History of the greenhouse effect

by M.D.H. Jones and A. Henderson-Sellers

The greenhouse effect is now commonly accepted by the scientific community, politicians and the general public. However, the misnomer 'greenhouse effect' has perpetuated, and there are a number of aspects of the effect which are poorly understood outside the atmospheric sciences. On such misconception is that greenhouse research is a recent phenomenon; another is that glasshouses are warmed by the same mechanism as lies at the heart of the greenhouse effect. This review traces the theory as far back as 1827, highlighting new directions and significant advances over that time. Four main themes can be discerned: 1) certain radiatively active gases are responsible for warming the planet; 2) that humans can inadvertently influence this warming; 3) climate models are designed to permit prediction of the climatic changes in the atmospheric loadings of these gases but that they have not yet achieved this goal of prediction; and 4) many scenarios of changes, and especially of impact, are premised on relatively weak analysis. This latter point is illustrated by an examination of the relationship between increasing temperature and sea level change (the oceanic response to atmospheric warming). Current research suggests that sea-level rise is not likely to be as high as had previously been anticipated.

I Introduction

The greenhouse effect is a sustained, natural phenomenon: gases which are radiatively active have 'warmed' the surface of the Earth since the planet and its atmosphere were formed about four and a half billion years ago. Mankind's activities, particularly those associated with industrialization, large-scale land clearance and chemically improved agriculture, are adding increasingly large amounts of these radiatively active gases to the atmosphere. At present there seems little likelihood that this global scale atmospheric pollution will cease much less that removal of the pollutants will be initiated. This planet therefore seems to be committed to a global scale warming, an intensification of the hydrological cycle (the coupled processes of evaporation, cloud formation, precipitation and runoff) and many associated climatic shifts. It is thus *essential* that policies be developed which recognize the reality of the predicted changes.

The greenhouse effect is an unambiguous theory which is well understood by atmospheric and climatic scientists and which successfully predicts temperatures on the Earth and on other planets. There are, however, a number of controversies associated with the greenhouse effect which are beloved by the media. These include:

1) The warming observed so far this century (Figure 1) cannot be stated unambiguously to be the result of additional greenhouse warming caused by mankind's activities. Moreover, *it is unlikely that such an unambiguous statement will be possible in less than 10 to 15 years.*
2) Precise predictions of the increase in the Earth's surface temperature resulting from a specified increase in one or more trace greenhouse gases differs somewhat from model to model as a function of the number of feedbacks incorporated and the realism of the physical parameterizations.
3) Reconstructions of the Earth's surface temperature (e.g. Figure 1) for the past century may be contaminated by the urban heat island effect.
4) The term 'greenhouse' is a poor one and probably not generally applicable to unheated horticultural glasshouses.

Nonetheless, the scientific basis for the predictions of global greenhouse-induced climatic change are very firmly founded. In 1985, a large (and representative) group of atmospheric scientists met in Villach, Austria – the result of this meeting was the 'Villach Statement' (see foreword in Bolin *et al.*, 1986) which has come to be recognized as a turning point in awareness of greenhouse issues. This statement opens by saying: 'as a result of the increasing concentrations of greenhouse gases, it is now believed that in the first half of the next century a rise of global mean temperature could occur which is greater than any in Man's history', and continues:

> Many important economic and social decisions are being made today on long-term projects – major water resource management activities such as irrigation and hydropower, drought relief, agricultural land use, structural designs and coastal engineering projects, and energy planning – based on the assumption that past climatic data without modification are a reliable guide to the future. This is no longer a good assumption . . . It is a matter of urgency to refine estimates of future climatic conditions to improve these decisions.

The question generally posed is whether policy actions are premature in view of the many remaining scientific uncertainties. This question is not one which should be directed to climatic scientists since it requires a value judgement, not a scientific evaluation. The question is simply whether individuals or the societies which they comprise fear rapid future change, which is potentially dislocating if not totally disruptive, more than they fear real financial cost levied now in order to implement policies ranging from engineering countermeasures and mitigation through reduced emission policies to orchestrated passive adaptation.

II The greenhouse theory

The greenhouse theory is based upon the fact (readily demonstrated by experiment) that whilst gases in the Earth's atmosphere are transparent to incoming solar radiation, some of them absorb outgoing thermal (or heat) radiation emitted from the Earth's surface. This radiative interaction between selected gases in the atmosphere (termed the greenhouse gases) and the outgoing heat radiation causes those gases to warm, and consequently they themselves

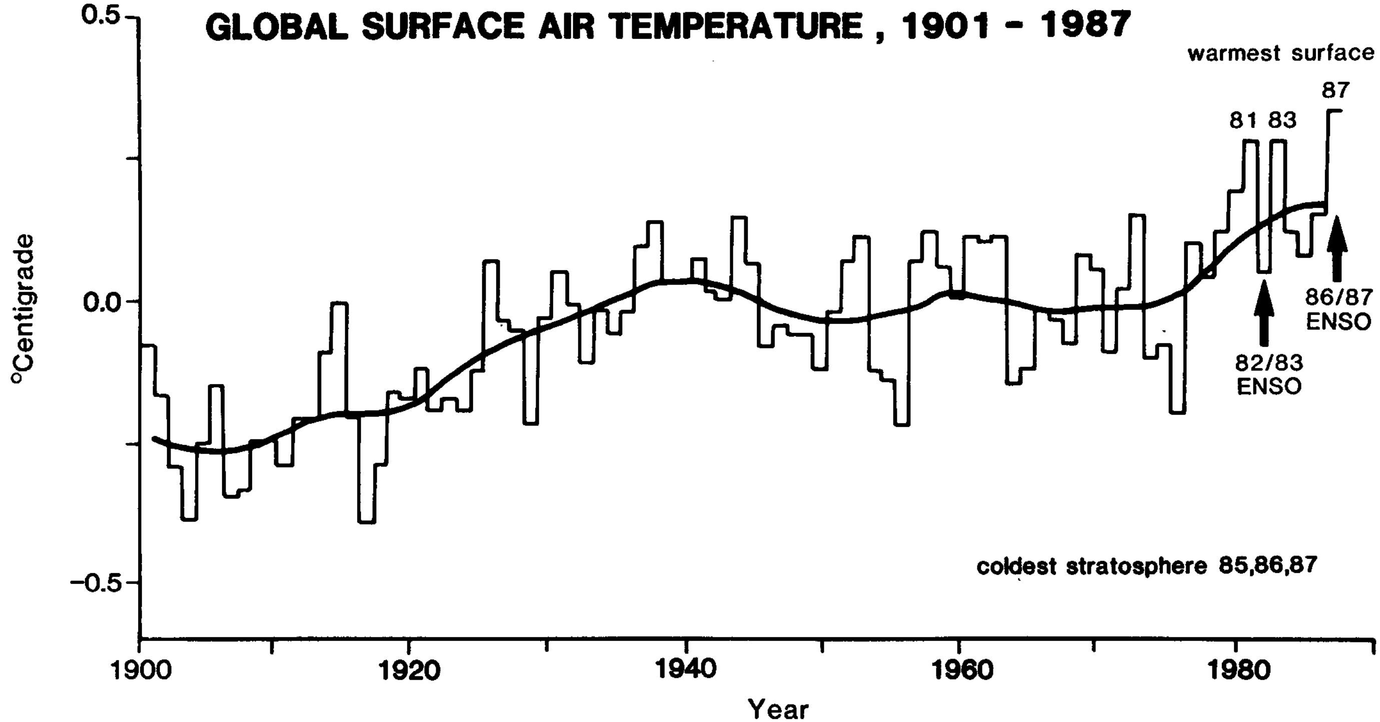

Figure 1 Measured globally-averaged (i.e., land and ocean) surface air temperatures for this century (derived from a variety of sources see e.g., Jones *et al.*, 1988). Note that the number and distribution of observations vary very widely through the century. Note also that there are two periods of 'warming': 1915–35 and 1975 to date. The latter period has been dominated by two large ENSO events.

reradiate heat in all directions. Some of this reradiated energy travels back down through the atmosphere to the surface and it is this additional heating of the surface over and above the heating due to the absorption of solar radiation, which is termed the greenhouse effect. 'Natural' greenhouse heating turns the Earth from a planet unable to support life with a global mean temperature of −18°C into its present habitable state with a global mean temperature of +15°C. Similarly, the dense, almost purely, CO_2 atmosphere of Venus causes that planet's surface temperature to be hotter than 500°C and a tenuous CO_2 atmosphere around Mars raises Martian surface temperatures only a little above the frigid atmosphereless state.

In the Earth's atmosphere, only trace gases (less than a few per cent of the total atmosphere) contribute to this greenhouse warming. These trace gases are water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), tropospheric ozone (O_3) and the chlorofluorocarbons (CFCs) although other gases such as carbon monoxide and sulphur dioxide also make very small radiative contributions to the surface warming.

The most significant greenhouse agent in the Earth's atmosphere is water vapour which contributes about 100 of the 148 watts of additional, radiatively induced heating of each square metre of the surface termed the greenhouse effect. Unfortunately, the amount of water vapour in the atmosphere is essentially uncontrollable as the major source is evaporation from the oceans. Mankind's activities do, however, modify the atmospheric water vapour loading since as temperatures rise in response to increases in CO_2 and other greenhouse gases, more water evaporates into the atmosphere prompting greater temperature increases and thereby inducing further evaporation. This strong positive feedback coupling between temperature and water vapour produces much larger temperature changes than would CO_2 and other gas increases alone.

Trends in the more important greenhouse gases have been established from measurements made over the decade 1975 to 1985. In that period the following increases were observed: CO_2 – 4.6%; CH_4 – 11.0%; N_2O – 3.5%; CFC11 – 103.0%; and CFC12 – 101.0%. The recognition of the main sources of these gases: energy production (CO_2 and CH_4); industrial activities (CO_2 and CFCs); agriculture (CH_4 and N_2O); and land clearance (CO_2 and N_2O), has prompted the use of simple equations (e.g., Schneider, 1989) such as:

$$\textit{Future greenhouse gas emissions} = \frac{\textit{emission}}{\textit{technology}} * \frac{\textit{effluent}}{\textit{capita}} * \textit{total population size}$$

where the first term represents the level of engineering skill, the second the standard of living and the third demography.

The reality of future greenhouse warming becomes all the more obvious when these terms are considered. The counties which are likely to achieve the 'cleanest' technology, i.e., who manage to decrease the magnitude of the first term, will probably see relatively small increases in population size while the developing nations which have very fast growing populations are also likely to employ very much 'dirtier' technology at least in the medium term.

III A brief history of greenhouse

The effects of radiative transfer of energy have been observed and described empirically for well over 100 years. Indeed heat was recognized as similar (and later as identical) to light (i.e., a part, albeit invisible, of the electromagnetic spectrum) by Herschel in 1800 (Scott Barr, 1961). Although theoretical understanding of the interaction between gases and radiation was impossible before the development of quantum theory in the early years of this century, the observation that certain gases absorbed heat radiation prompted the recognition over 150 years ago that there is considerable potential for mankind's activities to modify the natural radiative budget of the planet. Carbon dioxide was the first, obvious culprit and is, indeed, still used by most climate modelling groups as a surrogate for all radiatively active gases; hence experiments are still described as 'doubled CO_2' simulations.

Since the history of greenhouse is not well known outside the atmospheric sciences, the following review provides a brief summary of key papers within the field. Emphasis is placed on the historical context of the subject and the significant papers that represented new directions and advancements in the state-of-the-art knowledge at their time.

The initial research associated with greenhouse focused on the understanding of the role of carbon dioxide in relation to atmospheric processes and radiative transfer. The emphasis throughout the nineteenth century and early in the twentieth century focused strongly on long-term geological implications of changes in the carbon dioxide content i.e., as a means to understanding cyclical glacial theory (e.g., Chamberlin, 1899).

The French physicist, Fourier, was probably the first person, in 1827, to allude to the greenhouse effect when he compared the influence of the atmosphere to the heating of a closed space beneath a pane of glass. Fourier may also be credited with the suggestion that human activities could influence the climate (Ramanathan, 1988). In England, Tyndall (1861) conducted an analysis of the radiative and absorptive properties of atmospheric gases (primarily water vapour and carbon dioxide – referred to as carbonic acid). By investigating the relationships between aborption, radiation and conduction, Tyndall's study was among the first to attempt to calculate the infrared flux within the atmosphere.

Towards the end of the nineteenth century an increasing interest focused upon the atmospheric role of carbon dioxide. Langley (1884) appreciated the absorptive properties of the atmospheric gases and their beneficial effects on maintaining Earth surface temperatures at their present levels:

> The temperature of the Earth under direct sunshine, even though our atmosphere were present as now, would probably fall to −200°C, if that atmosphere did not possess the quality of selective absorption.

Langley's work (1884; 1886), although correct in principle, overestimated the effect (the surface air temperature if greenhouse gases were removed would be close to −18°C assuming that the planetary albedo retained its current value).

In 1895 Svante Arrhenius presented a paper to the Royal Swedish Academy of Sciences on '*The influence of carbonic acid* (carbon dioxide) *in the air upon the temperature of the ground*'. This paper was later communicated to the Philosophical Magazine and published in 1896. He disagreed with Tyndall's conclusion that the absorptive properties of water vapour were such that it made a larger contribution than carbon dioxide. He went on to calculate the variations in temperature under five different scenarios where carbon dioxide was 0.67, 1.5, 2.0, 2.5 and 3.0 times the observed atmospheric level (circa. 300 ppmv). He also calculated latitudinal variations from 70°N to 60°S. The mean global warming for a doubling of carbon dioxide was 6°C (not too far removed from the current estimates between 3–5°C). On the basis of his calculations, Arrhenius concluded that past glacial epochs may have occurred largely because of a reduction in atmospheric carbon dioxide. In 1903, Arrhenius further suggested that most of the excess carbon dioxide from fossil fuel combustion may have been transferred to the oceans, displaying a remarkable awareness of cycling processes.

Between 1897–99 T.C. Chamberlin presented a series of three papers detailing the geological implications of carbon dioxide theory. In 1897 he reviewed the current hypotheses of climatic change and in 1898 and 1899 postulated the effects that limestone-forming periods (e.g., Carboniferous, Jurassic and Cretaceous) may have had in contributing to subsequent glacial epochs.

Moving away from the carbon dioxide theory of climatic change, in 1909 the multitalented physicist R.W. Wood provided notes on a brief experiment suggesting that glasshouses retained heat through lack of convection and advection rather than through the glass absorbing and re-emitting longwave radiation. In other words, the 'greenhouse effect' as it has come to be known does not actually work for greenhouses. In more recent experiments the radiative component of the heating of glasshouses has been shown to be less than 20%.

A key paper in the history of terrestrial radiation studies is the work of G.C. Simpson in 1928a. By attempting to verify earlier calculations of outgoing radiation, Simpson identified the latitudinal variability of longwave radiation emissions (uniform between 50°S and 50°N decreasing at the poles by around 20%). The conclusions questioned the assumption that water vapour is the only constituent of the atmosphere which absorbs and emits longwave radiation, leading to the suggestion that carbon dioxide could appreciably modify the figures of outgoing radiation. This supposition was dealt with further in later works (Simpson, 1928b; 1929).

By the late 1930s the role of atmospheric carbon dioxide had re-emerged. Callendar in 1938 estimated that between 1890 and 1938 around 150 million tons of carbon dioxide had been pumped into the atmosphere from the combustion of fossil fuels, of which 75% had remained in the atmosphere. Further, if all other factors remained in equilibrium then anthropogenic activities would increase the mean global temperature by 1.1°C per century, another remarkable example of foresight given that state-of-the-art GCMs currently estimate that global temperatures should have risen by about 1°C since about 1880. Subsequent work (Callendar, 1949; 1958) reiterated the role of human climate forcing, suggesting that the increase in atmospheric carbon dioxide may account for the observed slight rise in average northern latitude temperature during the first four decades of the twentieth century. This was fundamentally a re-examination of the hypotheses of Arrhenius (1896) and Chamberlain (1899) in the context of human activities. This represents the transition from a theory of glacial climatic change through to the human influence on atmospheric carbon dioxide levels, and its subsequent role a a climate-forcing mechanism.

During the 1950s the development of the greenhouse theory took on new dimensions. Research moved towards calculating the temperature increase given an atmospheric doubling of carbon dioxide. Gilbert Plass (1956) calculated that the mean global surface temperatures would increase by 3.6°C if atmospheric carbon dioxide doubled and would decrease by 3.8°C if it halved. These estimates were strongly criticised by Kaplan (1960) who rejected the hypothesis of a 'clear atmosphere' model that took no account of atmospheric water content. Kaplan was, however, concerned more with the effect of halving the carbon dioxide content and concluded that if atmospheric water vapour and cloud cover were accounted for then the decrease would be closer to 1.8°C than 3.8°C as Plass has suggested. There followed an exchange of views (Plass, 1961; Kaplan, 1961) which provided stronger evidence of the frailty of human egos than of scientific method.

It was around the beginning of the 1960s that the misnomer 'greenhouse effect' was used to support an educational analogy of the Earth's atmosphere (cf., Hare, 1961:15). Unfortunately the term soon became popularized and by 1963 (Fleagle and Businger, 1963:153) there were already vain attempts to clarify the confusion between a 'greenhouse' and an 'atmospheric' effect.

Möller (1963) provided the first attempt at a one dimensional atmospheric model using fixed relative humidity and cloudiness. An increase in temperature of 1.5°C was estimated for a doubling of carbon dioxide from 300 ppmv to 600 ppmv. He concluded that cloudiness diminished the radiation effects but not the temperature changes and that the effect of a 10% increase in carbon dioxide could be compensated for completely by a change in atmospheric water content of 3% or cloudiness of 1% (of its value). In 1967, Manabe and Wetherald provided quantitative results for carbon dioxide induced warming on the basis of a one-dimensional radiative-connective model with fixed relative humidity and cloudiness. They estimated a mean surface temperature increase of 2.4°C. In 1971, Manabe was able to refine the Manabe and Wetherald model with a more elaborate treatment of infrared radiation transfer. The early 1970s also saw sufficient concern about climate modification to initiate the SMIC (Studies of Mans Impact on Climate) report in 1971. In the same year, Rasool and Schneider observed that over the last few decades atmospheric carbon dioxide had increased by 7% and the aerosol content of the lower atmosphere by as much as 100%. They also calculated the change in tropospheric temperature through a doubling of carbon dioxide as being 0.8°C using a one-dimensional planetary radiation balance model with a fixed lapse rate, relative humidity, stratospheric temperature and cloudiness.

Moving briefly from the development of climatic models, Lee (1973; 1974) and Berry (1974) exchanged views on whether the greenhouse effect really did work for glasshouses. Lee (1973) suggested that the greenhouse effect was not primarily a result of radiation imbalance caused by the absorptivity of the glass, but rather the difference in convective losses for the glass-enclosed space. Berry (1974) proposed that the effect could in fact be attributed to the spectral properties of the glass. The final word in this exchange of views was by Lee (1974) who concluded that the secret of a glasshouse is that it permits a relatively normal radiant energy exchange whilst trapping a small volume of air near the surface. The notion of heat transfer had therefore not weakened between Woods' original experiments and Lee's confirmation of the processes involved.

Perhaps one of the most significant advances in the estimation of temperature change and a doubling of carbon dioxide was the development by 1975 of a three-dimensional global climatic model reported by Manabe and Wetherald (1975). In comparison with modern GCMs, this limited area model with idealized topography, fixed cloudiness and no heat transport by the oceans represented a very simplistic view. It was however able to provide some indication of how an increase in carbon dioxide concentration might affect the distribution of temperatures in the atmosphere, as opposed to simply Earth surface temperatures. It suggested that whilst the air temperatures in the troposphere would be likely to increase, the stratospheric temperatures would be likely to decrease. Furthermore, for the first time a model suggested that the hydrological cycle would be likely to increase in intensity. The 1975 model of Manabe and Wetherald now forms the basis of the current Princeton University Geophysical Fluid Dynamics Laboratory (GFDL) model.

In 1981 Hansen *et al.* at the Goddard Institute of Space Studies examined the main processes known to influence climate model sensitivity by inserting fixed absolute humidity, relative humidity, cloud formation (from fixed temperatures) and a moist adiabatic lapse rate individually into a one-dimensional radiative-convective (1-D RC) model. By doing so, they were able to examine the effects of various climatic feedback mechanisms, particularly clouds and water vapour. They concluded that by the end of the century, the anthropogenic carbon dioxide warming factor will have risen above the 'noise level' of natural climatic variability (caused in part by variations in volcanic aerosols and the atmospheric dust veil index).

The importance of the atmospheric water vapour feedback mechanism was compounded by the findings of Ramanathan *et al.* (1983) using the National Centre for Atmospheric Research (NCAR) GCM. For the first time they were able to examine important mechanisms such as the way in which the vertical distribution of water vapour minimizes the lower stratospheric longwave cooling and the dependence of the emissivity of cirrus clouds on liquid water content. The latter suggested that not only are clouds important in the modelling of atmospheric processes but also that the type of cloud and the radiative properties are crucial i.e., high level cirrus clouds appeared to significantly enhance the radiative cooling of the polar troposphere.

By 1988 the model groups had increased the sensitivity of their GCMs by an order of magnitude, mainly through advances in computer technology and the development of supercomputers. Hansen *et al.* (1988) provided three different scenarios using the GISS GCM, assuming a continental exponential trace gas growth for scenario A, a reduced linear growth of trace gases in scenario B, and a rapid curtailment of trace gases in scenario C. This transient carbon dioxide increase experiment also recognized the importance of the other radiatively active gases in contributing to the greenhouse effect – not only atmospheric water vapour, methane and nitrous oxide, but also CFCs and ozone trends. They concluded that scenario B appeared the most plausible, doubling carbon dioxide by 2060 AD (from 1958 levels). The GISS model was also able to distinguish some macroregional scale variations i.e., regions where an unambiguous warming is likely to appear earliest are low latitude oceans, ocean areas near Antarctica, China and the interior areas of Asia.

Ramanathan (1988) provides a good up-to-date view of the greenhouse theory, emphasizing the importance of water vapour as a radiatively active gas as well as a summary of important climate feedback mechanisms i.e., water, ice-albedo, cloud and ocean-atmosphere interactions. By 1989, the greenhouse literature has established a permanent niche in climate theory. Schneider (1989) however, provides a new dimension with his examination of science and policy making. This multidisciplinary approach to the problem of the greenhouse theory argues the need for greater involvement in future planning given the 'knock-on' effects of a global warming i.e., sea-level rise, economic refugees, social and landuse planning changes etc. This holistic approach represents a switch in emphasis, acknowledging the trend in global warming and opening the way for a greater involvement by other disciplines and, more importantly, decisionmakers to incorporate possible future climatic change into policy-making decisions.

The general circulation modellers are still improving the current models and investigating ways of improving the sensitivity of their models. Although there is a broad consensus of agreement, each model differs somewhat from its counterparts in physical construction and in the physical realism of the parameterizations employed, the number and complexity of the feedbacks included and the outcome of increased carbon dioxide levels. Intermodel variability still provides a high margin of uncertainty, for example temperature changes of 1.5–4°C dependent on feedback mechanisms and responses.

IV Greenhouse and sea-level change

Mean sea levels (MSL) have been rising since the last glacial maxima. Variations in sea levels on glacial time scales may be seen as a response of the oceans and polar ice sheets to periods of glaciation and deglaciation. At the height of the last glaciation (circa 18 000 years BP) for example, sea levels were over 110 metres lower than the present day. There are in fact only two periods in the recent geological past that have superseded the present MSL; between 120 000–125 000 years BP (+6 metres above MSL) and 135 000 years BP (+2 metres above MSL). Over the past century, the rise has been estimated at 15.1 cm ± 1.5 cm per century (Barnett, 1983) and 17 cm per century (Revelle, 1983), based on eustatic sea level changes and isostatic readjustment. A further consideration is the background warming of the atmosphere which is very slowly altering the ratio between the oceans and ice sheets (the melting of the Greenlandic ice cap is at present more than adequately compensated by the growth of Antarctic ice). With the inadvertent warming of the atmosphere by humans, these processes are accelerated and as the atmosphere gradually warms, the oceans will follow suite. The lag time is estimated at about 25 years by Revelle (1983) for the upper mixed ocean layer (approximately the top 100 metres of the ocean). The net result will be a thermal expansion of the oceans as temperatures increase and the density of the oceanic waters decreases, so occupying a greater volume (assuming the areal extent does alter appreciably).

Since the link between global warming and rising sea levels was made, estimates of sea-level rise have been linked very closely to those of temperature increases. Revelle (1983) estimated that by 2060 AD carbon dioxide levels will have doubled and surface air temperatures will have risen by 3°C. Thermal expansion and the partial melting of the temperate glaciers and possibly also the Greenlandic ice cap would mean that by 2085 AD (including the oceanic lag effect) there would be an additional rise of 54 cm on top of his basal trend of 17 cm giving a total rise of 71 cm over the next 100 years. Hoffman *et al.* (1983) estimated the global warming effect from a doubling of carbon dioxide alone would lead to a temperature increase of between 1.5–5.5°C. If the other radiatively active gases are included, this increase is estimated at somewhere between 3–9°C. As a consequence of assuming the cryospheric contribution as being between 1–2 times that of thermal expansion they predicted a sea-level rise between 56–345 cm by the year 2100 AD.

Meier *et al.* (1985) concluded that carbon dioxide will have doubled by 2050 AD leading to a temperature increase of between 2–4°C. As a result, they predicted that sea levels would rise between 50–200 cm through the partial melting of polar and temperate ice. This rise also includes the break up of the western Antarctic ice shelf, which some authors (e.g., Van der Veen, 1988) have questioned as being initiated too early given the limited temperature rise and short time step involved.

Hoffman *et al.* by 1986 had revised their earlier predictions by also including the disintegration of the western Antarctic ice shelf and a similar temperature increase of 2–4°C. They saw a rise in sea levels as a trigger which would separate the ice shelf from the land mass of Antarctica and given a constant rate of ice-berg removal on the oceanic side of the ice shelf, this would contribute quite rapidly to the overall sea-level rise. They concluded that by 2060 AD the sea-level rise would be somewhere between 30–102 cm. The difference between this and Meier *et al.* (1985) is the estimated contribution of the Greenlandic ice cap, temperature glaciers and more significantly, polar ice over such a short time step.

Robin (1986) used sea-level data from Gornitz *et al.* (1982) and temperatures from Hansen *et al.* (1981) to arrive at a sea-level increase between 20–165 cm. The variations in this study however highlighted the problem of multiplying the errors apparent in the initial data sets. In 1988, Van der Veen estimated a mean sea-level rise of 28–66 cm by 2085 AD, though this is based only on a response to a doubling of carbon dioxide and not the other radiatively active gases which Hansen *et al.* (1988) have shown to be extremely important in influencing future projections of temperature increase.

The relative contributions of thermal expansion and the cryosphere to the overall rise in sea levels is still in the process of being fully understood. It is only with refinements in the new generation of ocean models that the contribution by thermal expansion can be predicted with any degree of certainty. A recently submitted paper by Church *et al.* (1990) from the CSIRO Division of Oceanography bases its estimates of thermal expansion on the thermal exchange of heat between ocean layers over the globe. Assuming a gobal mean temperature rise of 3°C by 2050 they predict the thermal expansion component to be between 0.3–0.4 m by 2070. Furthermore, they envisage that the expansion will be relatively uniform across the globe although the model suggests that in the region of the Antarctic Circumpolar current, the expansion will be less. When added to the cryospheric component, they obtain a total sea-level rise of 0.2–0.9 m by 2070 AD given a temperature rise of 1.5–4.5°C by 2050 AD.

V Predicting greenhouse/induced climatic change

There are only two ways presently available to estimate how climate will change in the era of the greenhouse effect: the use of computer-based global climate models and analogies drawn between historical and palæoclimatological records of periods when the Earth was warmer and the future.

The historical analogue approach has been used by a number of authors to construct warmer climate scenarios for Europe, America and Australia: there are two basic methods of using the instrumental record to create an analogy for the future: (1) comparison between climates of a preselected number of years, usually 10 to 20, which are the hottest on record and their coldest year counterparts; and (2) selection of a warm period and for comparison a cold period. For example, in one study for Australia, the cold period 1913–45 has been compared with the more recent warm period of 1946–78. Comparison is made between rainfall, and sometimes even cloudiness, from the warm years as compared with the cold years. The assumption is that the same incremental change added to today's conditions will give us a picture of how the climate will be in the next century.

This historical analogue method of climate estimation has two major faults. First, there is no reason to believe that the cold to warm changes seen in the historical record were caused by greenhouse gas increases, and therefore extrapolating these changes may indeed offer a picture of a warmer climate but this may be nothing like the climate which will be caused by greenhouse warming. The other major problem is that the temperature differences between cool and warm periods this century are about 10 times smaller than the temperature differences that are expected by the middle of next century: differences of approximately 0.5°C as compared with predicted temperature increases of 4°C or 5°C by 2030 AD. One of two assumptions must be made: (1) a linear scaling can be employed; or (2) the tenfold difference in temperatures can be ignored and the rainfall or cloudiness differences derived from the historical record employed directly as 'predictions' of the future climate. Since neither of these assumptions seems acceptable, the historical analogue method of climatic prediction is losing favour. The only alternative mode of climatic prediction is the use of computer-based global climate models.

Numerical global climate models (termed GCMs or sometimes now AGCMs to emphasize the fact that most such models represent predominantly the atmospheric component of the climate system) comprise an intricate set of computer programmes that solve well understood equations describing how pressure changes cause winds to blow, how energy is absorbed, temperature change, moisture evaporates from the surface and precipitation falls (Figure 2). As is widely recognized, these global climate models offer a less than complete representation of the real climate system. In particular, the incorporation of ocean processes and sea ice, important components of the long-term climate, is still very simplistic, and clouds and surface features are modelled only very sketchily at present. Moreover the spatial resolution is poor (grid elements are approximately 500 km × 500 km) so that details of relatively small atmospheric phenomena, such as thunderstorms, cannot be described explicitly in these models, although modellers go to great pains to capture the ensemble effects of this 'subgridscale weather' over a few years and over broad regions. In one sense, this coarse resolution is unimportant: since global climate models are designed to be useful for long periods of time, they do not have to forecast the exact timing and shape of each weather system precisely; rather they only have to capture the statistics of a large number of these events. On the other hand, predictions made at the spatial resolution of current models are of little use to planners and policy makers.

The poor spatial resolution of current AGCMs is the direct result of the very large number of calculations required for each model time step. At present the spatial resolution is as fine as is possible using the fastest supercomputers in the

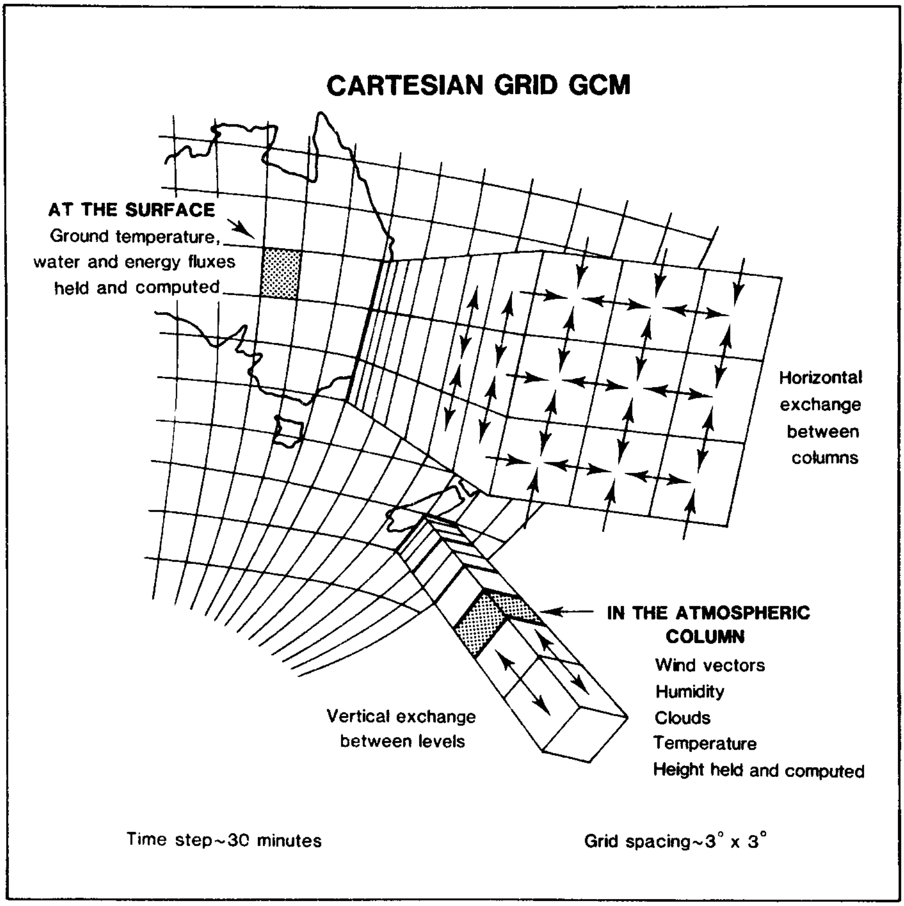

Figure 2 Schematic representation of the processes which are parameterized in numerical climate models. Note the rather coarse resolution (~a few degrees of latitude and longitude and about 10 layers in the atmosphere) as compared with the rather fine temporal resolution (~30 minutes).

world. Computer power places other constraints on gobal model simulations too. The real-world experiment which humanity is currently conducting with the Earth involves a gradual increase in greenhouse gases. All but the most recent computer simulations have, in contrast, been 'instantaneous doubling' experiments i.e., the usual method of simulating the climate in a doubled-CO_2 world is suddenly to double the amount of CO_2. Thus the model suddenly has twice as much radiactive heating due to CO_2 as it had the day before. This sudden switch on of extra heat causes immediate disequilibrium so that the model has to be run on for a number of years until the atmosphere, surface and the upper ocean catch up with the instantaneous doubling. Although this time for re-equilibration is a few years, it is still *very* much shorter than a simulation that allows a gradual increase in CO_2

from the middle of last century to the middle of the next. 'Transient' experiments (e.g., Hansen *et al.*, 1988) which follow the real-world gradual increases are very much more expensive in computer time, and hence costs, than the much more common 'switch on doubling' experiments.

The constraint of computer power on simulation time and spatial resolution may be the primary reason for the failure, to date, to validate current climate models by hindcasting of temperature changes over the last century. Since the Industrial Revolution, the atmospheric burden of CO_2 has increased from between 260–280 ppmv to the 1988 value of 350 ppmv. When a 25% increase in atmospheric CO_2 concentrations is imposed upon model simulations, predicted warmings are of about 1°C. The temperature record, however (see Figure 1), shows a warming of only about 0.7°C. Moreover, recent critical evaluations of the impact on some of the temperature records included in this 88-year-long global average indicate that urban warming has enhanced some of the temperature increase. However, even if the most stringent corrections yet derived for the USA were applied, the global data still indicate a 0.5°C warming this century. In addition the 1980s appear to be the warmest decade on record and 1981, 1987 and 1988 are the warmest years this century. Nonetheless there is a discrepancy between the climate model predictions and the observed facts. Possible explanations for this discrepancy include:

1) The assumption of linearity in processes (this is the basis of the use of one quarter of doubled CO_2 predictions as representative of the effects of the 25% increase already observed) is invalid;
2) Climate models are too sensitive by a factor of two to increases in greenhouse gases;
3) Atmospheric climate models do not fully or correctly account for the take up of heat by the oceans;
4) The data record shown in Figure 1, being incomplete and inhomogeneous, actually *underestimates* the global warming this century.

VI Summary and discussion

Four themes run throughout this review: 1) the fact that radiative heating caused by certain gases in the Earth's atmosphere warms the planet; 2) the deduction that mankind could influence this warming (e.g., by increasing carbon dioxide levels); 3) attempts to predict (model) climatic changes prompted by changes in the atmospheric loading of these gases; and 4) (the subplot) the question 'are glasshouses warmed by the same radiative mechanism that warms the planet Earth'?

Initial researches into carbon dioxide concentrated on its role in influencing long-term climatic change. Between 1827 and the early part of the twentieth century, research centred on this theme culminating at the turn of the century with the works of Arrhenius and Chamberlin. The carbon dioxide theory then declined in general acceptance for a number of decades until the 1950s when the level of interest was again raised by, among others, Plass and Kaplan. During the mid-twentieth century, there were notable exceptions, for example Callendar (1938; 1949) whose work highlighted a new direction in the theory, namely the recognition that humans were inadvertently influencing the atmospheric carbon dioxide content, mainly through the processes of rapid industrialization.

By the late 1960s climate modellers had begun to predict temperature changes based on a doubling of carbon dioxide. These ranged from 1.5°C to as much as 9°C using the same model (Möller, 1963) emphasizing the early stage of model development. The development of these models into fully interactive global climate models (GCMs) has continued through to the present day. The modellers are now recognizing the importance of feedback mechanisms, particularly those relating to atmospheric water vapour and the oceans. The latest advancements include increasing the resolution of the models and embedding mesoscale models within the GCMs to predict regional scenarios as well as global.

As the modellers refine their algorithms, the consistency achieved within and between models increases. One 'knock-on' effect, apart from increasing the resolution, has been to refine the predictions for sea-level rise based on temperature change. Initial research suggested that sea levels might rise by as much as 345 cm by 2100 AD with a range of 289 cm (Hoffman *et al.*, 1983), however, with a greater understanding of the lagged cryospheric response and refinemements in temperature changes down to between 2–4°C have reduced both the range and the upper limits considerably. For example, Van der Veen (1988) now suggests a more plausible scenario is somewhere between 28–66 ccm over the next century.

The most recent new direction appears to be the realization that a complete multi-disciplinary approach encompassing social science and planning is needed to respond to the climatic changes that are likely to occur on such an unprecedentedly short time scale.

The review includes only *published* works, but a very useful source of information is a set of five reports produced by the US Department of Energy in 1985, reflecting what was then 'state-of-the-art' knowledge, emphasizing modelling of physical processes and biochemical feedbacks. The reports are entitled:

1) 'Detecting the climatic effects of increasing CO_2'
2) 'Characterization of information requirements for studies of CO_2 effects'
3) 'Projecting the climatic effects of increasing CO_2'
4) 'Direct effects of increasing CO_2 on vegetation'
5) 'Atmospheric carbon dioxide and the global carbon cycle'

These may still be obtained from the National Technical Information Service, US Department of Commerce, Springfield, VA 22161, USA.

For an even quicker review of the greenhouse literature, Ramanathan's (1988) paper provides familiarization with the atmospheric physics and climate modelling overview. Schneider (1989) provides the observational caveats as well as planning and policy implications. An introduction to climate modelling may be found in Henderson-Sellers and McGuffie (1987). Further reading should focus on Schneider (1975) and Callendar (1938), the former concentrating on how greenhouse heating of the Earth works and how it may influence climatic change.

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