PART I

CARBON DIOXIDE and the GLOBAL CLIMATE

Introduction

The planet Venus is similar in both size and composition to Earth. In contrast however, to Earth's hospitable environment so richly abundant in diverse lifeforms, the viscous atmosphere of Venus exerts a pressure of 40 atmospheres at the surface where temperatures reach 480°C and chemical rains have a pH of 1. The reason for this more hostile environment, stems from the high concentration of "greenhouse gases" in the Venusian atmosphere, particularly carbon dioxide (CO_2) which is the most abundant gas (Young, 1974). These gases which are radiatively active in the part of the spectrum where much of the surface thermal emission occurs, trap outgoing radiant energy so maintaining the high temperatures found on the planet. It has been estimated (Rasool & de Bergh, 1970) that had the Earth formed a mere 6% closer to the Sun, the subsequent vapourisation of water (H_2O) and CO_2 by thermal outgassing from its virgin rocks would have raised the temperature above the boiling point of water. This would have prevented the formation of the oceans, consequently removing a major sink of carbon, and the temperature would have continued to increase due to the greenhouse effect in a runaway fashion, until the conditions on Earth were rather similar to those now found on Venus.

Fortunately, the Earth is bathed in radiant energy from the Sun 150 million kilometres distant. However, the development of intelligent life which occurred as a consequence of this now threatens a new, though less dramatic perturbation on the future evolution of the biosphere. From the middle 19th to the middle 20th century, human activity has added around 90 Gtonnes ($9x10^{10}$ tonnes) of carbon dioxide to the atmosphere. Since 1950 a further 90 Gtonnes has been added, and the energy and agricultural demands of a rapidly growing population mean that the rate of output is still increasing. Due to certain time lags associated with greenhouse warming (Section I.5) it is possible that we are now just on the threshold of bearing the consequences of the last 100 years' agricultural and industrial activities. It is therefore of great importance to predict the inevitable climatic effects as soon as possible, to permit adjustments of land practices (in particular agriculture) to be carried out in time. Furthermore, a better understanding of the impact of CO_2 pollution on the eco-system will permit the implementation of sensible controls in the future.

I.1 The Greenhouse Effect.

Energy is removed from a beam of sunlight incident on the top of the atmosphere by two processes: reflection and absorption, both within the atmosphere and at the Earth's surface. The major gaseous absorbers of sunlight in the atmosphere are water and stratospheric ozone which, together with dust, absorb around a quarter of the incident energy (Dickson & Cicerone 1986). Almost double this amount of energy reaches ground level and is absorbed there, leaving around 30% of the energy which is reflected at the ground surface (by ice caps, oceans, deserts etc.) and within the atmosphere, principally by cloud tops.

The energy which is absorbed by the ground, heats the surface until a balance is reached between absorbed and emitted heat flux. About a third of the absorbed energy is liberated as thermal radiation in the near- to mid-infrared (4μm-100μm) and approximately 70% of this is prevented from escaping the atmosphere through absorption principally by H_2O and CO_2. It is the trapping of this re-radiated thermal energy and subsequent heating or "forcing" of the atmosphere which has come to be known as the "greenhouse effect", water being the most effective "greenhouse gas". More than half of the surface heat is released as latent energy through evaporation of soil moisture and oceans. Thus a crucially important coupling, or feedback occurs between the cause and effect of atmospheric warming: atmospheric water vapour increases in response to ground and consequently air heating, and this in turn leads to further heating via the greenhouse effect. We shall come across other such couplings between cause and effect in Section I.4.

Although H_2O and CO_2 are important greenhouse gases, they are not the only ones. Vibrational-rotational bands of water attenuate radiation at wavelengths shortward of 8μm, and CO_2 dominates the absorption from 12μm to 18μm. At longer wavelengths, the rotational bands of water again dominate. Thus, although about three quarters of the surface emission is subject to attenuation by CO_2 and H_2O, the remainder lies in the 8-12μm waveband, the so called "atmospheric window". This window is far from transparent however, since methane (CH_4), ozone (O_3), nitrous oxide (N_2O) and the chlorofluorocarbons CCl_3F and CCl_2F_2 are all active absorbers between 8μm and 12μm. Since the industrial revolution, increased human activity has added greenhouse gases to the atmosphere at a rate which has accelerated alarmingly and there are signs that this has already altered the radiation budget of the atmosphere by a significant amount (Section I.6). Table I.1 below (adapted from Tables 1,2 & 3 of Dickson & Cicerone 1986) summarises the relative importance of the various atmospheric components for trapping thermal radiation.

Table I.1

Values of the estimated pre-industrial revolution concentrations of the various greenhouse gases along with the change in concentration; contribution to current total attenuation of thermal radiation, Qtot; and the change in this quantity since the industrial revolution δQpre-ind. Concentrations are in parts per 10^6 by volume (ppmv) or parts per 10^9 by volume (ppbv), and 1ppmv <=> 44.64 μmoles m^{-3}.

GAS	PRE-IND. CONC.	1985 CONC.	Qtot	δQpre-ind
CO_2	280ppmv	345ppmv	50Wm^{-2}	1.3Wm^{-2}
CH_4	0.7ppmv	1.7ppmv	1.7Wm^{-2}	0.6Wm^{-2}
O_3	0	10-100ppbv	0.2Wm^{-2}	0.2Wm^{-2}
N_2O	285ppbv	304ppbv	1.3Wm^{-2}	0.05Wm^{-2}
CCl_3F	0	0.22ppbv	0.06Wm^{-2}	0.06Wm^{-2}
CCl_2F_2	0	0.38ppbv	0.12Wm^{-2}	0.12Wm^{-2}

Assuming the climate to have been in equilibrium in pre-industrial times, it is the change in the amount of attenuated energy δ Qpre-ind which is significant when quantifying the relative importance of the different greenhouse gases in perturbing the climate to-day. Notice that the combined effect of the trace gases CH_4, O_3, N_2O and the CFCs is comparable to the increase in trapping due to CO_2

I.2 Ozone Depletion and the Greenhouse Effect.

Of particular concern is the pollution of the atmosphere by CFC's. Projected trends (Dickson & Cicerone 1986) suggest that by the year 2050 the amount of energy attenuated by these gases alone could exceed that by CO_2 (partly as a consequence of the increasing saturation of the absorption bands of CO_2). Therefore not only is there a danger that pollution by CFCs is depleting the stratospheric ozone layer and thereby increasing harmful fluxes of ultra-violet radiation at the ground surface, but it also seems likely that in the near future they could be the single main cause of global climatic change. A possible negative feedback between global warming and ozone depletion may exist however (Oeschger & Dutsch, 1989). Current climate models predict a cooling of the stratosphere (Hansen *et al.*, 1988; Wilson & Mitchell, 1987) which will inhibit the chemical processes which occur there, and through which CFCs remove ozone from the atmosphere. The effect of increased stratospheric levels of CFCs may be therefore partly compensated for by the greenhouse effect. Such statospheric cooling may already have been observed (Angell, 1986; Jones *et al..*, 1988).

It is also possible that the consequences of a depleted ozone layer may aggravate the already worsening climatic situation. It is thought (Calkins, 1982) that the increased flux of ultra-violet radiation at the ocean's surface may inhibit the photosynthesis of phytoplankton. Increased levels of CFCs in the atmosphere could therefore indirectly enhance the impact of the greenhouse effect, by reducing a potential sink of atmospheric CO_2, although the significance of this impact is still uncertain (Section I.4).

Although the effects of the trace gases are clearly not negligible, we shall concentrate here on the evidence for increasing levels of atmospheric CO_2 and its sources and sinks, primarily because of its importance in its connection with the biosphere. When we later come to consider climatic effects, due consideration will be given to the contributions from all the greenhouse gases.

I.3 Evidence for a Rise in Atmospheric CO_2 Concentration.

~~Large-scale~~ changes in CO_2 concentration are known to occur seasonally in response to changes in photosynthetic rate. The amplitude of these variations has a maximum of 15ppmv at a latitude of +60° and decreases to zero as latitude decreases to -90°, in response to the reduced seasonal contrasts in the southern latitudes (Tucker *et al.* 1986). However underlying this periodic fluctuation is a monotonic increase of approximately 1.5ppmv yr^{1} (1982-1984) of anthropogenic origin.

Atmospheric CO_2 concentration (denoted hereafter atmospheric $[CO_2]$) has been monitored directly from the Mauna Loa weather observatory since 1957 when the concentration was 315ppmv. The current level, 30 years later is 345ppmv which represents a 10% increase, and the rate at which CO_2 is added to the atmosphere is continuing to increase. As we shall see in Section I.5, the Earth's climate is probably only now responding to the effect of CO_2 concentrations of more than 50 years ago. Therefore in order to quantify the effects of $[CO_2]$ on climate we must know what these levels were, at times before it became apparent that we should monitor them. One way to do this is to measure the ratio of $^{13}C/^{12}C$ in tree rings which is sensitive to the amount of photosynthetically cycled CO_2. The conclusions from such experiments, and possible problems are discussed in some detail in the following Section, but resulting estimates of the pre-industrial concentration of CO_2 range from 240ppmv to 280ppmv.

A more direct method involves the analysis of bubbles of air trapped during the laying down of the polar ice caps. Samples of air trapped in ice bubbles locked in deep ice cores can be aged by dating the surrounding ice using oxygen isotope stratigraphy, and applying corrections for the fact that the ice is older than the contained air (Pearman *et al.* 1986). The results presented by these authors show that between 1600 and 1800, [CO_2] remained constant at 281 +/- 7ppmv. From 1800-1900 the mean level increased to 288 +/- 5ppmv, to be followed by an approximately exponential increase in concentration to the present level of 345ppmv, a consequence of explosive population growth and increased energy demands.

The observed rise in [CO_2] in the past 100 years represents only a fraction of the total amount expelled during the same period. Both the ocean and biosphere are capable of absorbing large amounts of carbon dioxide from the atmosphere. However mass destruction of the rainforests encouraged by bodies such as the World Bank as well as at the governmental, corporate and individual level, coupled with the non-linear response of the ocean to impulse rises in CO_2 concentration, call into question the ability of these potential sinks to buffer the effect of rising CO_2 emissions.

I.4 The Ocean and Biosphere as Carbon Dioxide Sinks.

The ocean is often envisaged as being composed of two distinct reservoirs (Hansen *et al.*, 1985; Siegenthaler & Oeschger, 1978; Oeschger *et al.*, 1975). The surface layer of thickness around 75m is known as the mixed layer, precisely because its vertical strata are well mixed due to surface agitation by winds. This layer is in good thermal and chemical contact with the atmosphere. Below this is the "deep ocean" and contact between this level and the mixed layer is usually mediated by diffusion processes with associated large timescales compared with mixed layer processes. In the absence of significant perturbations in [CO_2], atmospheric CO_2 is exchanged with the mixed layer CO_2 on a timescale of approximately seven years. Exchange between the mixed layer and deep ocean is slower with a typical residence time in the mixed layer of 20 years. However once in the deep ocean, it remains there for between 700 and 1000 years before latitudinal circulation brings it back to the surface. Sedimentation of oceanic-borne inorganic carbon apparently occurs solely as a result of deposition of carbonates, following the death of shell-forming organisms such as protozoa (Warneck, 1988). In open sea, as a consequence of increasing solubility with depth, most carbonates redissolve before settling on the ocean floor. Consequently most oceanic sedimentation involves organic (reduced) carbon, and occurs in shallow continental waters of high photosynthetic potential where it is mixed with inorganic (oxidised) river-borne carbon, originating from the weathering of crustal rocks. Because of the large geological timescales associated with the transfer of sedimentary carbon back to the ocean-atmosphere system, sediments harbour the largest pool of carbon; around 6.5×10^{19}kg about 25% of which is of organic origin. This is around 1000 times the total atmosphere (2.6×10^{15}kg) -ocean (3.7×10^{16}kg) content and is five orders of magnitude greater than the carbon locked up in the living and decaying biosphere (e.g. plant debris, soil humus etc). The capacity of the ocean to absorb CO_2 makes it a potentially important buffer against atmospheric pollution. However, although atmospheric CO_2 is exchanged with CO_2 in the mixed layer at equilibrium with a timescale of around seven years, the situation is quite different when [CO_2] is perturbed to the present extent (Siegenthaler & Oeschger, 1978). CO_2 is taken up by the ocean through a process involving the following chemical equilibrium between aqueous CO_2 and the production of bicarbonate and carbonate ions (Warneck, 1988).

$$CO_{2,gas} \underset{H_2O}{\rightleftharpoons} CO_{2,aq} \underset{-H^+}{\rightleftharpoons} HCO_3^- \underset{-H^+}{\rightleftharpoons} CO_3^{2-} \underset{Ca^{2+}}{\rightleftharpoons} CaCO_3$$

In fact dissolved CO_2 gas accounts for less than 1% of the uptake of CO_2, which goes predominantly to form the bicarbonate (90%) and carbonate (9%) ions. Significant positive perturbations in the atmospheric concentration of CO_2 shift this equilibrium in favour of dissolved molecular CO2. This results both in a reduced capacity for the ocean to accept atmospheric CO_2 , and also a reduced rate of uptake. If the atmospheric levels increase by p percent, then the uptake by the ocean increases by only p/γ percent, where γ is the so-called "buffer factor" which increases with atmospheric CO_2 concentration and with temperature. According to Siegenthaler & Oeschger, an acceptable value for the present day γ lies in the range 7-10, and an empirical relation was used to extrapolate for the higher projected levels of $[CO_2]$. Using lower and upper extremes for the input of CO_2 to the atmosphere by the burning of fossil fuels, Siegenthaler & Oeschger arrive at the conclusion that between 46% and 80% of the total amount of CO_2 ejected into the atmosphere over the next hundred years will remain airborne. In comparison, during the period 1958-1978, the increase in the amount of CO_2 in the atmosphere corresponds to about 54% of the cumulative emission from fossil fuels over the same period (Warneck, 1988).

To arrive at their result, Siegenthaler & Oeschger assumed that the rate of CO_2 uptake by the biosphere remained constant or increased with time; i.e. was a net sink of CO_2. One of the biggest uncertainties in predicting future atmospheric $[CO_2]$ concerns the role of marine biota, in particular phytoplankton, in pumping carbon to the deep ocean. Although marine organisms contain a tiny fraction (<0.01%; Warneck, 1988) of the total oceanic carbon reservior, the high turnover rate means that even a small leakage of carbon to the deep ocean could result in a significant impact on atmospheric $[CO_2]$. Present estimates suggest that biological and physical processes in the ocean are about equal in importance to the land biomass as carbon dioxide sinks. However the relative importance of the biological processes in the ocean is as yet uncertain, but may only be responsible for a few percent of the total uptake of CO_2 by the oceans (Williamson, private communication). Nevertheless, a strong positive response to the changing climate could redress the balance. Unfortunately, the direction and magnitude of the response is uncertain at present. The predicted decrease of the latitudinal temperature gradient across the oceans will result in a reduction of the mixing which occurs between the various layers of the ocean. In particular the dredging of deep, nutrient rich waters to the surface layers will be reduced, and hence the marine biomass will decline in tandem with surface nutrient concentration. Another important factor which governs both the size of the phytoplankton biomass and the rate of transport of carbon to the deep ocean is the interaction with zooplankton. The faeces of zooplankton provide an important medium for transporting carbon to the deep ocean by preventing it from redissolving (see above). It is presently not known whether the changes in the climate will result in an increase or decrease in the predation rate of zooplankton (Williamson, personal communication). It is clear that a significant amount of further research is required to determine the degree to which the oceans are capable of absorbing the excess atmospheric CO_2. The terrestrial biosphere contains a significant amount of carbon, with tropical rainforests as the primary sink. Now most trees are C_3 plants which in simple terms means that they will respond with increased photosynthesis to increased concentrations of CO_2

(Section III.2). It therefore seems feasible to suppose that the biosphere could act as a net sink of CO_2 (possible limitations on the exploitation by land biomass of increased atmospheric CO_2 imposed by soil nitrogen and trace element concentration are discussed in Part II). However tropical rainforests are presently being denuded at a rate of two hundred thousand square kilometers annually, to be replaced at best by plants of lower biomass. In addition to the reduction in sink by removal of the trees, CO_2 accumulated over the past 60 or 70 years is released simultaneously when the forests are burned. Attempts have been made to discover if the biosphere has acted as a net source or sink of CO_2. The process of photosynthetic fixation of carbon discriminates in favour of the lighter ^{12}C isotope of carbon over ^{13}C compared to their atmospheric abundances. Since both fossil fuels and living plants are made from carbon obtained by photosynthesis, the diluted ratio of $^{13}C/^{12}C$ in the atmosphere will attest to the extent of CO_2 pollution by both sources. In order to determine the fractional contribution to the ratio from biospheric sources, a correction must be applied corresponding to the deviation from the current $^{14}C/^{12}C$ ratio (Francey & Farquhar, 1988)) which is lower in fossil fuel derived CO_2. Work on analysing the carbon content of tree rings suggests that anywhere between 0 and 50% of the input of CO_2 to the atmosphere is derived from burning of forests (Warneck 1988). However, back extrapolation (Peng *et al.* 1983) of implied atmospheric concentrations give a pre-industrial concentration some 15% lower than estimates made from air trapped in Antarctic ice-sheets (Pearman et al. 1986), suggesting an over-estimate of the contribution to the biosphere. Indeed there are a number of uncertainties associated with the tree-ring data which concern variable fractionation of the carbon isotopes during uptake and photosynthesis (Francey & Farquhar, 1982) making this method rather controversial. Druffel & Benavides (1986) applied a similar analysis to the growth rings of a sea sponge, which accretes carbon non-photosynthetically in equilibrium with the surrounding water. They found that around 38% of the excess CO_2 expelled into the atmosphere from 1820 to 1972 originated in the terrestrial biosphere. Back-extrapolation yielded a pre-industrial concentration of CO_2 in agreement with the ice-bubble data.

In light of these arguments, it seems reasonable to admit the possibility that the results of Siegenthaler & Oeschger which assumed the biosphere to be a net sink of CO_2 represent an optimistic picture. Therefore even allowing for dramatic reductions in CO_2 emission, a doubling of [CO_2] by the end of the next century is almost without doubt, and could conceivably occur as early as 2020. We now turn our attention to the impact of rapidly rising atmospheric CO_2 levels on the global climate.

I.5 The Climatic Response to Raised CO_2- Feedback Effects.

A conclusion which is independent of any climatic dynamical model is that in order to restore the radiation balance after CO_2 levels have doubled, the Earth would have to warm by at least 1.2 to 1.3°C (Manabe & Wetherald 1967; Hansen *et al.* 1984). A tacit assumption is made however, that the radiative properties of the planet remain constant as the temperature rises. In fact a number of feedback effects occur, which together amplify the effect of CO_2 warming, and it is these effects that harbour the main uncertainties in predicting the sensitivity of the global climate to changing CO_2 levels.

The sensitivity of the climate to the various feedback processes can be quantified in the amplification factor f, by which the equilibrium temperature rise in the absence of feedbacks Tnf is multiplied to give the actual temperature rise i.e.

$$\delta T = f\, \delta T_{nf}$$

(see Appendix A). ~~The nature of the feedback mechanisms is such that~~ should a number of such processes occur together, they do not combine ~~linearly~~. A consequence of this property is that should a strong positive feedback exist in the influence of a far weaker feedback, the combination can produce a very large change in the sensitivity of the climate. Total net feedback factors in current general circulation models range from around 2 (e.g. Manabe & Wetherald 1975) to 4.3 (e.g. Wilson and Mitchell 1987). In all of these models, three major feedback processes stand out in importance (Hansen *et al.* 1984): water vapour, snow/ice, and cloud.

(a) Water Vapour Feedback.

An increase in the global temperature results in an increase in the amount of water vapour in the atmosphere through raised evaporation rates and an enhancement of the atmosphere's ability to store moisture (Hansen *et al.* 1988, Wilson & Mitchell 1987). Since atmospheric H_2O is the most important greenhouse gas (Section I) this is the largest feedback process, with a feedback factor f=1.6 (Hansen *et al.* 1984, Manabe & Wetherald 1967). The existence of this strong positive feedback implies that any additional moderate positive feedback effects can greatly increase the climate sensitivity for the reasons outlined above. A major uncertainty in the treatment of atmospheric water vapour in climate models is the scheme employed to model the transport of moist convection. The resulting uncertainty in the climate sensitivity may only be resolved in a real-time comparison with the actual climatic changes.

(b) Snow/sea-ice feedback

The polar ice caps contribute significantly to the albedo (reflectance) of the Earth. However, a rise in the mean global temperature will reduce the extent of the polar sea- ice, and hence reduce the Earth's albedo. Consequently the amount of sunlight absorbed will increase, thereby giving rise to an additional increment in global temperature. Similarly with the seasonal coverings of snow in the tundra areas, where albedo effects are all the more important because of the lower zenith angle of the Sun. Additional masking by increased vegetation cover may also be important in these areas. Hansen *et al.* (1984, 1988) assign a value of f=1.1 for this feedback process.

Notice that the combined feedback factor for the superposition of water vapour and snow/ice feedbacks is 1.87 compared to 1.76 if the superposition was multiplicative (Appendix A).

(c) Cloud feedback.

Current cooling effects of cloud cover amount to more than five times the expected positive forcing due to doubled CO_2 (Ramanathan *et al.* 1989). Clearly, any change in the quality or quantity of cloud cover could have crucial implications for model predictions. The feedback caused by the change in cloud albedo and cloud height (affecting cloud temperature and hence radiative flux) is somewhat controversial. Charlson *et al.* (1987) have suggested a "Gaian" effect on cloud albedo, whereby they propose that cloud albedo may increase as a consequence of enhanced production of cloud condensation nuclei (dimethylsulphide) by oceanic phytoplankton in response to the greenhouse effect, and that this should offset any net heating effect. Firstly, the success of this theory rests with the unsubstantiated assumption that phytoplankton should increase respiration of dimethylsulphide in response to raised $[CO_2]$. However the productivity of marine phytoplankton is primarily limited by phosphorus and nitrogen, and not carbon (Broecker 1974) which is in relative abundance. Therefore, the enhanced productivity would have to be in response to the rise in sea-surface temperatures which arise from greenhouse warming. Secondly, should dimethylsulphide emission increase the albedo of clouds, then a similar increase should be observed due to anthropogenic increases in SO_2 in the northern hemisphere. The fact that no such effect has occured (Schwartz, 1988) calls into question the reality of this negative feedback effect on cloud albedo.

In the transient model of Hansen *et al.* (1988) cloud cover provides a positive feedback f=1.28, because of reduced cloud cover and a slight increase in mean cloud height as the climate warms. However this result depends quite sensitively on the assumptions made about the optical properties of the clouds in the model (Senior, private communication; Hansen *et al.* 1984; and Table I.2 in this Report) although similar efects have been found by Wilson & Mitchell (1987).

In conclusion to the discussion on feedback effects, one very important omission in all the climate models to date must be emphasised. Because of computational difficulties, no account is made of possible feedback on the horizontal transport of heat in the ocean. Heat is transferred by ocean circulation from the equator to the poles which experience larger warming as a consequence (Spelman & Manabe, 1984). Therefore, models with no oceanic transport of heat whatsoever, are more sensitive because of the larger extent of sea ice into lower latitudes that results as a consequence. For models where horizontal heat transport is prescribed, the inclusion of a feedback on ocean currents could have a crucial effect as sea surface temperatures homogenise and thermally driven oceanic currents decrease. The loss of the North Atlantic Drift, for example, would have a dire effect on the equilibrium temperatures of western UK and Europe. Omission of feedback on the oceanic circulation may also prevent the model climate from undergoing a realistic temporal evolution (Broeker *et al.* 1985).

In addition to their effect on the final equilibrium temperature of the globe, feedback processes, which act in response to changes in temperature rather than changes in forcing, also delay the rise to equilibrium. In the next Section, we shall examine the crucial role of feedback processes and heat dissipation to the oceans, in the transient response of the climate to radiative forcing by ~~increasing [CO_2].~~ increased concentrations of greenhouse gases

I.6 *The Transient Response of the Atmosphere.*

Since the rapidity of any impending change in climate can have more serious consequences than the actual magnitude of the change (e.g. in natural adaptation of vegetation; breeding strategies, Part VI; the response of pests, Part IV) it is essential to understand the temporal response of the Earth's climate to a perturbation in the radiative balance conditions. Furthermore, any real-time quantitative assessment of the validity of the various model predictions must make allowances for this effect. Unfortunately, many climate models predict the equilibrium temperature change for doubled [CO_2], without making meaningful predictions for the time required by the climate to attain this equilibrium - principally due to constraints on computer power.

In the absence of climate feedback effects and heat dissipation to the deep ocean, the Earth will equilibriate with a doubled CO_2 forcing in an e-folding time, τ_b of around 3.5 years (the time required for the temperature to attain 1/e or 0.34 times the equilibrium value). The delayed response induced by feedback effects restores temperature equilibrium more slowly as the various factors responsible for restoring it come into play. In the presence of feedbacks then, the e-folding time becomes (Appendix B)

$$\tau = f \, \tau_b$$

where f is the feedback factor (Section I.5). For an equilibrium temperature rise for doubled [CO_2] of around 4C°, the e-folding time is approximately 15 years for an averaged oceanic mixed layer depth of 110m. This value however, still ignores the dissipation of heat from the mixed layer which is in good thermal contact with the atmosphere, to the deep ocean. Inclusion of this effect has a dramatic consequence for the response time of the climate model.

Heat is transferred to the deep ocean by slow convective overturning at both poles where cooled surface waters sink as part of the global oceanic circulation. At lower latitudes, heat diffuses nearly horizontally from a shallower mixed layer. Treatment of the combined effect is clearly complex, although fairly reliable estimates are possible for the timescales required for the surface sea temperature in different regions to reach equilibrium . Current estimates put the e-folding time for the area-weighted mean mixed layer temperature to reach equilibrium, at 125 years (Hansen *et al.* 1984) for an equilibrium temperature rise of 4.2C° with doubled [CO_2]. A less sensitive climate model will reach equilibrium more rapidly. It is therefore clear that the bulk of the effect of added CO_2 to the atmosphere has yet to be felt by the global climate. Indeed Hansen *et al.* (1984) point out that using realistic past CO_2 accumulation rates, the present equilibrium temperature rise ignoring the delayed response should be around 1.5C°, but that due to the effect of feedbacks and heat dissipation to the deep ocean, only about 0.5C° of that rise would presently be realised.

A crucial test of both the model's representation of climatic feedbacks and deep oceanic heat transport is evidently the recorded temperature rise since industrial times, in the light of known historic atmospheric CO_2 concentrations. It is to this that we turn our attention next.

I.7 Evidence for a Rise in Temperature.

Useful data regarding the global temperature over the past 130 years have been collected both on land and at sea. The land data represent a reasonably homogeneous set, since methods of measuring temperature have remained essentially unchanged from early times. However, significant changes in the methods used to record maritime air and sea-surface temperatures have occurred (e.g. changes in the thermal capacity and speed of ships relevant to maritime air temperatures; and changes in the insulating properties of buckets used to collect sea water for sea-surface temperature measurements). Since the oceans comprise more than 70% of the Earth's surface, any measure of past globally averaged temperature could only be reliable if data on ocean temperatures were incorporated. A recent attempt to homogenise historic sea-surface and maritime air temperature data has yielded some results of relevance to present climate models. Jones *et al.* (1986) compared historic maritime air temperature data pertaining to coastal regions, with those corresponding to continental air temperatures made over the adjacent land masses. Although for the period after 1950 when reliable maritime temperatures were made there were no significant differences between the two temperatures, during some earlier periods systematic differences did occur which were attributable to the sort of non-climatic effects mentioned above. Corrections based on these discrepancies were applied to the maritime air data, and similar corrections were made to the sea-surface temperatures. These data, together with the continental data provided globally averaged annual mean temperatures for the period 1860 to 1984. The results showed that although there was little trend in temperature during the latter half of the last century, significant warming from 1900 to 1940 did occur. Temperatures then levelled off until 1970 when again there was a marked rise to 1984, bringing the total net rise in global mean temperature to 0.5C° since 1860. As a cautionary note however, the greater spatial coverage obtained using modern satellite surveillance has meant that more accurate determination of sea-surface temperature is now possible. A recent study (Strong 1989) suggests that the global ocean is warming at a faster rate (perhaps twice as fast) than the conventionally collected maritime data would suggest. The warmest three years inferred from the Jones *et al.* study all fell in the 1980's. A recent update of the study (Jones *et al.*, 1988) using improved data for the 1980's period confirmed their earlier results, and also found that the warming is most evident in the southern hemisphere, where seven out of the eight warmest years since 1900 have all occurred in the 1980's. Since even that study was completed, the warmest annual global mean temperature since 1860 was recorded for 1988. It must be stressed at this point that unforced internally driven fluctuations in temperature of this magnitude are possible (Lorenz 1968, Hansen *et al.*, 1988). However, the magnitude, direction and timescale of the change reported here are all consistent with modelled consequences of the inferred increase in CO_2 concentration since the industrial revolution.

The tongues of valley glaciers are particularly sensitive to changes in the radiation budget of the atmosphere (Oerlemans 1986). This arises because of the advective transfer of heat above the valley sides, to the boundary layer over the glacier. By definition, the transfer of heat from the boundary layer to the glacier is driven by the temperature gradient, and since the glacier surface is maintained at 0°C, heat is transferred into the glacier rapidly, and significant melting occurs. Oerlemans studied the retreat of three valley glaciers in the Alps and one in Norway in terms of a simple model for the rate of retreat in the presence of a CO_2 forcing of $6Wm^{-2}$ (the effective quantity of radiant energy trapped by CO_2 absorption), a value on the large side for doubled CO_2, but acceptable if the effects of other trace gases are included. The observed recessions are indeed impressive and, at first sight, consistent with the simple theory. However two of the glaciers show a retreat beginning around 1750, long before any major anthropogenic injection of CO_2 into the atmosphere, while all had started to recede by 1850. The discussion in Section V calls into question whether this is consistent with the time lags associated with the activation of feedback effects. Furthermore, the value of $6Wm^{-2}$ adopted for the forcing term is rather high for the periods considered, since such a level is not expected until around 2050. The principle of the amplified heating effect should be valid however, and perhaps some adjustment of the transfer coefficients of heat from the valley sides to the glacier surface could improve the quantitative details of the model. The recession of the fronts of some European valley glaciers is indisputable.

Another possible indicator of raised global temperatures is the large-scale bleaching of Caribbean corals reported by Roberts (1987). Photosynthetic brown coloured algae (dinoflagellates) reside within the cells of corals in a symbiotic relationship, whereby the algae provide the coral with oxygen and energy in exchange for nutrients. When the algae are under stress, caused for example by a sudden increase in water temperature or salinity which interrupts photosynthesis, they become an energetic drain on the corals and are expelled. It is the expulsion of the algae leaving the white coral bare that is the cause of the bleaching. An even more extensive bleaching event, followed by widespread mortality of corals occurred in the Pacific in response to the unusually warm sea-water temperatures which resulted from the anomolous 1982-1983 El Niño event (Roberts 1987, Philander 1983). The ubiquitous nature of the bleaching in the Caribbean, precluding any water-borne pollutant as the cause, again points to raised sea-surface temperatures as the likeliest culprit. Indeed water temperatures in some parts of the Caribbean around the time were anomolously high, at between 30°C and 32°C. The cause of the temperature rise is as yet unknown, although a drop in the trade winds leading to reduced cooling of the surface has been blamed. In the context of global climatic change, it is interesting to note that according to Hansen *et al.* (1988) because of its shallow ocean mixed layer and slow rate of heat diffusion to greater depths (meaning the mixed layer and deep ocean are essentially uncoupled) the Carribean is especially sensitive to the effects of greenhouse warming. Indeed, their model indicates that by the early 1990's a 2 sigma temperature rise should have occurred there.

Although largely suggestive, the evidence for a forced rise in global mean temperatures since the industrial revolution is compelling, especially in light of the work on the transient response of the climate to CO_2 forcing which predicts temperature rises consistent with present findings (Hansen *et al.* 1985). It is clear that we may be just on the threshold of feeling the effects of mankind's first significant global perturbation of the environment.

I.8 Predictions of Climate Change by General Circulation Models.

The desire for knowledge outside the realm of experience necessitates the use of a model representation of the system under study. The validity of such models must be tested against observation before extrapolation allows exploration of new scenarios. Modern research in climatology has produced sophisticated computer models which simulate the world's climate with a sufficient accuracy to permit accurate and detailed forecasts to be made. These models, the basic principles of which through day-to-day use are continually being tested against the real climate, provide the tool with which the consequences for climate of the expected modification to the atmospheric radiation budget may be explored. Their predictions allow strategic planning to be undertaken with a measured level of confidence, in sufficient advance of the effect.

Recent studies of the effect on climate of enhanced [CO_2] using general circulation climate models (GCM's) suggest that the globally averaged temperature will rise by between 2.3 and 5.2C° for doubled [CO_2] (see Table below).

Table I.2

Summary of predictions from recent GCM's for the rise in global temperature for doubled [CO_2].

Reference	$\delta T_{2x[CO2]}$ (C°)
Manabe & Wetherald 1987	2.3[1]
Washington & Meehl 1984	4.5
Wilson & Mitchell 1987	5.2[2]
Hansen *et al.* 1988	4.2

1. Using prescribed cloud cover. By modelling cloud cover, predicted temperature rise for doubled [CO_2] is 4C°.
2. More realistic modelling of optical properties of clouds reduce sensitivity to 2.7C° for doubled [CO_2] (C. Senior, private communication).

The major discrepancies between the models are due to the uncertainties regarding feedback effects, and the transport of moisture and latent energy. For the sake of clarity, we shall here discuss the results of the Goddard Institute for Space Studies Model II (Hansen *et al.* 1983) which has a horizontal resolution of 8° in latitude and 10° in longitude, and predicts a rise of 4.2°C for double [CO_2], a value midway between the above range. Furthermore, we shall concentrate on changes brought about during the next 20 years, which as pointed out by Hansen *et al.* (1988) are rather unaffected by the models sensitivity to doubled [CO_2].

The Goddard model includes a full treatment of the vertical transport of heat in the ocean, taking account of the seasonal variation in the depth of the mixed layer, and allowing diffusion of heat from the mixed layer to an eight-layered, 1km deep thermocline below. It is this more detailed description of ocean heat transport which makes realistic transient prediction possible. However, the pattern of horizontal transport of heat in the ocean is fixed, and no allowance can therefore be made for possible feedback between global climate change and horizontal heat transport. This precludes the type of rapid "phase transition" effects discussed by Broecker *et al.* (1985) which could flip the climate system into a new stable mode over very short timescales(i.e. changes in global temperatures of 7°C in 50 years (Dansgaard *et al.*, 1989)); and also does not allow for El Niño-type phenomena to arise which could modify the temperature changes on a more localised scale.

Cloud opacity is specified according to the cloud type and height, i.e. the possibility of feedback into cloud-type opacity is not considered, although cloud height and cover are computed by the model. Changes in surface albedo (vegetation and snow cover etc.) are included, both as a seasonally variable effect and in response to changing climatic conditions, with snow and sea-ice albedo also changing in response to snow age. Feedback effects are included according to Section IV, and injection of stratospheric aerosols (particularly sulphur dioxide) by volcanic eruptions is also accounted for. This is an important forcing effect, as demonstrated by the 0.5C° drop in global temperature experienced after the 1963 Mt. Agung eruption on Bali (Hansen *et al.* 1978). A full discussion of the ~~societal effects and~~ societal implications of major historic volcanic eruptions is given in Part ~~VIII~~ at the end of the document. In the model major eruptions are simulated to occur with their frequency of occurrence over the last 30 years (Agung in 1963 & El Chichon in 1982). Mt. St. Helens which erupted in 1981 had little impact on the global climate because of the anomalously low levels of sulphur dioxide vented to the stratosphere.

The model was run for a simulated duration of 100 years with an atmospheric composition fixed at 1958 levels; both to serve as a control experiment, and to compare the "natural" interannual variabilty of the model with observed values. The annual mean at the beginning and the end of the run were similar, and the standard deviation about the 100 year mean temperature varied with latitude in a manner largely consistent with observation. The model was rerun with a value of [CO_2] which increased in accordance with observations since 1958, and subsequently according to three different estimates of the future rate of growth. The first scenario had [CO_2] increasing indefinitely at an exponential ~~rate, representing~~ the pessimistic case. The second scenario optimistically assumed that ~~CO_2~~ emissions (and those of the other greenhouse gases) were curtailed to such an extent that the climate forcing (the quantity of heat trapped by radiatively active gases) remained constant after the year 2000. Finally, the third scenario (their scenario B) assumed that ~~[CO_2]~~ increased linearly such that the rate of change in forcing remains approximately constant at the present level. In this scenario, [CO_2] will have doubled compared to pre-industrial levels by the year 2080. This is somewhat later than present estimates suggest (Bolin *et al.*, 1986) but is consistent with the study of Siegenthaler & Oeschger (1978) which modelled the effect of oceanic uptake of CO_2 in some detail. The results quoted in the following pertain to this scenario.

Little significant warming was found to occur until the 1990's when warming at the 2 sigma level was predicted to occur in low latitude oceanic regions; in particular the Caribbean and large areas of the tropical Indian and Pacific oceans. In the 1990's, warming of between 0.5C° and 1C° (above the control run mean for that decade with 1958 atmospheric composition) is expected over Britain at the 2 sigma level and over much of the rest of Europe and the US. By 2010, the UK should have warmed by between 1 and 2C° at greater than 2 sigma significance, with winter increases greater than in summer. The largest increase in temperature occurs at the poles (4-5C°) in response to the strong feedback effect of the reduction in sea-ice cover there. The significant warming at low latitudes in this, and the ~~British~~ Met. Office model (Wilson & Mitchell 1987) was not seen to such an extent in the models of Washington & Meehl (1984), presumably as a consequence of the different method used to calculate moist convection, which governs the vertical temperature gradient in the model atmosphere (Hansen *et al.* 1988)

At European latitudes, the warming is predicted to be greater in the winter months (Dec-Feb) than in summer (Jun-Aug), with temperatures likely to increase more rapidly in continental interiors than in oceanic regions (C. Senior, private communication). An interesting conclusion from the Goddard study is that the shape of the distribution of excursions about monthly averaged minima and maxima for July and January, seems to remain essentially unchanged. In other words, it seems valid to take present monthly temperature distributions and simply add the relevent temperature rise to all the values to obtain the future distributions. The amplitude of the diurnal temperature cycle was also found to remain unchanged.

The prediction of regional rainfall is more difficult because of the problems involved in the treatment of evaporation and moist convection, together with the sensitivity of rainfall patterns to atmospheric circulation (see e.g. Folland *et al.* 1986). It does seem clear however that precipitation will increase almost everywhere, and the increase will be greatest in the higher latitudes (1mm/d for UK in winter; smaller increase or a decrease in rainfall during summer). Soil moisture content is predicted to decrease over Britain and Europe in summer (Jun-Aug), (available water capacity change of 10-20mm in equilibrium for 2x[CO_2]) while in winter (Dec-Feb) soil moisture content may increase by a similar amount in N. Britain, but remain decreased over the rest of the UK and Europe (Wilson & Mitchell 1987) although the results are uncertain.

Finally, the effect of the predicted climate change on sea level is still rather controversial. Although temperature rises are predicted to be greater at the poles, the temperatures may still be too low to cause significant melting of land-borne ice and snow. Since it is floating, sea-ice will have no effect on sea level when it melts. Thermal expansion of the ocean, along with melt water from low-latitude continental valley glaciers, will contribute to any rise in sea level. As a counter to this rise however, the predicted increase in precipitation at the poles may lock up more of the Earth's water in the polar ice caps to the extent that the net effect is a global fall in sea level. Current opinion (C. Senior, private communication) would suggest that for a climate in equilibium with atmospheric [CO_2] at double the pre-industrial level, the rise in sea level will be less than, or roughly 30cm.

I.9 Concluding Remarks.

The current knowledge and uncertainties concerning the evidence for global climatic change in response to raised atmospheric ~~carbon dioxide levels~~ has been reviewed. Models, backed up by observation, suggest that within twenty years, the UK and much of Europe will have warmed by 1-2C° from 1960 averages. This dramatically short timescale underlines the immediacy of the problems involved in quantifying and ameliorating the impact of global warming. Predictions regarding rainfall also suggest an increase, although the magnitude of the increase is rather uncertain. Major difficulties in the model predictions concern the treatment of moist convection, and the transport of heat by the oceans. Furthermore, the coarse horizontal resolutions currently employed (8° x 10° in the Goddard model) mean that predictions at the regional level are impossible. For example, it is not possible at the moment to determine in any detail the consequences of raised global $[CO_2]$ across areas smaller than that of the U.K. In light of these problems, the most honest and rational approach in the present study, rather than adopting a single scenario in common with most other studies, is to consider a spectrum of feasible scenarios, guided by the best available projections outlined above. In this way, it will be possible to identify those aspects of climate prediction which have the greatest potential impact for agriculture, and to gain a quantitative perspective on the likely implications.

In what follows, we shall assume as a baseline, that by 2010 UK temperatures will be warmer by between 1 and 2°C in winter, and by around 1°C in summer. In light of the uncertainties, the effects of wet or dry summers and winters will be discussed. In this way, an accurate perspective will be gained on the problems and possible advantages of the imminent and almost inevitable change in the global climate.

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TO END

This will give an accurate perspective on

By working within these bands of uncertainty, it will be possible to identify those aspects of climate prediction which have the greatest potential impact for agriculture. This in turn will provide an accurate perspective on the problems and possible advantages of the imminent and almost inevitable change in the global climate.