hydrogen; e.g. 880 m³ CH_4 and 700 m³ CO_2 are produced out of 1 t of coal (awf) containing 85% C. Therefore, the total CO_2 emission is about 6% higher than burning coal directly.

3. CO_2 emission during the gasification process can be avoided if the hydrogen needed is produced by processes which do not involve C (e.g. electrolysis, thermal water splitting). Therefore, total emission would be reduced by about 40%. Of course, CO_2 emission could be avoided altogether if the hydrogen were used as an energy carrier directly.

e) Coal liquifaction. In principle the same cases apply as given under d). If methanol (CH_3OH) were produced by using hydrogen which is not provided by carbon/water reactions, then the total emission could be reduced by about 30%.

Conclusions

It is found that large differences in future atmospheric CO_2 concentration may be estimated due to different energy supply strategies. At present there seems to be no immediate need to reduce fossil fuel consumption. However, considering the magnitude of possible effects, efforts should be made to keep the increase of fossil fuel consumption as low as possible. Especially with regard to the CO_2 strategy given in figure 6 it should be borne in mind that fossil fuel plants which are planned today are expected to operate beyond the 1st decade of the next century.

Climatic effects of increasing atmospheric CO_2 levels

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Introduction

There is a wide consensus among scientists that the continued use of fossil fuels at about the present rates together with the ongoing deforestation might lead to adverse climatic and environmental effects that could seriously impair the well-being of mankind. Uncertainties in the predictive tools used and the scenarios developed from them have given rise to much speculation. Intensive research can, however, reduce the uncertainties and hence remove the basis for speculation. The following is an account of such research efforts emphasizing the climatic impact of increasing atmospheric CO_2. Specifically, this review starts with an overview of the world's fossil fuel resources, the future world energy demand and energy mix, and the likely effects of different energy scenarios on the CO_2 level. This can give an indication of the potential climatic effects that are due to man's activities in general, and those that are due to the use of fossil fuels in particular. Because the emphasis in this paper is on the climatic effects of increasing CO_2, the potential consequences of a climatic change are also briefly discussed.

1. *World fossil fuel resources*

In the past the world energy market has depended almost completely on fossil energy resources. During the first industrial revolution from 1870–1914 coal was the dominant energy source with an annual consumption growth rate of about 5% (Häfele and Sassin, 1978). The two world wars and the world economic crisis reduced the average growth rate of energy consumption to about 1.78%/year. The former annual growth rate of 5% was resumed between 1950 and 1970, when oil and gas became the dominant energy sources supplying more than 70% of the global primary energy consumption.

While oil and gas can be expected to continue to dominate world energy trade at least until the end of this century, a major shift from their use in combustion processes to petro-chemical usage is, however, imminent. Present global energy planning and development predicts not only a greater share of the nonfossil fuel energy resources (Bach et al., 1979b), but also a revitalization of coal made possible by innovative extraction and conversion technology (Griffith and Clarke, 1979), an intensified search for unconventional fossil fuel resources, and an accelerated development of a synthetic fuels program (Dickson, 1979). It is clear that the future climatic impact of fossil fuel consumption will depend on its relative share in a future global energy mix. Therefore, a discussion of the potential future impact must be preceded by an appraisal of the world fossil fuel resources and by estimates of the magnitude of the individual energy resources and their relative shares in the future global primary energy consumption. The following summary information on coal, oil, and gas has been extracted from a report to the Conservation Commission of the 1977 World Energy Conference (1978).

1.1. *World coal resources*

The current world coal resources are estimated at about $10{,}000 \times 10^9$ tons of coal equivalent (1×10^9 tce $\triangleq$ 1 TW-year). It is estimated that from this some

640×10^9 tce are technically and economically recoverable. Based on the planning policy of the major coal producing countries the present world coal production rate of 2.6×10^9 tce is expected to increase to 3.9×10^9 tce in 1985; 5.8×10^9 tce in 2000; and 8.8×10^9 tce in 2020. This would require an average annual growth rate of 2.7% during the period 1975–2020 compared with 2.2% during the period 1950–1975. A 3-fold increase in world coal production is a formidable task involving such major obstacles as the construction of an adequate infrastructure with suitable transportation facilities, long lead times in opening up new mines, the recruitment of qualified miners and engineers, and the availability of capital.

1.2. *World oil resources*

The ultimately by recoverable worldwide conventional oil resources are estimated to be about 260 Gt compared with the 1977 petroleum consumption of about 3 Gt (0.7 Gt ≙ 1 TW-year). The 260 Gt include about 100 Gt of proved and probable reserves already discovered, and 160 Gt of reserves still to be discovered. It is clear that conventional oil reserves are running out fast.

Unconventional oil reserves have so far been inadequately evaluated because of their low profitability under present economic conditions. The present oil shale reserves are estimated at 400 Gt, of which only 30 Gt are exploitable with current technology. World reserves of tar sands and heavy oils are estimated at about 300 Gt, of which only 5–10% are exploitable on the surface. Overall it may be possible to exploit some 200–300 Gt of unconventional oil (oil shales, tar sands, heavy oils, oil from deep offshore and polar zones, synthetic oils and enhanced oil recovery) around the year 2000 at a price of $20–25 per bbl. at 1976 prices.

1.3. *World gas resources*

The current world conventional natural gas production is about 1.32×10^{12} m^3 (0.8×10^{12} m^3 ≙ 1 TW-year). The proved reserves are estimated at about 66×10^{12} m^3, and the remaining undiscovered resources are estimated at about 215×10^{12} m^3. In addition, innovative recovery methods could add enormous amounts of gas from unconventional sources. For the USA alone estimates are 8 to 23×10^{12} m^3 from coal-bed degasification; 14 to 17×10^{12} m^3 from Devonian shales; 17×10^{12} m^3 from tight formations; and 85 to 1440×10^{12} m^3 from geopressurized gas.

2. *World energy demand and the effects of different energy scenarios on the atmospheric CO_2 level*

An assessment of the impacts from present and future fossil fuel use involves estimates of the present and future world energy demands (Bach, 1979b). Energy models and energy scenarios based on technological, economic, demographic, social, political, and environmental factors are used to make demand projections for individual primary energy sources. The table shows the share of the primary energy sources in 1975, and the low and high supply scenarios developed at the International Institute for Applied Systems Analysis for the years 2000 and 2030, respectively. Whereas the fossil fuel share in 1975 was 90% of the total primary energy supply, it is projected to reduce to 76% in the year 2000, and to 65% in 2030 for both scenarios. The range of 17–26 TW from fossil fuel use in 2030, compared with the 1975 value of 7 TW, can be used as a yardstick for potential climatic impacts in the future.

The time scale is an important factor in the interaction of the various energy supply scenarios and the atmospheric CO_2 level. Assuming a population growth, from today's 4 billion to 12 billion people, an average energy consumption of 5 kW per capita, and an initial consumption of only oil and gas and coal thereafter, Häfele et al. (1976) obtained the cumulated energy consumption shown in figure 1. If one considers an energy scenario in which a 200% increase in CO_2 is the limit (due to the greenhouse/climate

Two supply scenarios, global primary energy (TW), 1975–2030

Primary source		Low scenario		High scenario	
	1975	2000	2030	2000	2030
Oil	3.61	5.23	4.73	6.77	7.39
Gas	1.51	2.09	2.45	2.80	5.45
Coal	2.26	3.79	9.93	4.68	13.69
Nuclear energy 1	0.50	2.70	1.63	3.40	4.12
Nuclear energy 2	0	0.04	5.38	0.04	7.97
Hydro energy	0.12	0.53	1.04	0.54	1.12
Solar energy	0	0.17	0.48	0.21	1.14
Other energies	0.14	0.20	0.55	0.25	0.71
Total	8.14	14.75	26.19	18.69	41.59

Source: Häfele (1979).

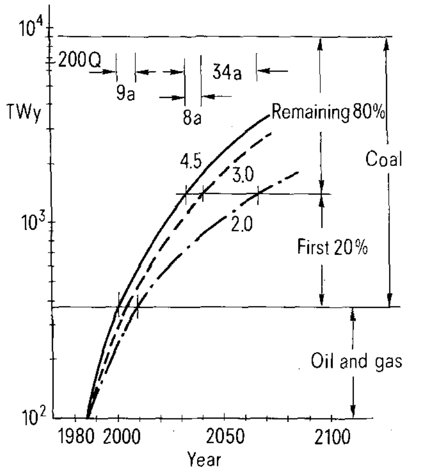

Fig. 1. Fossil energy reserves and cumulated energy consumption. Source: Häfele et al. (1976).

effects), then the use of coal is found to be curtailed to 20% of the presently known world coal resources. The exponential energy growth rates in figure 1 show very well that there is only a time span of about 42 years between the high and the low growth rates to reach the 200% ceiling. Apparently the reaching of some set limit for fossil fuel consumption is rather insensitive to technological and economic considerations. At the continuation of the present fuel mix and energy growth rates it is indicated that there will be 200% more CO_2 in the atmosphere than there is today, some time before or around 2050. The potential climatic effects of increasing CO_2 in the atmosphere are now discussed in some detail.

3. *Model studies of the climatic effects due to increased CO_2*

3.1. *Climate models*

The increasing CO_2 concentration in the atmosphere is suspected of being a major contributing factor to future global climatic change. Climate models are our best available tools for understanding the complicated climatic system sufficiently to predict climatic changes due to CO_2 increases. A hierarchy of climatic models ranging from 1-D to 3-D models has been devised to study the effects of CO_2. They can be grouped as follows:

- 1-D radiative-convective equilibrium models with a fixed lapse rate adjustment (e.g. Manabe and Wetherald, 1967; Wang et al., 1976; Augustsson and Ramanathan, 1977; Ramanathan and Coakley, 1978).
- 1-D and 2-D energy balance models in which meridional heat transport is parameterized by a simple mixing hypothesis (e.g. Budyko, 1969; Sellers, 1974); 2-D zonally symmetric models of the earth-atmosphere system which couple zonal dynamics as a function of latitude and altitude to the zonal surface energy balance (e.g. MacCracken, 1973; Potter, 1979).
- 3-D general circulation models in which eddy and hydrologic processes are computed explicitly (e.g. Manabe and Wetherald, 1975, 1980).

Figure 2 summarizes the specifications of a selection of the present state-of-the-art models, and it indicates that the sensitivity of the various climatic models to a doubling of CO_2 to 600 ppm results in an average increase in surface air temperature of about 1-3 °C. Recently the magnitudes of these temperature changes have been questioned (Newell and Dopplick, 1979). Using a static radiative flux model they find that at low latitudes a CO_2-doubling results only in a

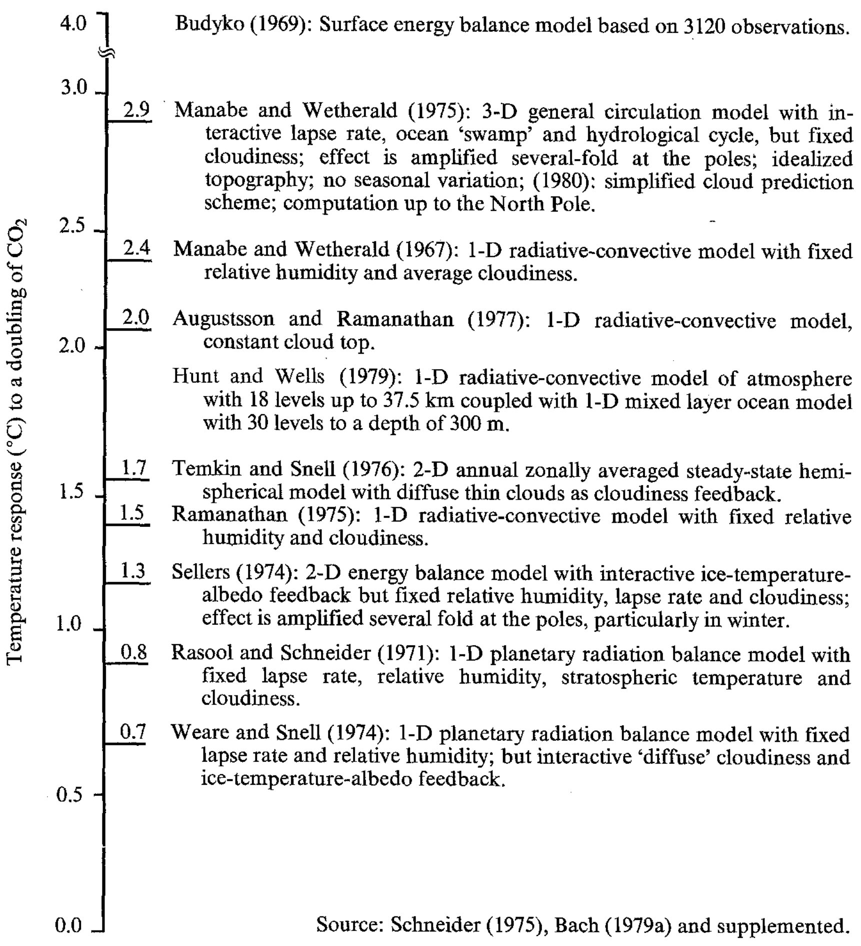

Fig. 2. Computed surface air temperature changes for a doubling of CO_2 to 600 ppm.

surface temperature increase of 0.25 °C which is smaller by a factor of about 8 than the findings generally accepted. They maintain that the larger values predicted by the other models result from the increasing water vapor in the model atmosphere rather than from the CO_2 itself. Furthermore, Choudhury and Kukla (1979) have presented calculations of spectral radiative transfer and scattering within a snow pack and water which suggest that CO_2 significantly reduces the shortwave solar radiation absorbed by the surface of snow and water. Although their model omits several important radiative and micrometeorological processes, such as the added heating of the atmosphere due to the increasing CO_2, they think that this solar energy deficit, if not compensated for by downward radiation, may delay the recrystallization of snow and the dissipation of packice and result in a cooling rather than a warming effect.

On the whole, most models predict an overall increase in surface air temperatures. It should, however, be realized that they represent only the sensitivity of the model climate to the produced perturbations in the atmosphere, and that the sensitivity of any particular model may not reflect the climate sensitivity of the actual earth-atmosphere system (Ramanathan and Coakley, 1978). Thus, the results may attest more to the great similarity of the models rather than be an affirmation of reality. With this caveat in mind, I shall now discuss a selection of major CO_2-modeling results.

3.2. *CO_2 experiments using a 1-D climate model*

Augustsson and Ramanathan (1977) have shown that the surface air temperature (Ts) is very sensitive to the radiative-convective model asssumptions related to cloud top temperature (CTT), cloud top altitude (CTA) and relative humidity. As figure 3 shows, a doubling of CO_2 at constant relative humidity leads to an increase in Ts of 3.2 °C for CTT, and 1.98 °C for CTA. The contribution from the individual CO_2-absorption bands to the total value of 1.98 °C is as follows: it is 1.61 °C for the 12–18-µm bands; 0.12 °C for the 10-µm and 7.6-µm bands; and 0.25 °C for the solar bands of CO_2 and H_2O (Ramanathan and Coakley, 1978). It is important to note that the greenhouse effect due to the 15-µm bands increases logarithmically with respect to CO_2, whereas the weak bands greenhouse effect increases almost linearly with increasing CO_2. This may have important implications for the CO_2-climate problem in that the warming effect of CO_2 on the global surface air temperature may never saturate, whereby the runaway greenhouse effect may become a distinct possibility (Bach, 1980).

Besides CO_2, there are a number of other man-induced gases, such as nitrous oxide, methane, and chlorofluoromethanes, which also absorb IR radiation and thus add to the greenhouse effect due to CO_2. Flohn (1979) has combined their climatic effects with that of CO_2 by adding 50% to the CO_2-effect on temperature. This gives a combined greenhouse effect which, expressed in terms of virtual CO_2-content, represents the actual CO_2-content plus the amount of CO_2 which is equivalent to the effect of the other trace gases.

Using the logistic CO_2-growth model by Zimen (1979) and the more conservative version of the Augustsson/Ramanathan 1-D climate model (i.e. constant relative humidity and a constant altitude of cloud tops, see figure 2) Flohn (1979) obtained the curves shown in figure 4. With a continuation of the historical CO_2 emission growth rate of 4.3%/year the probable limit of detection of a warming (i.e. a global temperature increase of about 0.5 °C) could be reached as early as 1990. Even at a reduced CO_2 growth rate of 2%/year this level would be reached shortly after the year 2000. A temperature increase of 1 °C, typical of the Medieval warm phase between the years 900 and 1050, would be reached either by 2000 or 2050 for annual CO_2 growth rates of 4% and 2%, respectively. The postglacial Holocene warm phase, circa 6000 ago, also known as the 'altithermal', was some 1.5 °C warmer than today. It is seen that similar temperature conditions could occur again around the year 2050. Finally, for an annual CO_2 growth rate of 3–4% a critical warming of 4 °C could be reached in the 2nd

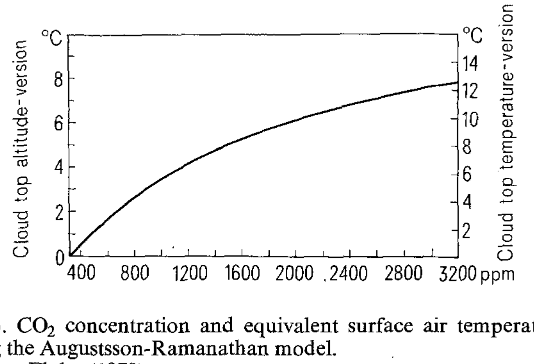

Fig. 3. CO_2 concentration and equivalent surface air temperature using the Augustsson-Ramanathan model.
Source: Flohn (1978).

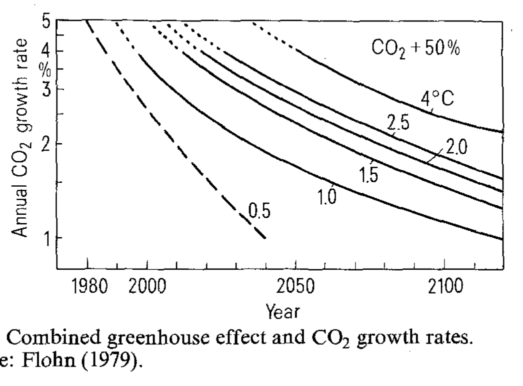

Fig. 4. Combined greenhouse effect and CO_2 growth rates.
Source: Flohn (1979).

half of the 21st century. Under similar such conditions the Arctic Ocean was ice-free from 12–2.5 million years ago, and it has not been ice-free since then. The relevant question is, of course, whether climate history can repeat itself.

3.3. *CO_2 experiments using a 2-D climate model*

Also 2-D zonal climate models have been used to compute the effects of increasing CO_2 concentrations. The model employed by Potter (1979) is based on the conservation equation and it calculates prognostic variables at 9 vertical levels and at intervals of 10° latitude. At each latitude the surface is divided proportionally into land of various types and elevations and into ocean that is either open or partially covered with ice. The land surface consists of as many as 10 layers of variable depth in which the thermal inertia due to diurnal and seasonal forcing is determinable, while the ocean is treated as an isothermal layer up to a depth of the thermocline. The model is integrated for 200 days starting from initial conditions similar to observed zonally-averaged temperature and moisture regimes. The control run and the model runs perturbed by a doubling and a quadrupling of the atmospheric CO_2 content are then integrated for an additional 200 days. When the net radiation at the top of the atmosphere approaches zero it is assumed that the model runs have reached a state of near equilibrium.

Figure 5 shows the latitudinal distribution of total precipitation (in cm per day) for the control run and for a decrease ($0.5\times CO_2$) and an increase ($2\times CO_2$ and $4\times CO_2$) in atmospheric CO_2 concentration. The globally averaged precipitation increases by 6% and 9% for the $2\times CO_2$ and $4\times CO_2$ perturbations, respectively. The enhanced precipitation is due to the increased CO_2 content, which increases tropospheric downward longwave radiation, which, in turn, increases the energy available at the surface for evaporation, thereby increasing the precipitable water in the atmosphere.

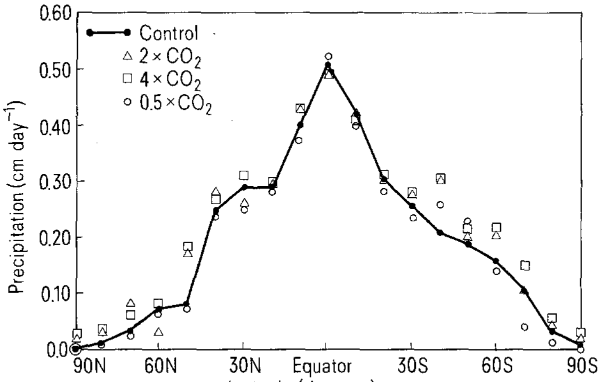

Fig. 5. Latitudinal distribution of total precipitation (cm/day). Source: Potter (1979).

Similar to other model experiments, those with the 2-D zonal model also show the large temperature response to a CO_2-increase in polar regions. This results almost entirely from the weakening of the surface inversion and not from ice-albedo feedback which is found to be rather ineffective in amplifying temperatures in model experiments. The surface albedo of the northern hemisphere is found to decrease as the CO_2 content increases, i.e. from 22.4% for the control case to 22.2% for $2\times CO_2$ and 19.1% for $4\times CO_2$. Similar changes in surface albedo are not found for the southern hemisphere; this is essentially due to the complete lack of sea ice in high southern latitudes. As one might expect, the net longwave radiation loss at the surface is reduced with increasing CO_2 concentration. Together with a reduction in insolation this is found to result in an area mean increase in net allwave radiation of 4.2% for the $2\times CO_2$-case, and of 6.3% for the $4\times CO_2$-case.

3.4. *CO_2 experiments using a 3-D climate model*

In a further attempt to study more realistically the sensitivity of the internal model climate to man-made external forcing, such as the increasing atmospheric CO_2 content, Manabe and Wetherald (1975, 1980) have deployed a 3-dimensional general circulation model (3-D GCM). Whereas for simplicity of interpretation and economy of computation the 1975 GCM still contains many simplifying assumptions such as those listed in figure 2, the 1980 GCM version additionally incorporates a simplified scheme of cloud predicition and the computational domain is extended to the north pole, permitting the study of geographical differences of the CO_2-induced climatic change over the northern hemisphere.

The 3-D GCMs are based on the fundamental dynamical equations that determine the large-scale behaviour of the atmosphere. A typical set consists of the prognostic equations, such as:

the equations of motion (expressing the conservation of momentum)

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - w\frac{\partial v}{\partial z} + f(Ug-u) - \frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\partial}{\partial z}\left(K_z\frac{\partial v}{\partial z}\right)$$

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - w\frac{\partial u}{\partial z} + fv - \frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\partial}{\partial z}\left(K_z\frac{\partial u}{\partial z}\right)$$

the thermodynamic energy equation (expressing the conservation of heat energy)

$$\frac{\partial \theta}{\partial t} = u\frac{\partial \theta}{\partial x} - w\frac{\partial \theta}{\partial z} + \frac{\partial}{\partial z}\left(K_z\frac{\partial \theta}{\partial z}\right)$$

the equation of continuity

$$\frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0$$

and a diagnostic equation such as the equation of state $p = \rho RT$

where u, v, w are the velocity components in the x, y, z directions; ρ is the density of air; Ug is the component of the geostrophic wind; p is the pressure; K_z is the vertical eddy coefficient (assuming that the exchange coefficients for heat, momentum and water vapour are equal, i.e. $K_h = K_m = K_q$); θ is the potential temperature (which is related to the ordinary temperature, T, by the relation $\theta = T\ ((p_o/p)^k$, were $p_o = 1000$ mb and $k = 0.286$ is the ratio of the specific heat); and R is the gas constant for air.

In the 1980 Manabe and Wetherald versions of the model the numerical integration of the prognostic equations is carried out at 9 vertically-spaced finite difference levels reaching from the Ekman boundary layer to the lower stratosphere. The horizontal finite differencing is carried out over a regular latitude-longitude grid system with a meridional spacing of 4.5° and longitudinal spacing of 5.0°. Beginning with the initial conditions of an isothermal and dry atmosphere, the numerical time integrations of the model are carried out for 3 values of atmospheric CO_2 content, namely 300 ppm (standard case), 600 ppm ($2 \times CO_2$), and 1200 ($4 \times CO_2$) over a period of 1200 days. The time-mean state of the model atmosphere over the last 500-day period of each integration is taken as representative. It is considered to be long enough so that the response of the model climate to a doubling of CO_2 is much larger than the ambiguity caused by a failure of the model to achieve a complete statistical equilibrium. Some of the results are now highlighted.

3.4.1. *Response of surface and upper air temperatures*
Figures 6a and b show the latitude-height distributions of the zonal-mean temperature response of the model atmosphere to a doubling and quadrupling of CO_2. The global area mean temperature of the lower model troposphere increases by about 3 °C for a doubling of CO_2, and by about 6 °C for a quadrupling of CO_2; similarly, the amplifications in polar regions are 8 °C and 15 °C again indicating that a doubling in CO_2 results in a doubling of the temperature changes. In contrast, the temperature in the stratosphere decreases with height, reaching −8 °C and −15 °C at an altitude of about 30 km for the $2 \times CO_2$- and $4 \times CO_2$-cases, respectively. The cooling in the stratosphere is due to the heat loss both to space and to the troposphere.

3.4.2. *Response of the meridional temperature gradient*
These figures also show that an increase in CO_2 reduces the meridional temperature gradient in the lower troposphere. There are several reasons for this, namely:
- the poleward retreat of the highly reflective snow cover which results in an enhanced polar warming;
- the confinement of the additional heat to the lowest layer of the model troposphere by the stable stratification in polar regions; and
- the large increase in the poleward transport of latent heat.

3.4.3. *Response of the hydrologic cycle*
The increase in poleward transport of latent heat is illustrated in figure 7, a–c, which shows the vertically integrated poleward transport of dry static energy (figure 7, a), latent energy (figure 7, b) and the sum of 7a and b which gives the moist static energy (figure 7, c). A doubling or quadrupling of CO_2 increases the poleward transport of latent energy in middle latitudes by as much as 7% and 16%, respectively (figure 7, b). The reason for this is the enhancement of the mixing ratio of water vapour in the lower model troposphere due to the increasing CO_2 content.
Based on these results we can postulate the following reaction scheme of plausible events: An increase of CO_2 in the atmosphere will:
- increase the air temperature, which will
- increase the mixing ratio of water vapour, which will

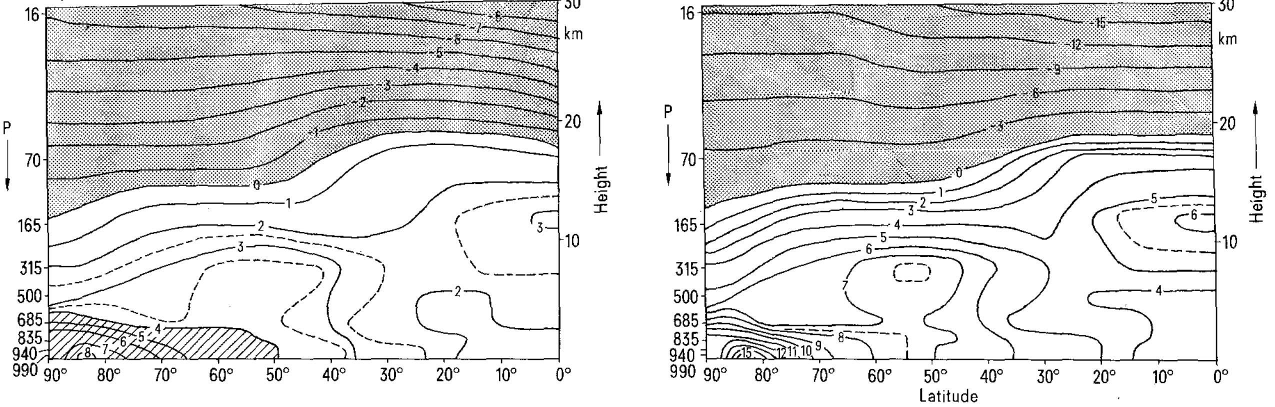

Fig. 6. a and b. Latitude-height distribution of the change of the zonal-mean temperature in response to *a* a doubling of CO_2, and *b* a quadrupling of CO_2. Units are in °C.
Source: Manabe and Wetherald (1980).

- increase the poleward transport of latent energy, which, in turn, will
- reduce the meridional temperature gradient, which will
- reduce the intensity of the global atmospheric circulation, which will
- lead to anomalous precipitation and temperature patterns, which, in turn, may
- affect the water supply, agricultural productivity, and energy supply systems.

3.4.4. *Geographic response*
The modeling results by Manabe and Wetherald (1980) show that an increase in atmospheric CO_2 significantly influences not only the zonal and area-mean distribution of climate, but also its geographical distribution. Figure 8 shows the horizontal distribution of the change of the precipitation rate minus the evaporation rate (P-E), which essentially corresponds to the runoff rate, in response to a CO_2 doubling. In the tropics and subtropics we find an increase in P-E along the east coast of the model continent. This is caused by the increase in CO_2 in the model atmosphere, which leads to an enhanced northward moisture transport along the periphery of the oceanic anticyclone, and which, in turn, intensifies the monsoonal precipitation.
In mid-latitudes, on the other hand, we find a reduction in P-E over the model continent in a zonal belt centered around 45° latitude. Responsible for the reduction in the precipitation rate in this belt is partly the decrease in eddy kinetic energy and partly the increased penetration of moisture into high latitudes which shifts the mid-latitude rainbelt poleward producing there an increase in precipitation. The details of the shown geographical distribution of climatic change must, however, not be taken too literally, because they were obtained from a climate model with an idealized geography, a flat topography and without seasonal variation. The results indicate, however, that the climatic impacts of increasing CO_2 may be far from uniform and may vary from region to region.

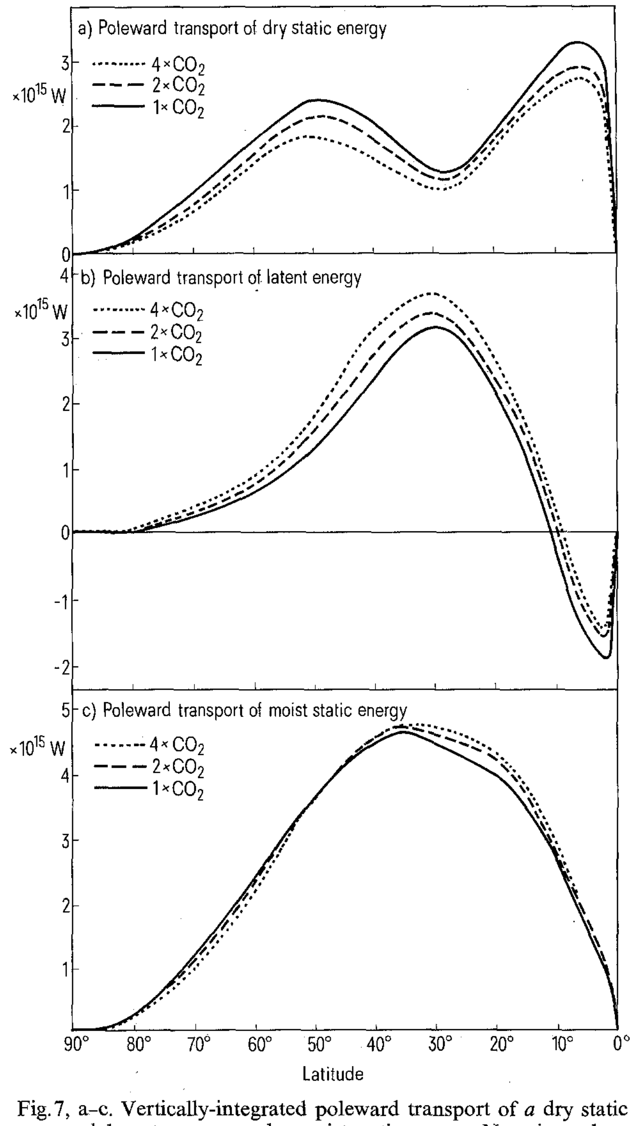

Fig. 7, a–c. Vertically-integrated poleward transport of *a* dry static energy, *b* latent energy, and *c* moist static energy. Negative values are equatorward transport.
Source: Manabe and Wetherald (1980).

3.4.5. *The effect of clouds*
Manabe and Wetherald's (1980) results show that the incorporation of a cloud-radiation feedback mechanism in the model has little effect upon the sensitivity of the climate. Apparently the change in terrestrial radiation caused by cloud changes is compensated for by the resulting change in solar radiation. Also Cess (1976) suggested that the 2 components of cloud amount feedback – the positive feedback from enhanced IR opacity of the atmosphere and the negative feedback from an increased planetary albedo – cancel each other, so that the cloud amount feedback may be unimportant zonally as well as globally. While the effect of clouds upon the sensitivity of climate may not be as large as originally thought, it is premature at this point to assume a negligible effect because of the uncertainties in the optical cloud parameters (e.g. reflectivity and absorptivity) and the preliminary state of the cloud prediction scheme.

3.4.6. *The role of the oceans*
Within the climate system the major role of the oceans is to store and redistribute heat. The difficulty of adequately incorporating the oceans in the climate models constitutes a major area of uncertainty. Smagorinsky (1979) has recently reported about Manabe and Stouffer's climate simulations which include a simple mechanism to take the heat storage in the first 68 m into account. The first ocean-coupled CO_2 sensitivity experiments, the results of which are now

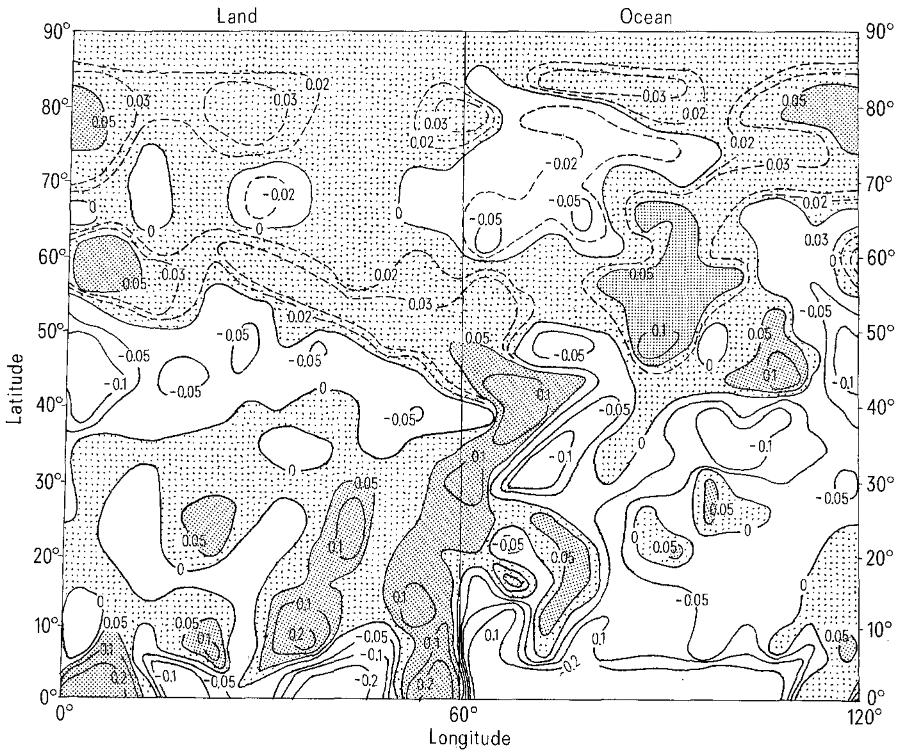

Fig. 8. Horizontal distribution of the change of the precipitation rate minus the evaporation rate (P-E) in response to a doubling of CO_2. Units are in cm/day.
Source: Manabe and Wetherwald (1980).
Two supply scenarios, global primary energy (TW), 1975-2030.
Source: Häfele (1979).

summarized, were conducted to determine the climatic response to a quadrupling of the atmospheric CO_2 content.

Although the Manabe and Wetherald (1975, 1980) model, which treats the oceans like a flat 'swamp', requires some 1200 days to achieve complete statistical equilibrium, it takes about 10 years for the combined atmosphere/mixed layer ocean model to reach a new climatic state. This would account for 50-75% of the change that would occur if deep ocean mixing were also considered.

The global-area mean surface temperature increase due to a quadrupling of CO_2 is about 4 °C, which is about 2 °C lower than that obtained from the non-ocean coupled models. At the equator the temperature increase is smallest, about 3 °C; at the poles it is greatest, about 6 °C at the south pole and about 10 °C at the north pole. The asymmetry of the response between the 2 poles is due to the fact that at the north pole there is an ocean normally covered with ice and at the south pole there is a continent covered with snow. The model results show that a 4-fold increase in CO_2 would be sufficient to melt the sea-ice of the north pole in summer, while the south polar snow cover would remain all the year round.

Control experiments with the current level of CO_2 yielded a good approximation of the contemporary climate, reproducing rather well the sea surface temperatures and the polar ice distribution in its seasonal variation. However, the geographical differences in the climate response must also be considered tentative for the coupled ocean/atmosphere model, because it still ignores ocean currents, which are strongest near east coasts and ocean upwelling, which is strongest near west coasts.

3.5. *Statistical significance of climate model results*

Climate models, just as the real atmosphere, have an inherent variability which is due to the high degree of non-linearity in the models. The models' inherent variability can be estimated, for example, by computing the standard deviations of monthly means of grid-point data resulting from a finite set of independent data (Chervin, 1976; Chervin and Schneider, 1976). In order to obtain an objective measure of significance a ratio, r, of the absolute difference of the time means of control and anomaly experiments, Δ, to the standard deviation, σ, is defined such that

$$r = |\Delta_{30}| / \sigma_{30}$$

where Δ_{30} is the algebraic difference between 30-day means in the prescribed changed experiment and an unperturbed control experiment calculated at each grid point. The results are tested for their statistical significance by relating the r-values to the test variate used in Student's t-test. According to the theory, the smaller the value of the significance level the higher the confidence that the computed change is due to the CO_2 addition to the model atmosphere.

3.6 *Future activity*

At present, it is beyond our capability, at least for periods beyond a few weeks or months, to make useful predictions of natural climatic changes which are caused by internal interactions between the different parts of the climate system. However, as the above examples have shown, it is possible to make another kind of prediction which is based on the response of the whole climate system to a certain change in some external boundary conditions, such as the increasing CO_2 content of the atmosphere. The success of such predictions depends on how realistically our model climates respond to given changes in boundary conditions (Bach, 1976).

As was shown above, the natural extension of the sensitivity experiments was to incorporate a cloud-feedback mechanism and to develop a coupled mixed-layer ocean/atmosphere model. The next step will be to use realistic geography and a seasonal variation of insolation. This will allow us to study climatic changes in their regional and seasonal diversity, information that is of great importance to agricultural production and energy resource allocation (Williams, 1978; Bach et al., 1979a).

Moreover, there is a need to make detailed intercomparisons of the performance of the different climate models in terms of their relative sensitivity to the various mechanisms involved in climatic change (Gates, 1979). This will permit us to explore systematically, and with somewhat more confidence, past, present and future climates, the latter being of vital interest to a world faced with food and energy shortages.

All of these research activities require a concerted effort with an interdisciplinary approach at the national and international level. The methods of the physical scientist must be complemented by the skills of the scientist with political, economic, or social expertise. The objective of such a coordinated effort would be a world climate program to conduct research on the climate system; to provide climate data, information and services; and to assess the climatic impacts. All of these activities could supply vital information for the overall decision-making process.

4. *Potential consequences of a climatic change*

If we accept the possibility of a man-made climatic change it is reasonable to ask what could be the implications of such a change? It has been suggested that changes in the cryosphere and in agricultural productivity might be some of the more serious of the ensuing consequences.

4.1. *Effects of a CO_2 increase on ice, snow and sea level*

The major components of the cryosphere which are affected by a potential warming include the floating sea ice or pack ice in the Arctic and Antarctic Oceans, the Antarctic and Greenland ice sheets, the snow cover on land, the permafrost, and the mountain glaciers. Using a simple sea ice model Budyko (1966) estimated that a 4 °C temperature increase in summer could completely remove the pack ice within 4 years. This would come close to an irreversible process. Other model experiments designed to simulate the effects of an ice-free Arctic Ocean show a substantial warming of the lower troposphere over the Arctic Ocean and a cooling over mid-latitude continents (MacCracken, 1970; Warshaw and Rapp, 1973). Calculations made by Budd (1975) for the Antarctic show that a change of 1 °C in annual mean temperature would correspond to a 70-day variation in the duration of pack ice. Although the melting of pack ice does not significantly alter the sea level, it could change the values of albedo and evaporation and hence the climate (WMO, 1977).

In the event of a complete melting of the 3 major ice sheets, namely the Greenland, and the west and east antarctic ice sheets, sea level could rise by about 80 m. Evidence suggests that such an event is highly unlikely within the next few hundred years because former ice sheets have responded to a climatic warming with a delay of thousands of years (Whillans, 1978). Apparently the ice sheets in Greenland and the east Antarctica have remained intact throughout all interglacials for the past 2×10^6 years.

The crucial area seems to be rather the relatively small section covered by the west antarctic ice sheet. It is feared that the CO_2 doubling expected over the next few decades and the resulting temperature increase with its large amplifications in polar regions may bring the margins of the west antarctic ice sheet to the melting point (Mercer, 1978). This would set in motion a chain reaction with the west antarctic ice sheet breaking up and opening the way for larger parts of the continental antarctic ice to slide rather quickly into the ocean. There it would melt leading to a sea level rise worldwide of some 5–6 m with adverse effects to low-lying coastal areas. The severity of the impact will obviously depend on how quickly it will become effective, that could be within decades, as some claim, or could be spread over a century as others maintain. LANDSAT imagery to monitor the breakup of ice shelves on both coasts of the antarctic peninsula should be used as a precautionary measure to detect early warning signs of a dangerous warming.

The response of snowfall and snowcover to the warming trend will differ according to latitude. In high latitudes, where snowfall is limited by low water vapor content, higher winter temperatures will result in more snowfall; in middle and low latitudes, where snowfall is rare, higher temperatures will further decrease the frequency of snowfall and the duration of snowcover on the ground (Barry, 1978). Higher temperatures also have a significant effect on soil moisture and vegetation growth in areas of discontinuous permafrost. The movement of individual mountain glaciers in response to temperature changes is often confusing, since the magnitude of surges may be inversely related to temperature changes.

In summary, the best insurance policy is to monitor carefully any warning signs in the atmosphere in general, and in the west antarctic ice shelf in particular.

4.2. *Effects of a CO_2 increase on agricultural and marine productivity*

World food production is critically dependent upon climate and it is strongly affected by its variability. In the face of the food requirements of an increasing world population this dependence acquires special significance. The assessment of the climate/food interaction is one of high priority.

According to the modeling results the expected future increase in atmospheric CO_2 concentration would be accompanied by air temperature increases positively correlated with degrees of latitude resulting in a general poleward shift of agroclimatic zones (NAS, 1977). As a rule of thumb a 1 °C change in mean surface air temperature in summer at a given latitude corresponds to a 10-day change in the growing season (Kellogg, 1978). Whereas the increased warming may result in more drought at middle and higher latitudes (Baes et al., 1977), the impact of warming on tropical agriculture is likely to be small.

The impact of an enhanced hydrological cycle, which climate models predict for increasing CO_2 levels, is ambivalent. Whereas on the one hand agriculture may benefit from the increased precipitation, it may on the other hand suffer because the higher temperatures also enhance evapotranspiration which may diminish, rather than improve, the crop yield. The highest yields are achieved where crop species have found their optimal conditions through a series of adaptations. Consequently, the most serious impact on agricultural productivity will not come from gradual changes in average global conditions, but rather from shifts in the location of climatic zones. For example, such a shift may result in summer temperatures being too high for crops like corn and soybeans, thereby necessitating the northward shift of the Corn Belt into the acid podzols. This, in turn, would require more fertilization and intensive soil amelioration, in addition to substantial capital investment, for shifting a complete infrastructure which had become adapted to a specific climate.

Basically, agricultural productivity is dependent upon innovative technology (novel machinery, irrigation, fertilizers, pesticides, new varieties), environmental stress (pest outbreaks), cultural factors, and climate variability. In order to show the impact of the latter, McQuigg et al. (1973) developed a semi-empirical model for USA corn production which takes into consideration technology prior to 1973. By varying the climatic impact data, which has been available since 1890, and by holding technology fixed at the 1973 level, they were able to isolate the impact due only to climate variables. The results indicate corn yields of about 105 bushels per acre for 'normal weather' decreasing to less than 85 bushels per acre under drought conditions. Of special interest are the low corn yields in the 1930s and the consistently high corn yields over a 15-year period starting in 1958. An explanation for this is indicated by the above-or-below normal summer values of rainfall and temperature for that period. The low corn yields of the 'Dust Bowl Era' in the 1930s are clearly related to an almost uninterrupted 10-year period of below-normal rainfall and above-normal temperatures. Similarly, the 'High Yield Era' ending in 1973 was characterized by above-normal rainfall and below-normal temperatures, which are optimum conditions for high corn yields. According to McQuigg et al. (1973) the probability of having another period of 15 years of such favorable weather with high yields would be 1 in 10,000.

Detailed assessments of the climatic impact on agricultural and marine productivity have been made (CIAP, 1975) and are discussed in detail elsewhere (Bach, 1978). Here only the results for the major crops are summarized. Results from a crop-weather-soil moisture model show that corn production in the USA would change by about 11% for each 1 °C change in average maximum temperature over the summer months, and by about 1.5% for each 10% change in rainfall. In general, for the USA Corn Belt cooler and wetter conditions will increase corn yields, whereas warmer and drier conditions will decrease corn yields (Benci et al., 1975).

Results from multiple regression analysis for 6 midwestern wheat producing states indicated that wetter states, such as Indiana and Illinois, might experience a reduction in yields of up to 5–7 bushels per acre for temperature increases of 1–2 °C and precipitation increases of up to 30% (Ramirez et al., 1975). Drier states, such as Kansas and North Dakota, might gain from an increase in temperature and rainfall. Income losses due to climate impact have been assessed by Bryson (1975). He showed, for example, that a temperature increase of 1 °C and a rainfall decrease of 20% could each cost about $130 million in lost income.

Rice is the staple diet for the world's poorest and most densely populated countries. Estimates by Stansel and Huke (1975) indicate that an increase in both temperature and rainfall would result in a higher world rice production. Thus, although the production of corn and wheat might suffer, the production of rice might increase with the expected future warming.

Marine organisms are also affected by climate variability. Examples include the appearance and disappearance of tilefish off the east coast of the USA (Lorenzen, 1975) and the rise and decline of the West Greenland cod fishing (Cushing, 1976). The well-known El Nino phenomenon is another example of a climatic anomaly effect. Under such conditions coastal upwelling of nutrient-rich water is impeded and the Peruvian anchovy catch is reduced (Idyll, 1973; Cowles et al., 1977). A decrease of oceanic pH and a lowering of the super-saturation with respect to $CaCO_3$ caused by increase in dissolved CO_2 could influence the ability of marine organisms to form carbonate shells and skeletons (Elliott and Machta, 1978). In general, changes in atmospheric and oceanic circulation could affect marine productivity by changing the rate of upwelling, thereby influencing the fertility of surface waters.

It is often argued that some areas might benefit from an overall warming while others might suffer, insinuating that, on balance, there would be no adverse effects. Moreover, based on new developments in genetics and crop production methods some optimism has been expressed about the capability of some crops to adapt to slow changes in climate. There may be some justification for this regarding the industrialized nations with their highly developed organizational and technical skills, and the availability of capital and the necessary expertise. However, experience of the last decades has rather given rise to pessimism particularly in those developing countries that extend into areas with marginal climates. The increasing population pressure and the lack of capital and technological expertise make most developing nations, and hence the majority of the world's population, extremely vulnerable to even a slight variation in climate. Furthermore, there might be enormous costs for additional fertilizers, if, for example, the potential warming resulted in a shift of part of the USA corn and wheat belts into adjacent poorer soils. This would also necessitate a costly relocation of a complete infrastructure.

Finally, all of these factors may strain the finances of even the richest countries such that there may be little left to contribute to an aid program for the developing world. It would thus appear that any climatic change in any part of the world has to be viewed with great concern because the nations have become increasingly dependent upon each other.

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Measures of CO_2 control

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In the pessimistic, and tendentially masochistic, attitude that now seems to pervade western countries, measures of CO_2 control will be prima facie understood as rules and constraints that have to be imposed in order to reduce the consumption of fossil fuels.We may interpret the proposition of Prof. W.D. Nordhaus, to put a tax on CO_2 emissions, in this sense. This tax would be adjusted to keep the emission level under a predetermined value, that could be constant or a function of time (Nordhaus, 1977).

Such a proposal has much to recommend it. On the one hand, it respects the freedom of choice of the consumer, even if substantially restricting it, by operating in the conceptual framework of a market economy. On the other hand, it would find the enthusiastic support of bureaucrats and tax collectors, because it would add a new line to their activities. Properly injected with massive doses of guilty feeling, the consumer would presumably finally pay. Such a sequence has already been thoroughly tested in Europe, with the manipulation of gasoline prices.

The core of Nordhaus' reasoning is that the problem of CO_2 emission controls can be dealt with by a normal economic model where CO_2 *emission* is considered as a *resource* in short supply to be allocated between the various sectors of the economy in such a way as to maximize national income under this additional constraint.

The second line of thinking I strongly prefer as a matter of personal attitude, is that of the positive response: what can we do to avoid the worst?

Here 3 observations may help, in order to start thinking about a physically possible solution.

- Firstly, plants circulate in their system about 10% of the CO_2 in the atmosphere every year. The amount of CO_2 rejected by man is only a fraction of a percent. This fits with the parallel observation that plants have a metabolism in the range of 100 TW and man consumes less than 10 TW in the form of fossil fuel. So plants could give a hand, so to speak, to solve another of our problems.
- The 2nd observation is that the CO_2 ejected into the