintering of pests and pathogens in higher latitudes. There is also a feedback between ecosystems and climate with possible enhancement of the greenhouse warming by changes within ecosystems e.g. the melting of permafrost and changes in tundra areas.

7. Climate and Sea-Level Change in the UK. Although the IPCC data provides a global basis against which the position of the UK can be evaluated, the UK group has derived predictions, or rather scenarios, for the UK based on a selected group of the most advanced GCMs, using the BaU scenario for CO_2x2. In the UK summer temperatures are predicted to rise by levels equal to the overall global figure,+0.7°C by 2010, +1.4°C by 2030 and +2.1°C by 2050. Winter temperatures would show greater warming with a SW/NE gradient and figures of between +1.5-2.1°C by 2030, and +2.3-3.5°C by 2050. Assuming no change in the distributional pattern of temperature through the seasons the probability of a 1976 'event' would become 1 in 10. Summer precipitation is predicted to be similar to today but with high uncertainty (0±5% for 2010, 0±11% for 2030, 0±16% for 2050). Winter precipitation is similarly uncertain but very likely to rise, +3.3% by 2010, +5.5% by 2030 and +8.8% by 2050. Thus soil moisture will be similar to today during

the winter, but there will be a greater problem of soil moisture deficits in the summer. The estimates for sea-level change are very similar to those of the IPCC, +8cm by 2010 (range 4-13cm), +19cm by 2030 (19-29cm) and +31cm by 2050 (15-45cm). There is no basis for predicting any greater intensity of storm events or any greater variability in climate for the UK on the present evidence. The increase in summer temperatures is likely to lead to an increase in demand for water and for greater problems of meeting that demand. With a higher probability of warmer summers the increased winter precipitation is unlikely to offset the problem of storage. The increase in temperatures and greater probability of low flows will also have a potential impact on water quality and the ability of rivers to cope with pollutants. Greater stability of water bodies encouraging thermal stratification will also encourage the development of algal blooms. Although there is unlikely to be a problem from an increase in the frequency of extreme events, the possibility of more intense summer storms has to be considered. The main impact of higher sea levels will only be felt at those locations currently under threat from inundation although it will be necessary to survey all other locations which may become more threatened. Only if fresh water extraction takes place near to current sea level will there be a problem in the future.

8. Points for consideration by the NRA. It is of major importance that all planning takes consideration of the timescales involved. Up to 2030 the 'best estimate' figures are reasonable planning guides, especially where there are 'commitments to climate change' involved, as in sea levels and probably global temperature. Beyond 2030 the future effects of international responses to an acknowledged warming is likely to influence change and the worst estimates should be very unlikely. Current knowledge is remarkably limited in many areas but the recent impetus given to studies of all relevant aspects means that there will be a considerable expansion of knowledge over the next decade. Thus by 2000 the predictions will be more reliable and available at the regional scale, furthermore by then it should be possible to detect whether warming is actually occurring with greater confidence. For planning therefore it would be sensible to be flexible for the next decade with a view to more concrete responses in the early part of the next century. It will be necessary to develop a series of priorities for action and investment. Of highest priority will be an evaluation of the ability of the regions water resources to meet possible demands up to 2030, given a range of scenarios of climate and demand. There will also be a need to develop models which will ascertain the local effects of increased temperatures on water quality. Although not threatened to the same extent as other areas of the UK there will need to be a review of sea defence schemes to account for estimated levels, at least up to 2030. Because of the need for up-to-date informed decisions it will be advisable to closely monitor developments in the whole field of global warming and to communicate the state of knowledge both within the NRA and to customers and the general public. In the light of ever increasing media coverage it will be vital to be able to respond with convincing and reasoned answers to the inevitable questions and comments that will appear over the next few years.

9. Conclusion. Whilst recognising the potential gravity of global warming for all areas of NRA interest, it should also be noted that not all scientists are as convinced about the threat as those whose results are summarised in the IPCC reports and in the UK Climate Change Impacts Research Group. The whole problem is one which is 'theory-rich and data-poor', and it is only with the course of events over the next 10-20 years that the reality of the climatic responses to the presence of ever-increasing concentrations of greenhouse gases will observed.

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Appendix A Emissions Scenarios used as basis for assessments by IPCC (1990)

The following scenarios provided the basis for the range of assessments and predictions used by Working Group I of the IPCC, the group charged with the assessment of the information presently available on climate change and the links with athropogenic influences on the atmosphere. It should be noted that the other two working groups concerned with assessing the impacts of climatic change and response strategies did not use these specific scenarios as the groups worked in parallel. They did however use broadly similar estimates. The scenarios cover emissions of CO_2, CH_4, N_2O, CFCs, CO and NO_x to 2100.

Common to all scenarios were the following assumptions:

i) World population would be ca. 10.5 billion by the second half of the next century.
ii) Economic growth 1990-2000 would be 2 - 3% per annum for OECD (developed) countries, 3 - 5% per annum for East Europe and developing countries. After 2000 all these rates would decrease.

Scenarios:

A - Business-as-Usual (BaU) - coal intensive energy with only modest improvements in energy efficiency. CO_2 controls modest. Tropical forest depletion. Uncontrolled CH_4 and NO_x emissions from agriculture. Partial implementation of Montreal Protocol for CFCs.

B - Shift in energy mix to lower carbon fuels. Large efficiency improvements. Severe CO control. Tropical forest removal reversed. Full Montreal Protocol implementation.

C - Shift to renewable and nuclear energy after 2050. CFCs phased out and limited CH_4 and NO_x from agriculture.

D - Shift to renewable and nuclear energy before 2050 with an approximate stabilisation of emissions from industrialised countries. By 2050 CO_2 emissions at 50% of 1985 level.

Appendix B The structure of current and future global research

Research into all aspects of future climatic change is taking place at international level although within this framework there are also many separate national studies. The strategy for future research is largely determined within the World Climate Research Programme (WCRP) and the International Geosphere-Biosphere Programme (IGBP). These programmes are sponsored by the International Council for Scientific Unions (ICSU), and in the former case also the World Meteorological Office (WMO). The IPCC, sponsored by the WMO and UNEP (United Nations Environment Programme), acts to assess the current status of knowledge and is therefore a body which links all these programmes with governments and the world community as a whole. Within the WCRP and IGBP there are a number of major projects addressing specific aspects of the problem which highlight current areas of deficiency:

1. Control of greenhouse gases by the earth system.
2. Role of clouds in radiation control.
3. Precipitation and evaporation.
4. Heat transport and storage in the oceans.
5. Ecosystem responses.

The success of these, especially over the very limited timescales available, will depend upon the success of international and inter-governmental co-operation and funding, as well as the commitment to improve monitoring and observation of the processes involved, especially climatic processes.