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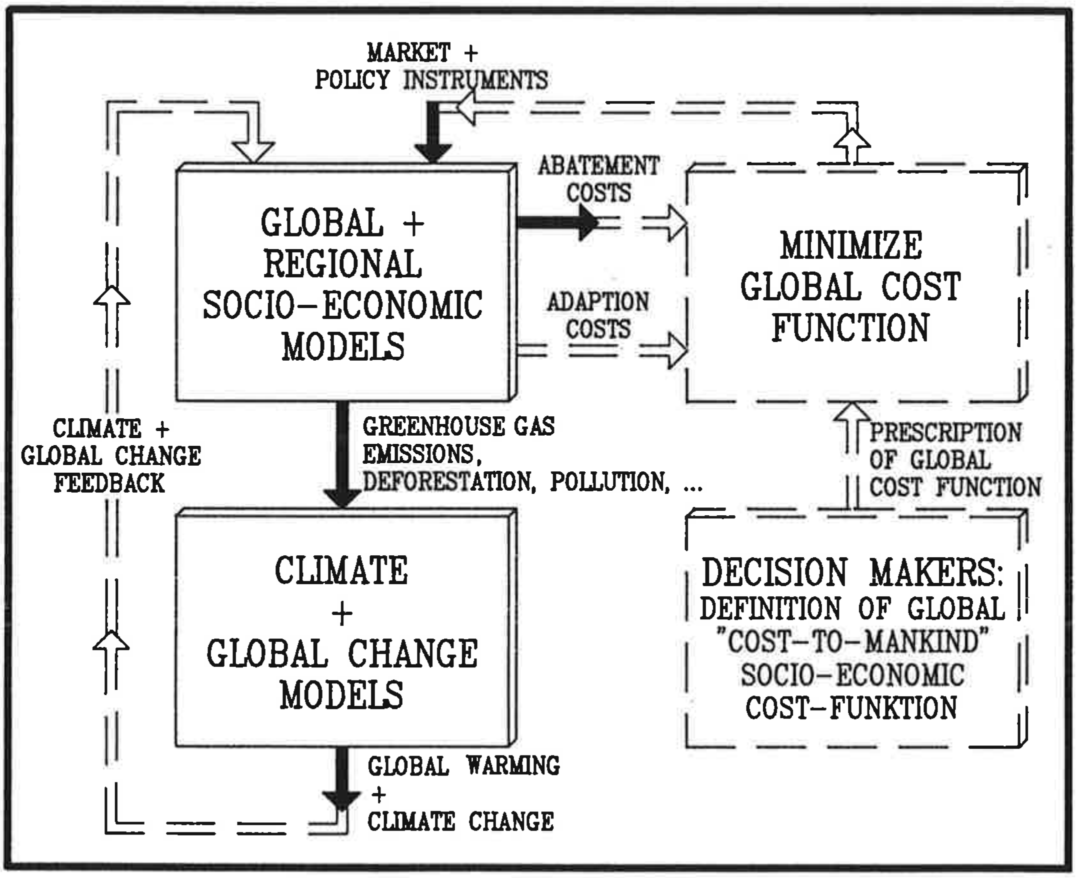

HOW WELL CAN WE PREDICT THE CLIMATE CRISIS

by

KLAUS HASSELMANN

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AUTHOR:

KLAUS HASSELMANN MAX-PLANCK-INSTITUT FUER METEOROLOGIE

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MAX-PLANCK-INSTITUT
FUER METEOROLOGIE
BUNDESSTRASSE 55
D-2000 HAMBURG 13
F.R. GERMANY

Tel.: (040) 4 11 73-0
Telex: 211092 mpime d
Telemail: MPI.METEOROLOGY
Telefax: (040) 4 11 73-298

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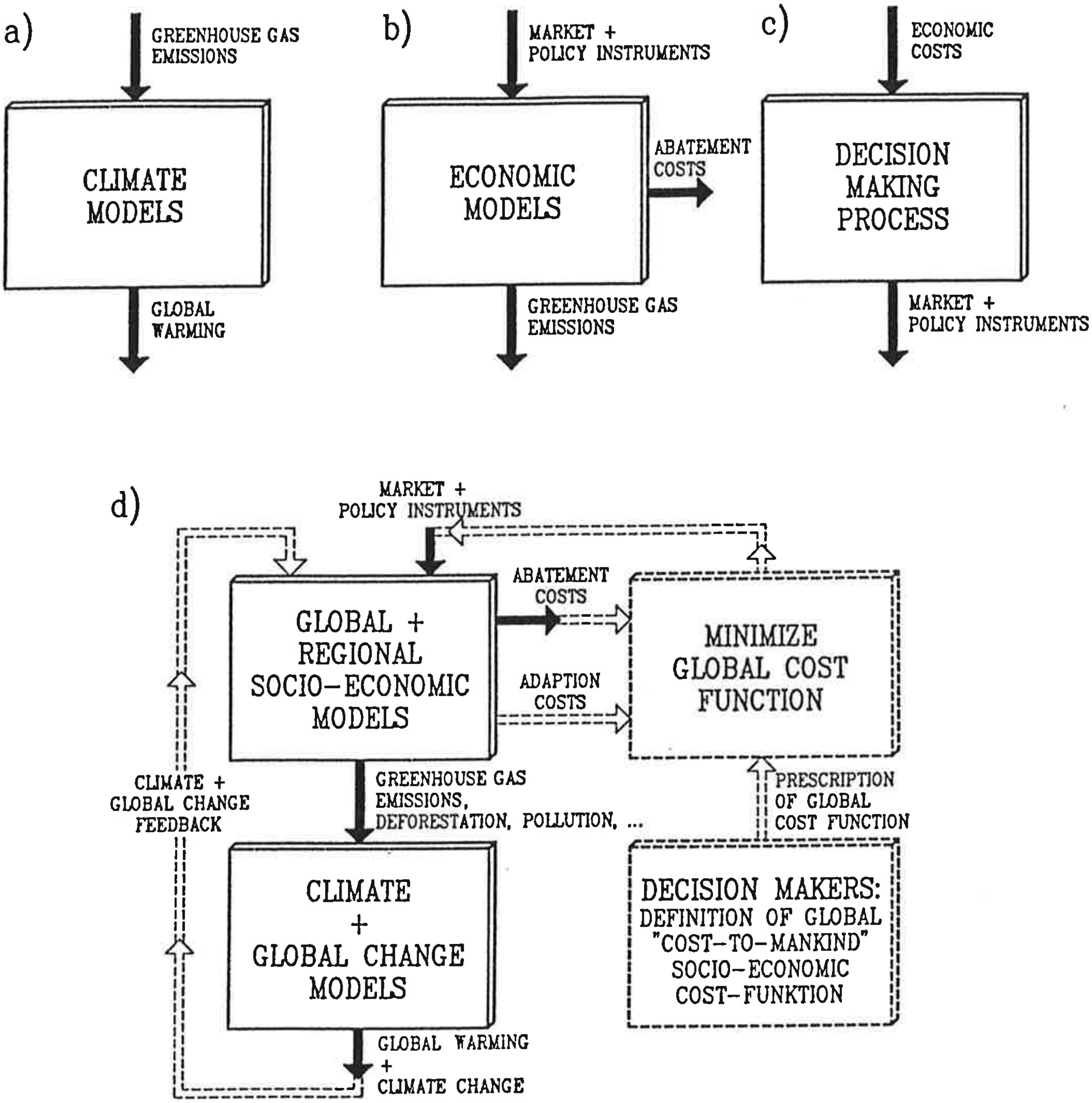
How Well Can We Predict the Climate Crisis?

Klaus Hasselmann

1. Interrelation between climate models, economic models and comprehensive Global Environment and Man (GEM) models

In our attempt to model the system earth and man's interactions within this system, climate models may be regarded as a simple black box. The input to the black box is man's impact (primarily the emission of greenhouse gases), the output is global warming (Fig.1, panel a). Most of the economic models discussed at this meeting may be represented as another black box,with one input: market or policy instruments, and two outputs: greenhouse gas emissions, and the costs incurred by greenhouse gas abatement measures (Fig. 1, panel b). Some of the models presented here have also addressed the decision making process. This may be represented by a third black box, with economic costs as input and market and policy instrument strategy as output (Fig. 1, panel c).

All of these models may be regarded as sub-models of a comprehensive Global Environment and Man (GEM) model, which represents the ultimate goal of our joint modelling efforts (Fig. 1, panel d). The full lines in panel d denote sub-components which have been largely developed. The broken lines indicate missing feedback links or inadequately developed sub-system models.



<u>Fig. 1</u>: Integration of climate models (panel a), economic models (panel b) and models of decision making process (panel c) in comprehensive Global Environment and Man (GEM) model (panel d).

The task of the decision makers (bottom right box) in such a GEM model is to agree upon the definition of a global 'cost-to-mankind' function. The task of the technical and political administration (top right box) is then to minimize the given cost function through the implementation of an optimal mix of market and policy instruments. For this purpose, the interactions between the climate/environment system and man's activities (left bottom and top boxes) must be determined. This will require a close collaboration between the climate and environment research community and economic analysists.

The construction of an integrated GEM model requires not only the improvement of climate models - discussed in this paper - and economic and decision making models - discussed in other contributions to this meeting - and their ultimate coupling, but also a significant extension of the models. Economic models, for example, need to be extended to include the socio-economic impacts of climate change. These can be properly modelled only through the inclusion of an additional feedback loop, the climate + global change loop, and an additional output term, the socio-economic costs ensuing from climate and global change (compare broken feedback lines in panel d, with panels a, b). The latter is required because the cost minimization sector (top right, panel d) requires two inputs, the costs due to greenhouse gas abatement policies and also the costs arising from the climate change resulting from a business-as-usual scenario. Only if both inputs are provided is it possible to meaningfully define an optimal political response strategy consisting of a mix of prevention and adaption strategies. These additional linkages will need to receive more attention if we wish to improve our understanding of the operation of the GEM model as an integrated system.

Another necessary model extension is the generalization of climate models to complete earth system models. This goal is being actively pursued in the international Global Change programme. The merging of climate and general environmental research in the Global change programme represents in many respects a natural development: it has never been possible to strictly separate the problems of climate and environmental change. Atmospheric chemistry models, for example, are needed for climate research because ozone, CFCs, methane, nitrous acid and other atmospheric trace gases represent important greenhouse gases. But the same models are also needed independently of the climate problem because stratospheric ozone shields the biosphere and humans from dangerous ultra-violet radiation, high tropospheric ozone levels are harmful to health, and because most of the gases mentioned interact with other trace gases in complex biogeochemical cycles which directly determine the concentration of many atmospheric pollutants. A similar linkage between applications to climate and the environment in general is found in models of the hydrological cycle, atmospheric and ocean transports, changes in the biosphere, soil erosion and many other processes.

In summary, it may be anticipated that many of the specific aspects of climate modelling which I shall attempt to review in this paper will be merged in the course of the developing Global Change programme with other disciplines. It is hoped that within this general context this review will contribute to a closer interaction between climate modellers and the socio-economic modelling community.

2. The greenhouse effect

The greenhouse effect is an important component of the earth's radiation balance. Natural trace gases in the atmosphere (mainly water vapour, carbon-dioxide, ozone, methan and nitrous oxide) absorb - in the same way as the glass in a greenhouse - most of the thermal infrared radiation emitted from the earth's surface, reemitting the absorbed radiation both out to space and back to earth. The back radiation results in an increase of the earth's global mean surface temperature relative to an atmosphere without greenhouse gases by about 35° C. Natural greenhouse gases are therefore essential for the maintenance of life on our planet. However, the accelerating increase in greenhouse gas concentrations since the beginning of the industrial era due to man made emissions is expected to lead to a further temperature increase of 2 - 5° C in the next 50 - 100 years. This is of the same order as the temperature increase since the last ice age and represents a major change of the climatic conditions of the earth on which present human society depends.

There exists a general scientific consensus on the strength of the additional man made greenhouse radiative heating and on the order of magnitude of the expected climate change. However, quantitative estimates of the detailed impact of this additional radiative forcing on the climate system are more uncertain. I shall try to summarize in the following what aspects of the response of the climate system to man's activities are believed to be fairly well understood, and where our principal uncertainties still lie.

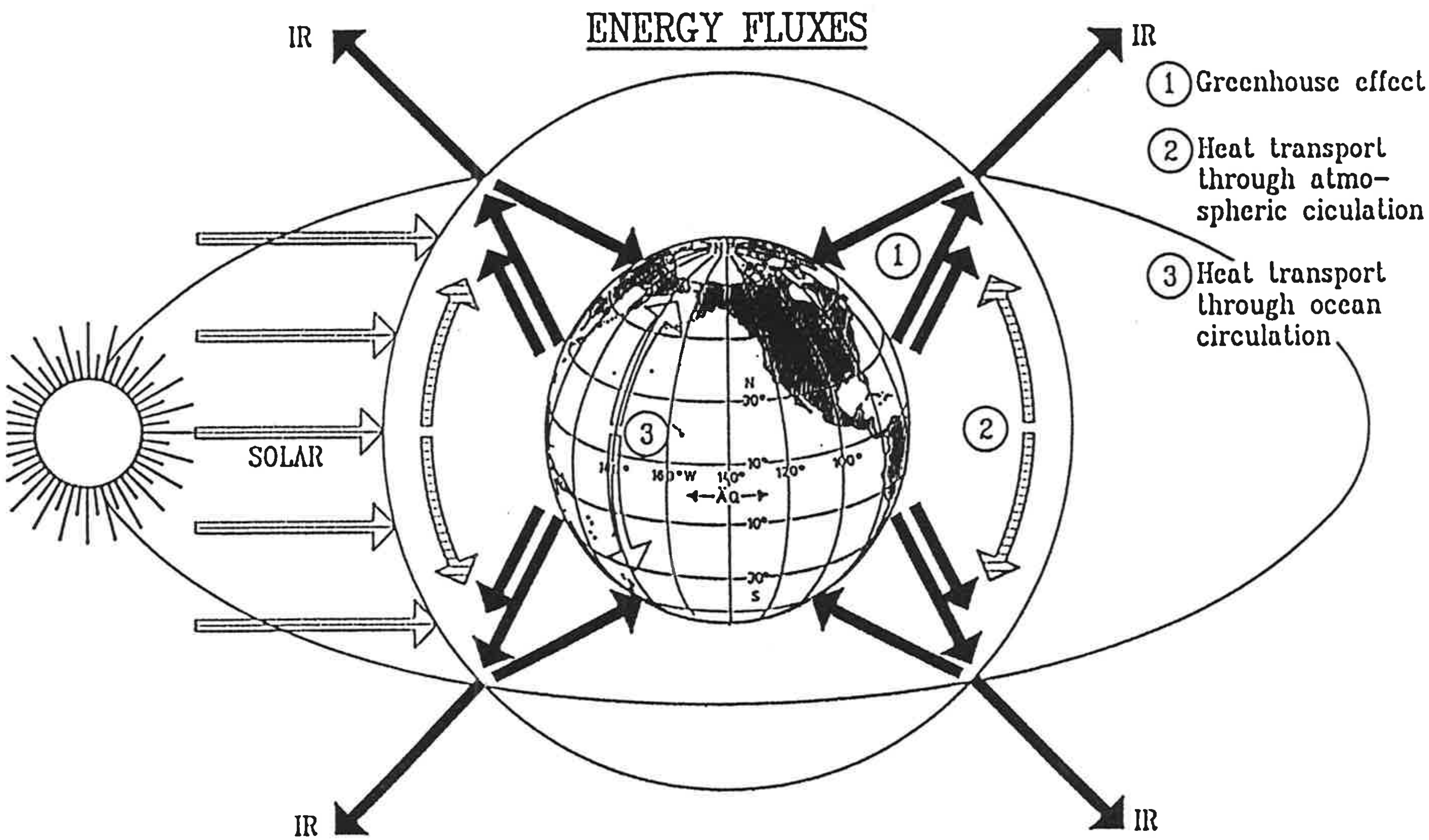


Fig.2. Principal energy fluxes determining the energy balance of the global climate system

3. The climate heat engine

To assess the reliability of climate model predictions, let me first briefly review the structure of the climate system which these models attempt to simulate.

The climate system is driven by the sun's radiation. If the earth were a perfectly conducting, perfect black body, which absorbed all of the sun's radiation, it would heat to a uniform temperature of 4° C. At this temperature the thermal radiation emitted by the earth would exactly balance the absorbed solar radiation. Fortunately, the earth is not a black body (Fig2).

Firstly, it absorbs only 70 % of the incident solar radiation; the remaining 30 % is reflected, principally from clouds, but also from the earth's surface itself. The equilibrium black body radiation temperature corresponding to this reduced absorbed radiation is -20° C.

Secondly, the occurence of natural greenhouse gases in the atmospere raises this temperature again by 35° C, to a habitable mean global temperature of 15° C.

Thirdly, the earth is not a perfect heat conductor, nor a perfect heat isolator. The temperature distribution on the earth is governed not only by radiative processes, but also by the horizontal heat transport by the atmospheric and oceanic circulation systems. Without this redistribution of heat from the tropical belt to polar regions through winds and ocean currents, the tropics - which receive significantly more solar radiation than the polar regions - would be approximately 20° C warmer than observed today, and the polar regions 30 - 40° C colder. The atmospheric and oceanic circulation systems therefore play a major role in maintaining the present habitable temperature distribution over most of the earth. The poleward heat transports by the atmosphere and the ocean are of comparable magnitude. Thus both systems need to be included in a realistic climate model.

Fig.3 shows schematically the major processes and subsystems which need to be considered in a complete description of the climatic system. In addition to circulation models of the atmosphere and the ocean, a complete climate model must include also models of the cryosphere, the biosphere and the biogeochemical cycles. The cryosphere (consisting of the components sea ice, ice shelves, continental ice sheets and snow) affects the earth's climate through the storage of water (principally in ice sheets), through the high reflectivity (albedo) of snow and ice, and through the shielding of the heat and moisture fluxfrom the ocean to the atmosphere by sea ice. The biosphere has a strong influence on the concentration of CO_2 in the atmosphere - the second most important natural greenhouse gas (following water vapour) and the most important anthropogenic greenhouse gas - and affects the climate also through the land vegetation cover, which modifies the albedo and the heat and moisture transfer. The biogeochemical cycles,finally control the atmospheric concentrations of other important greenhouse gases such as ozone, methane and the chloro-fluoro-carbons.

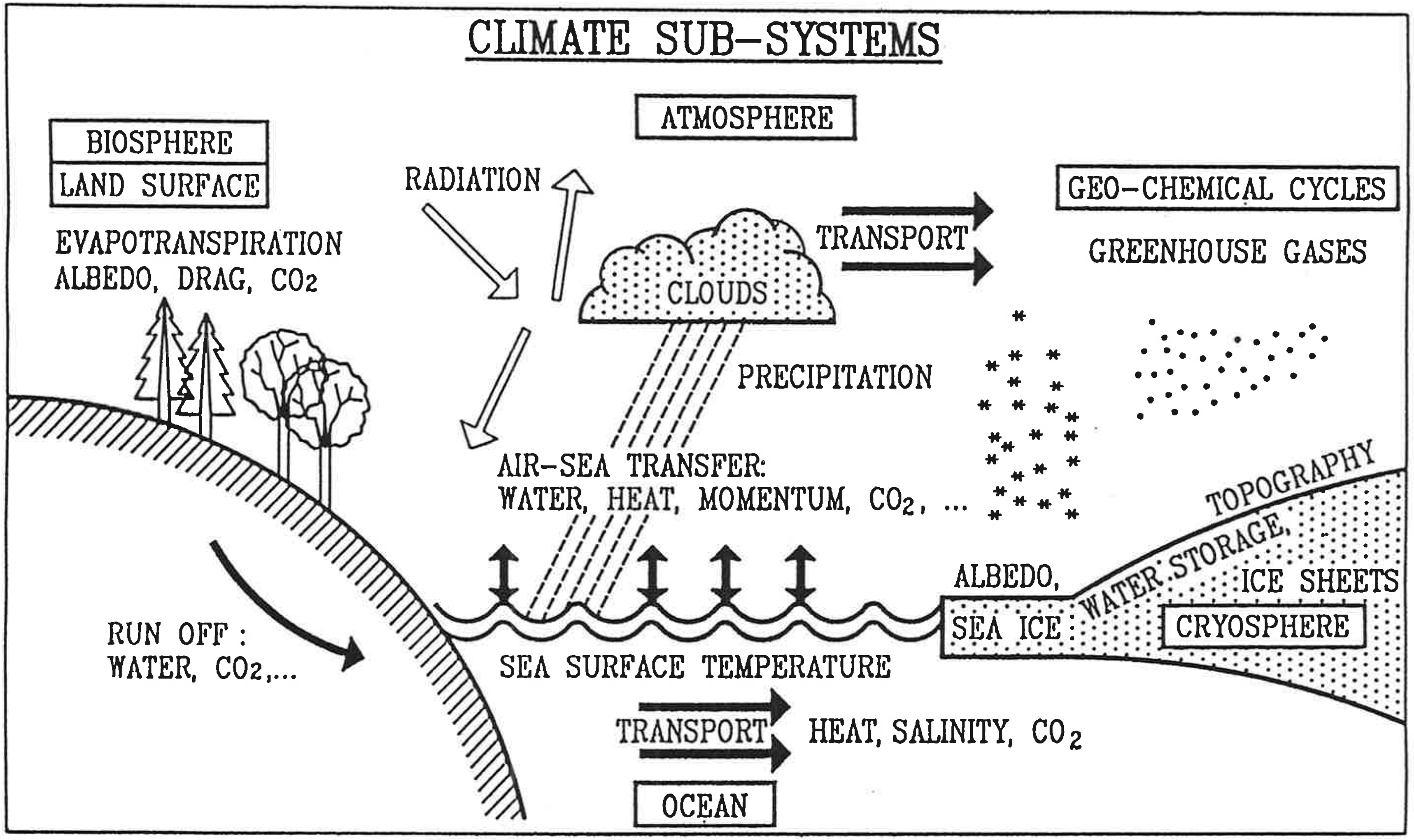


Fig.3. The principal processes governing the dynamics and interactions between the five major climate sub-systems: atmosphere; ocean; cryosphere; biosphere and land surface; and geo-chemical cycles

With the exception of the biogeochemical cycles, reasonably realistic three-dimensional models of all of the climate sub-systems have now been developed. The typical horizontal resolution of atmospheric and oceanic general circulation models used for climate research is of the order of 500 - 1.000 km, while the vertical structure is generally described by 10 - 20 separate layers (cf. Washington and Parkinson, 1986). Three-dimensional global carbon cycle models based on atmospheric and ocean circulation models (Maier-Reimer and Hasselmann, 1987; Bacastow and Maier-Reimer, 1990) and ice sheet models have similar resolution.

Modelling of biogeochemical cycles is an area of active current research. However, the complexities of the biogeochemical system, involving several hundred different chemical species interacting through a wide variety of radiation-dependent photo-chemical processes, are so great that realistic models which can be incorporated into existing global three-dimensional climate models will probably not be available for several years.

Despite significant progress in the modelling of most climate sub-systems, the various sub-system models have nevertheless not yet been systematically coupled together to integrated climate models. It is only quite recently that a few modelling groups (National Center of Atmospheric Research, Boulder; Geophysical Fluid Dynamics Laboratory, Princeton; Max Planck Institute of Meteorology, Hamburg and the Meteorological Institute of the University of Hamburg) have begun to carry out climate simulations with realistic coupled ocean-atmosphere models.

Nearly all published predictions on future global warming have been based on simulations with atmospheric general circulation models alone, without consideration of the remaining climate sub-systems. The usual approach is to first estimate the future CO_2-concentrations in the atmosphere for a given future CO_2-emission scenario using a carbon-cycle model, and then to use the computed CO_2-concentration as input for a subsequent simulation with an atmospheric general circulation model. An attempt is then sometimes made to determine the possible effects of the computed changes in the atmospheric climate on the ocean circulation, the biosphere and the cryosphere - for example, to determine the rise in global sea level (estimated as 1 m $\pm$ 0.5 m for a CO_2-doubling). However, these estimates are normally not derived from realistic three-dimensional models, and the effects of these changes on the original computations of the atmospheric CO_2-concentration and the resulting atmospheric climate change are not considered.

The main reason for the sparsity of coupled model simulations lies in various computational difficulties arising from the disparity of the time scales of the different sub-systems. Whereas the atmosphere responds to a change in external forcing within a few days or weeks - maximally a few months - the response time of the ocean (whose density is a thousand times greater than that of the atmosphere) lies in the range of hundreds of years to a thousand years. A separate numerical simulation of either the atmosphere or the ocean over a time period of the order of the natural equilibration time of the sub-system is computationally feasible. Comparable computation times are required for both systems. The shorter response time of the atmosphere is offset by the smaller numerical integration time step of the model atmosphere, so that essentially the same number of integration steps is needed to compute the equilibrium response of either the atmosphere or the ocean. When the atmosphere is coupled to the ocean, however, the atmospheric model must be integrated - with its inherently much smaller time step - over the longer time periods characteristics of the ocean response time scale in order to follow the slow evolution of the coupled system. This greatly exceeds the available resources of even present day super-computers. The few numerical simulations with coupled ocean-atmosphere models which have been carried out so far have therefore been limited to the study of the transient response of the climate system over relatively short integration times of the order of a few decades to a century and were unable to investigate the transition to the final equilibrium state.

The same difficulty arises when the atmosphere is coupled to the biosphere, whose time scales are comparable with those of the ocean, or the continental ice sheets, which have still longer time scales of the order of several thousand years. Various techniques have been proposed to overcome the basic time-scale mismatch problem - such as iterative integrations, or burst coupling techniques. However, these are still in the stage of development and have not yet been systematically tested. Further work in this area is needed.

4. Some results of climate modell simulations

Extrapolations of the measured increase in CO_2 and other greenhouse gas concentrations in the atmosphere (Figs. 4, 5) indicate that the 'equivalent CO_2-concentration' (the net effect of all greenhouse gases expressed in terms of an equivalent CO_2 increase) will double within the next 50 to 100 years if greenhouse gas emissions continue to grow at present rates. Approximately half of the greenhouse gas forcing is seen to be due to CO_2 (predominantly from fossile fuel use by the industrialized nations, with a small contribution - about 20 % - from tropical deforestation) while the chloro-fluoro-carbons (CFCs) and methane constitute most of the remainder.

Figs 5 and 6 show the equilibrium global warming for (northern hemisphere) summer and winter computed with three different atmospheric general circulation models (A-GCMs) for a doubling of present CO_2 levels. The global mean warming for all three models is about 3° C. All models show higher temperatures in higher latitudes than in the tropics, particularly during the winter season.

The atmospheric models used for such computations are essentially the same as the models used for numerical weather prediction, but are run at lower resolution (500 - 1,000 km, rather than 100 km for weather forecast models, which are integrated for only a few days). They simulate the full time-dependent dynamics of the atmosphere, including clouds, precipitation, monsoons and all transient tropical and mid-latitude

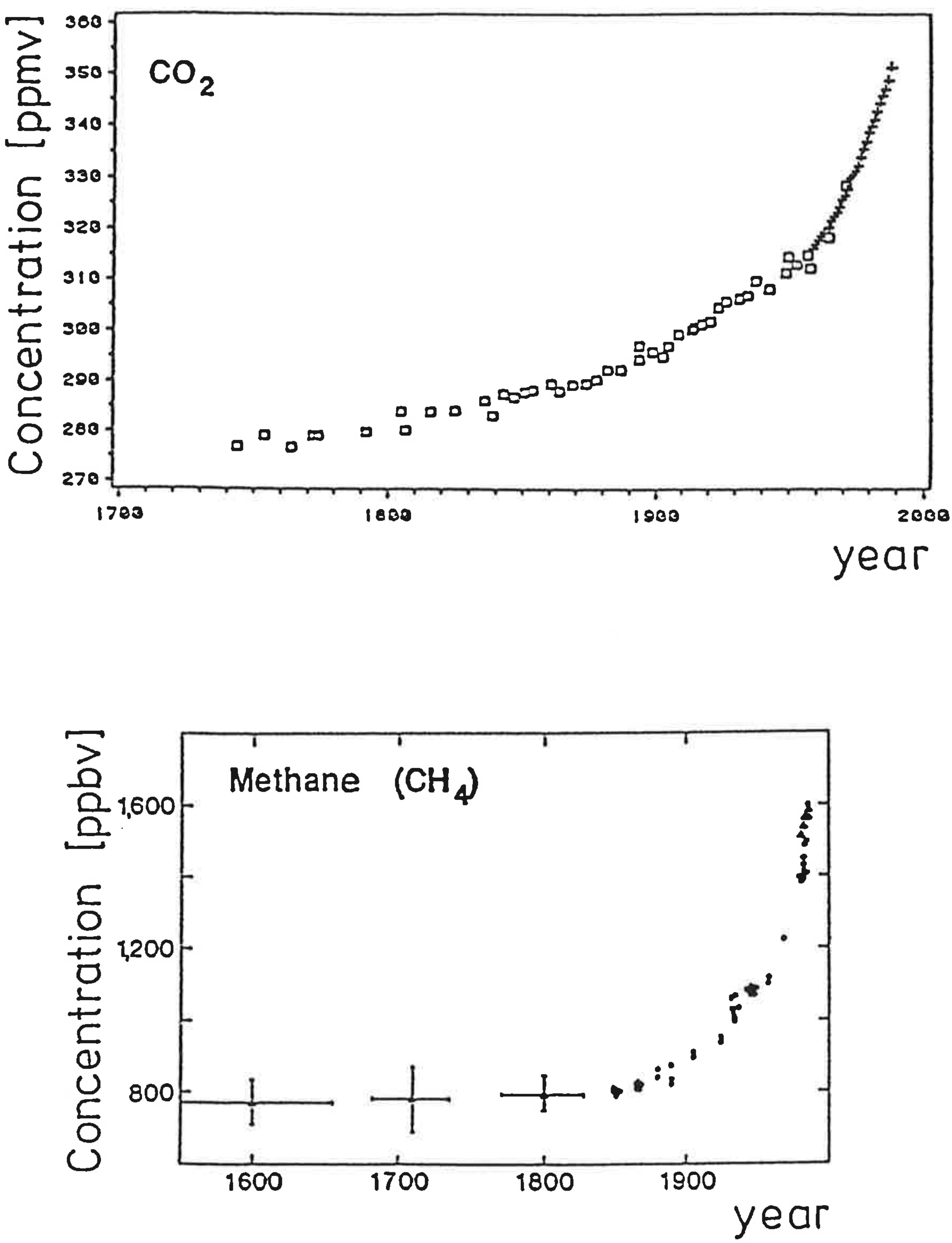


Fig. 4 Measured increase in CO2 (panel a)
and methane (panel b) since the beginning of industrialization.

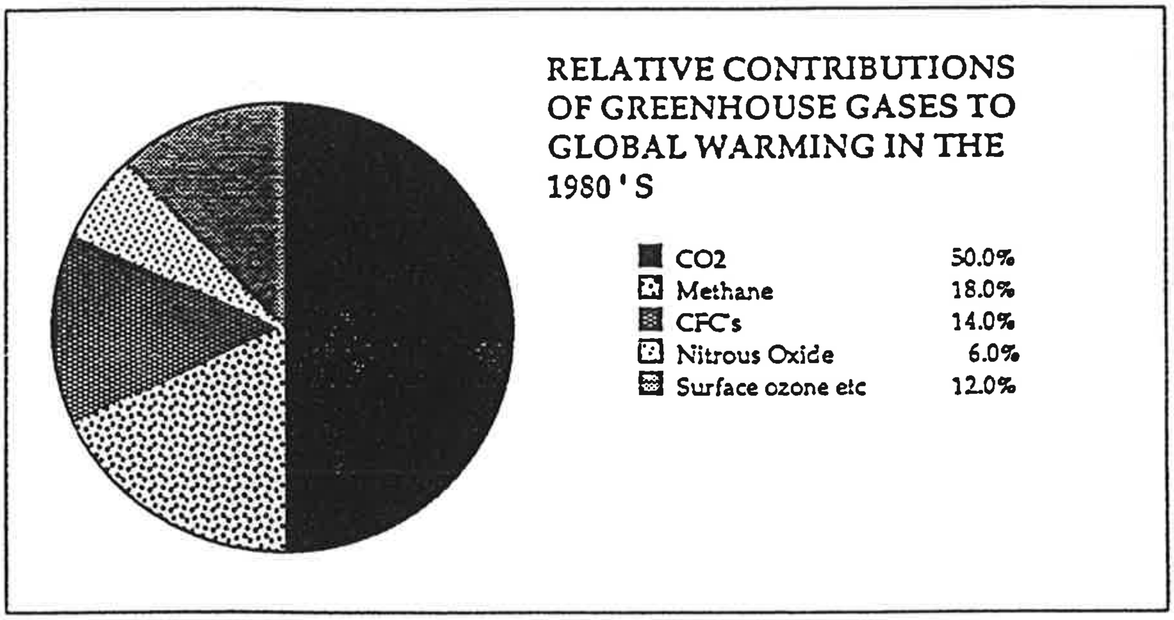


Fig. 5 Estimated contributions of different greenhouse gas as to climate warming in the 80's.

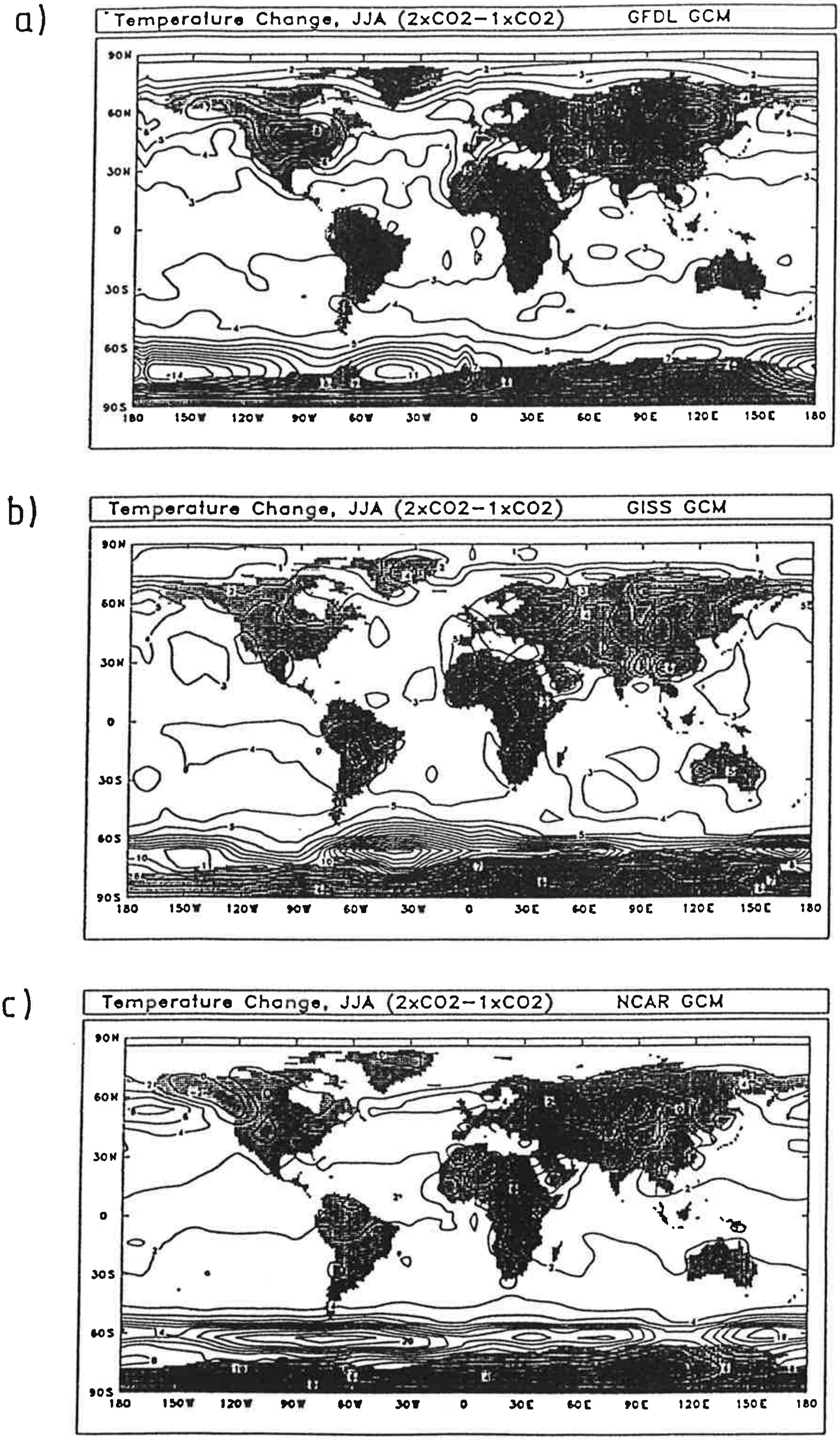


Fig.6 Global warming (surface air temperature) computed with three different atmosphere GCMs a) Geophysical Fluid Dynamics Laboratory, Princeton, b) Goddard Institute of Space Studies, c) National Center of Atmospheric Research) for northern hemisphere summer for a doubling of CO_2.

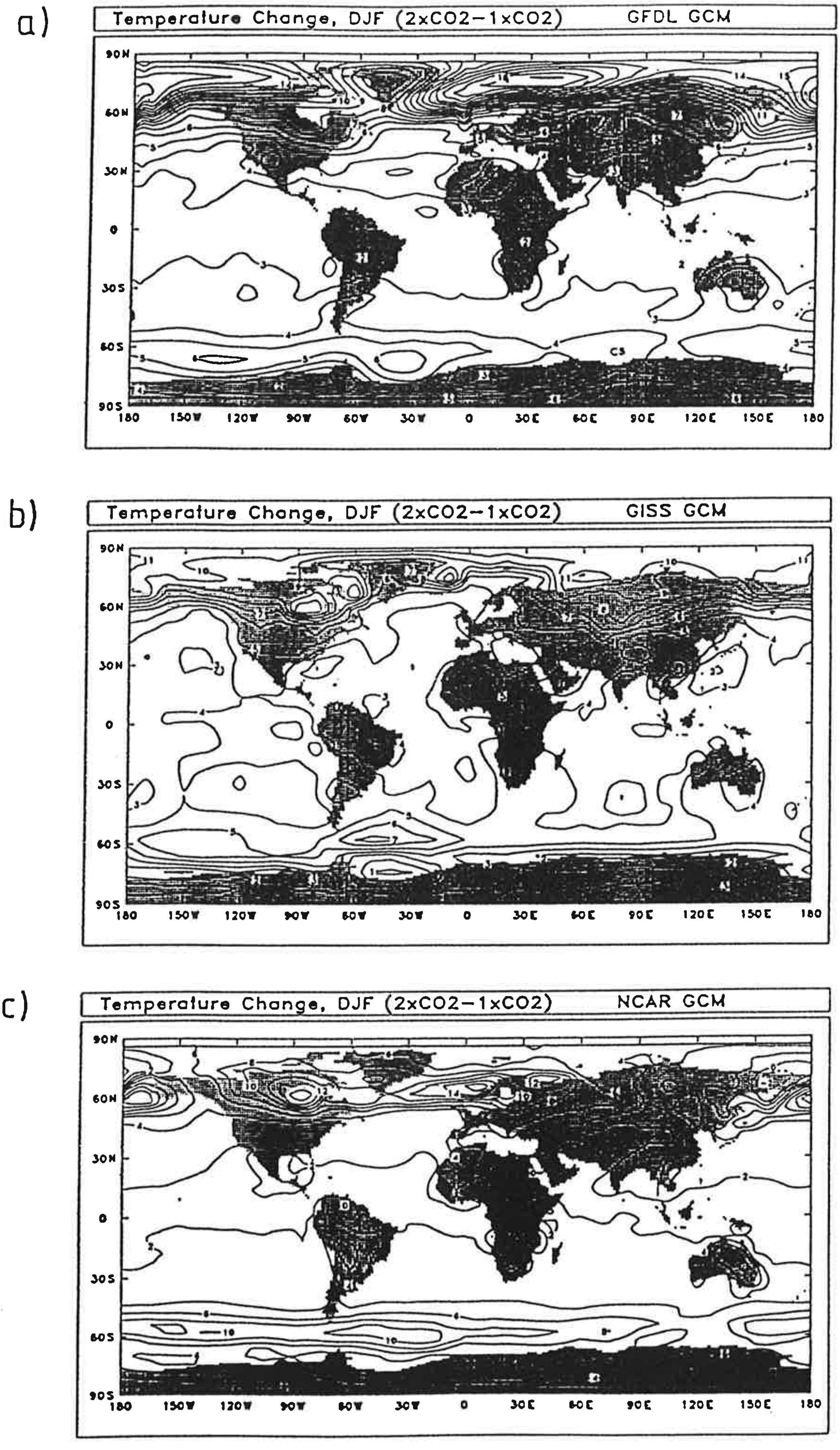


Fig. 7. Same as Fig. 5 for northern hemisphere winter.

weather phenomena. However, such simulations must still be regarded only as order of magnitude estimates in view of the significant differences between different models, particularly on the regional scale. The discrepancies can be attributed to different representations of poorly known physical processes.

One of the main sources of uncertainty is the treatment of clouds. Clouds strongly affect climate through two processes: the high reflectivity (albedo) of clouds, which cools the earth's surface by shielding it from the sun's radiation, and the greenhouse effect of the water vapour and liquid water in clouds, which increases the surface temperature. The net change in surface temperature can be of either sign, depending on the physical properties, latitude and height of the clouds. For low clouds the albedo effect is normally dominant, while for high clouds the greenhouse effect is more important. In general, changes in cloud cover of the order of 10 % can produce changes in the global mean temperature which are comparable to the changes induced by a CO_2 doubling. Unfortunately, we are not yet able to predict changes in cloud cover to this accuracy.

Fig. 8 illustrates the sensitivity of climate models to cloud parameterizations determined in a model intercomparison study of 14 A–GCMs of comparable resolution (Cess et al., 1989). The ordinate axis represents a measure of the change in global temperature induced by a given change in the external forcing of the atmosphere - for example a change of the CO_2 concentration, the solar constant or the sea surface temperature. The abscissa axis denotes a parameter characterising the 'climate effectiveness' of clouds. Without entering into the details of the definitions, the

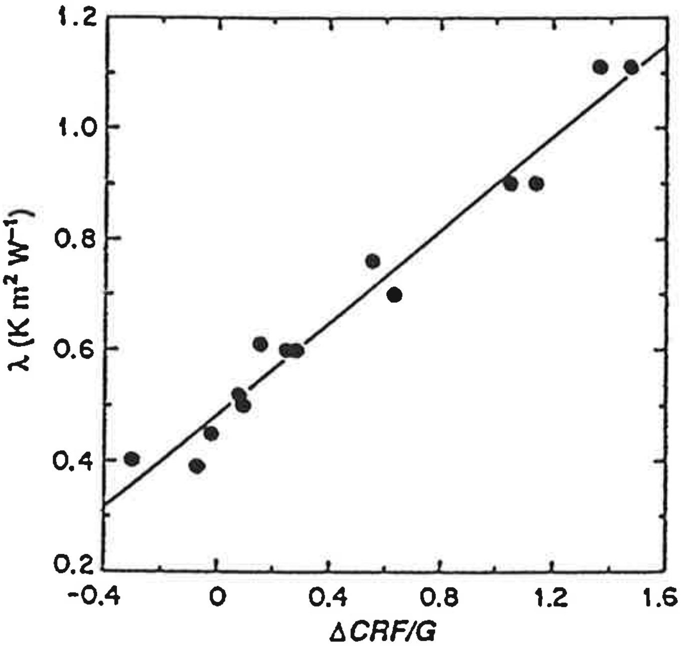


Fig. 8 The global sensitivity parameter λ plotted against the cloud feedback parameter ΔCRF/G for the 14 GCM simulations. The solid line represents a best-fit linear regression.

essential point illustrated by the figure is that one and the same forcing (in the particular experiment shown, a change in the prescribed sea-surface temperature) can produce changes in global mean temperature differing by factors of more than three for models using different cloud parameterizations but otherwise comparable physics and numerics.

The second major source of uncertainty in climate simulations using only atmospheric general circulation models is the effect of changes in the ocean circulation. Since the poleward ocean heat transport is comparable to that of the atmosphere, the neglect changes in of such a first-order process necessarily invalidates any attempts at detailed quantitative predictions with equilibrium A-GCM simulations. First results with coupled ocean-atmosphere-general circulation models (Washington and Meehl, 1989; Stouffer et al., 1989; Sausen et al., 1990) show, in fact, significant differences compared with A-GCM results.

Fig. 9 summarizes, for example, the evolution of the temperature field for a sudden doubling of CO_2 at time $t = 0$ computed with the Hamburg coupled ocean-atmosphere-GCM (Sausen et al., 1990) over a 55-year period. Shown are the changes of the zonally averaged surface temperatures as a function of latitude and time (Hovmøller diagram).

Fig. 10 shows the global distribution of the change in the (northern) summer and winter surface temperatures averaged over the last ten years of the integration. The figures demonstrate that

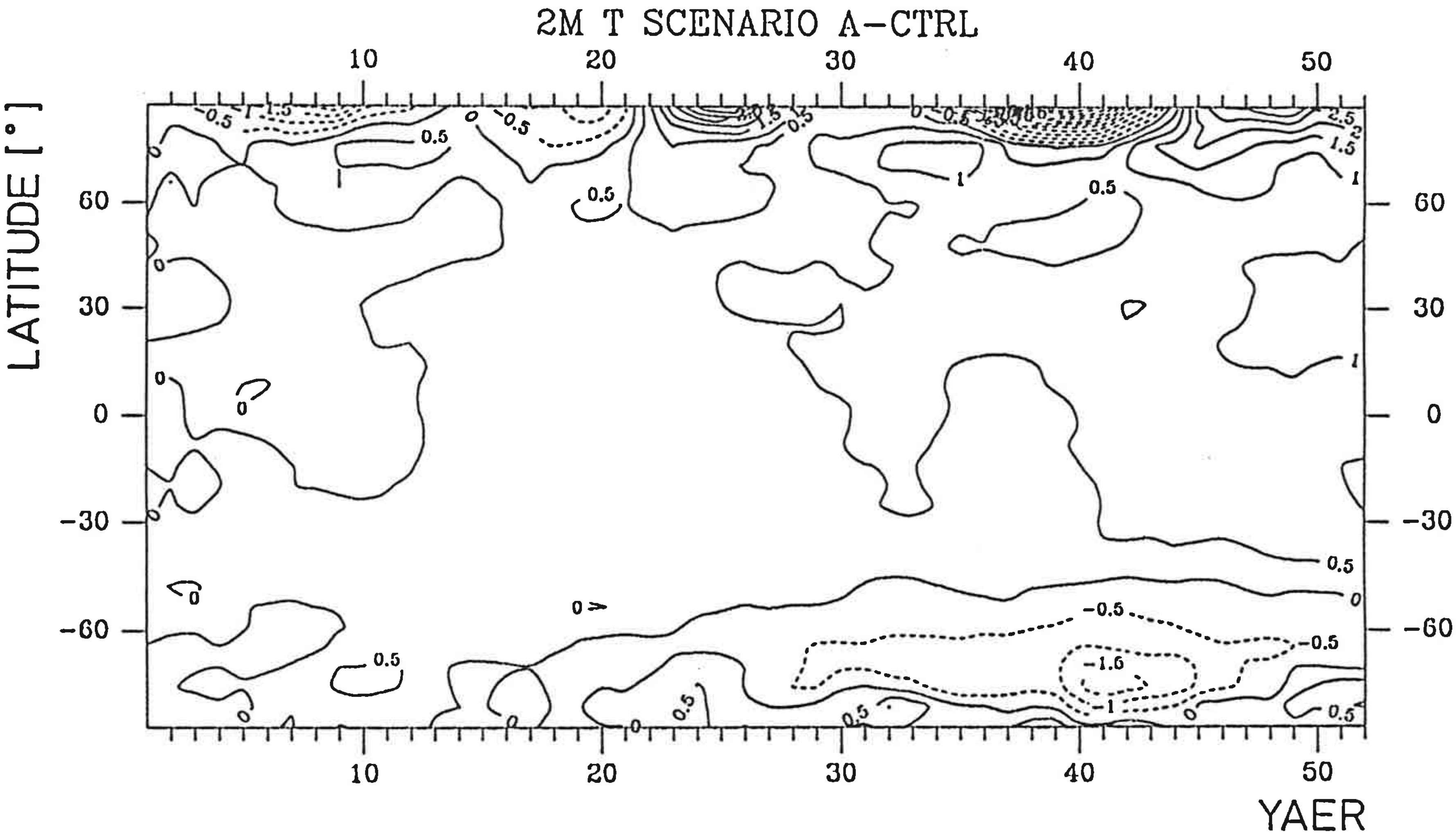


Fig. 9 Evolution of zonally averaged surface temperature as function of time computed with a coupled O-A-GCM for a sudden doubling of CO_2 at time t = 0 (from Sausen et al., 1990).

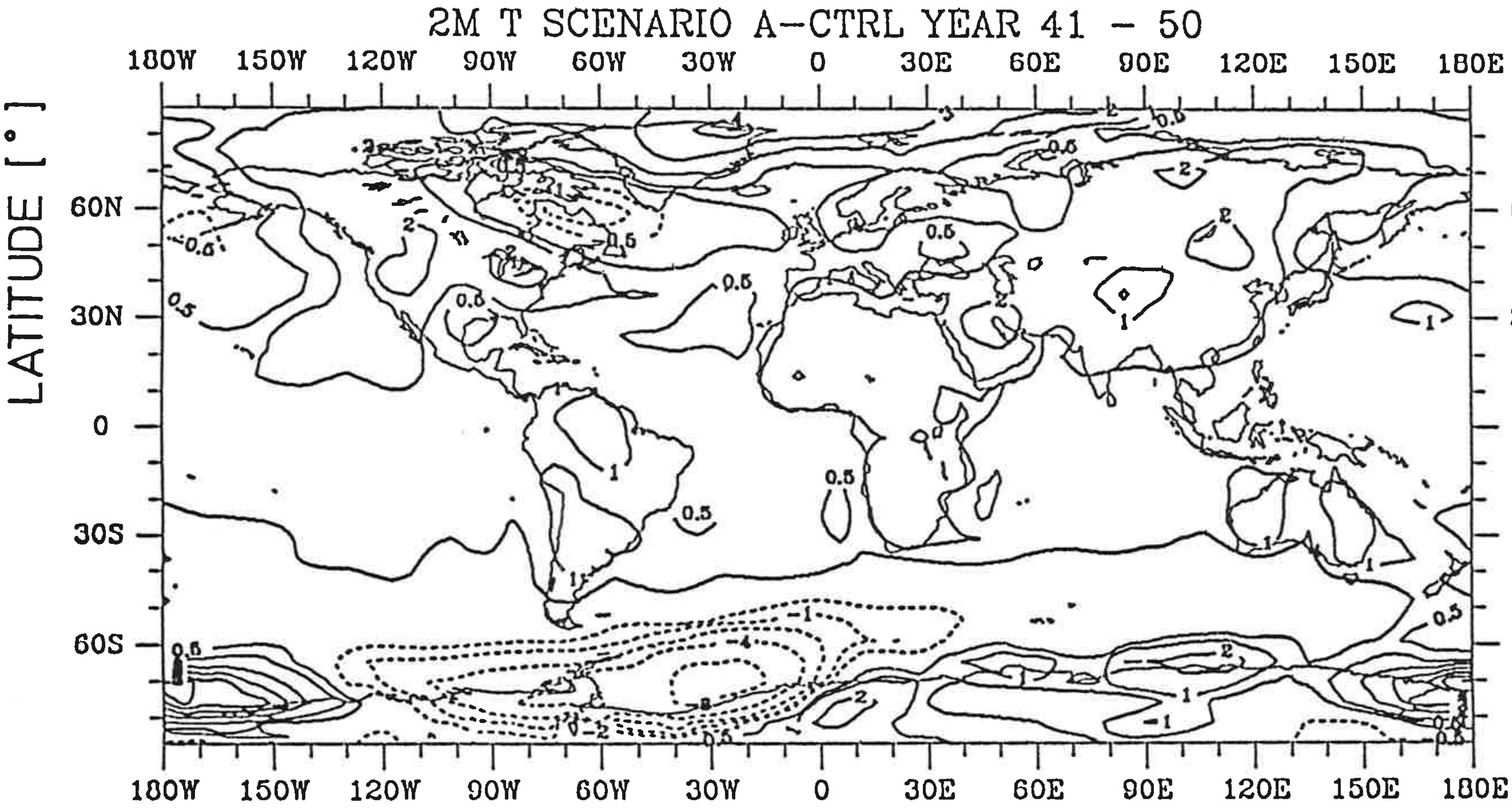


Fig. 10 Global warming computed with a coupled ocean-atmosphere model averaged over integration years 41 - 50 after a sudden doubling of CO_2 at year zero (surface temperature for northern hemisphere summer, panel a), and winter, panel b) from Sausen et al., 1990).

- the global warming is delayed by the heat uptake of the oceans by several decades;

- the delay is particularly pronounced in the southern ocean, which cover a large fraction of the earth's surface and where heat is more readily mixed into the deeper ocean (along the Antarctic Circumpolar Current) than in the tropics or the North Pacific, for example;

- the regional patterns of global warming generally differ significantly from the equilibrium response patterns computed with A-GCMs alone; however,

- some features of the regional response, such as the enhanced warming in the mid-continents, are common to both A-GCMs and coupled O-A-GCM simulations.

Although surface temperature is the most commonly used variable for summarizing global warming, other variables such as the precipitation, soil moisture or a drought index characterising the occurrence of long periods without precipitation are generally more useful climate indices for socio-economic impact studies. Unfortunately, these variables exhibit a still higher scatter between different models than the surface temperature. Nevertheless, certain general features appear to be common to most models, including A-GCM's and coupled O-A-GCM's, such as a tendency for dry areas to become dryer and wet areas to become wetter, an overall increase in the global mean precipitation due to the higher water content of the atmosphere and a more rapid overturning of the hydrological cycle.

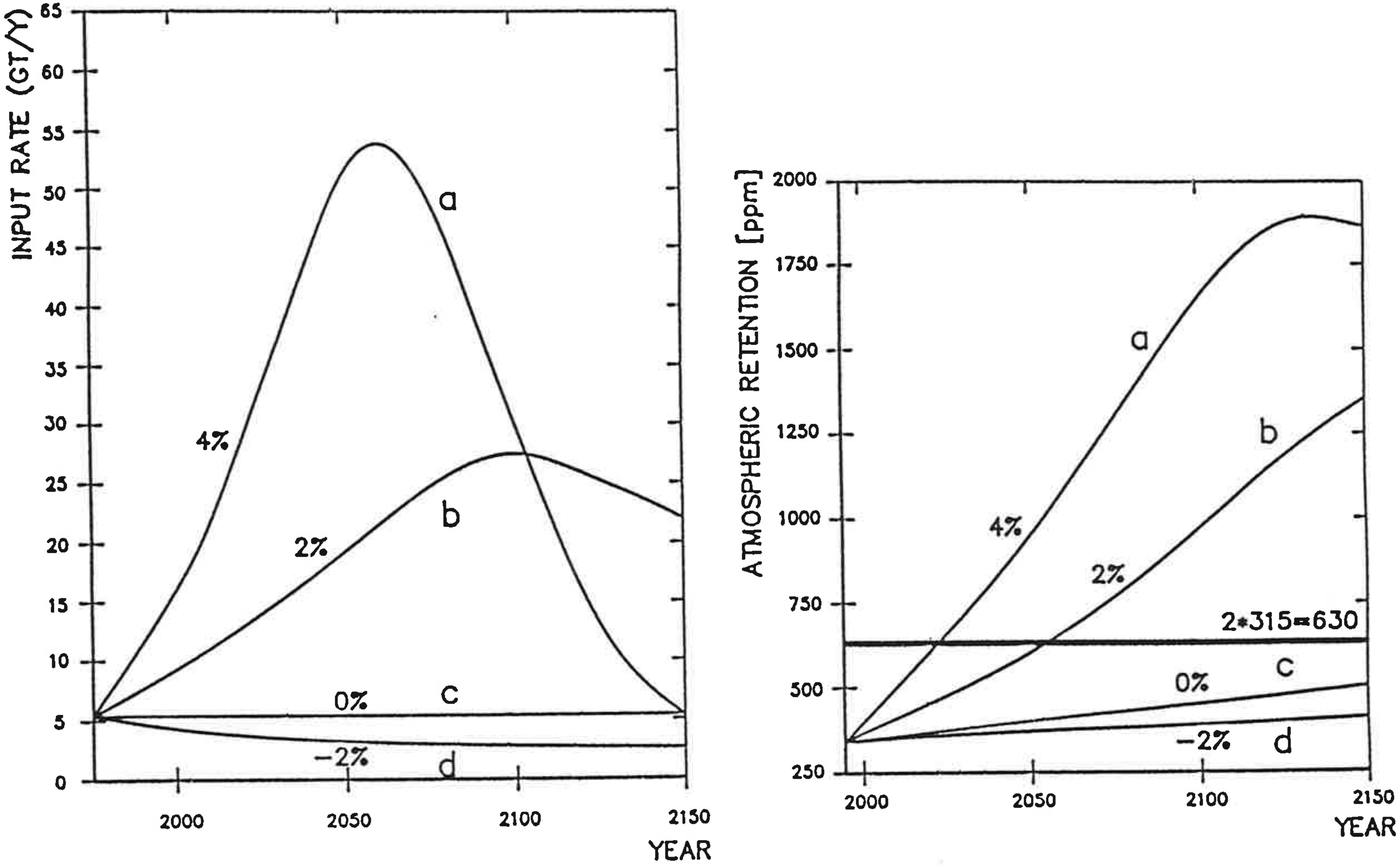


Fig. 11 Annual CO_2 emissions, panel a), and atmospheric CO_2 concentration computed with the Hamburg Carbon Cycle model, panel b) for four emission scenarios: (a) 4%, (b) 2% exponential-logistic growth; (c) zero growth, and (d) 2% decrease per year down to a 50% constant plateau.

5. Greenhouse gas predictions

Until we are able to carry out simulations with integrated climate-chemical cycle models, model computations of the climate change due to a given increase in atmospheric greenhouse gas concentrations require as input prior estimates of the anticipated greenhouse gas concentrations derived from known or assumed anthropogenic emission sources. The future atmospheric concentrations of non-CO_2 greenhouse gases cannot yet be reliably derived from chemical cycle models and are therefore normally estimated by the straightforward extrapolation of present trends. However, for CO_2 fairly realistic carbon cycle models have been developed which can be used to compute future atmospheric concentrations for given emission scenarios.

Fig. 11 shows, as example, four predictions of future atmospheric CO_2 concentrations for four different scenarios of future CO_2 emissions, computed with the Hamburg carbon-cycle model (Maier-Reimer and Hasselmann, 1987). An important conclusion from these simulations is that the future atmospheric CO_2 concentration depends not only on the total amount of CO_2 emitted into the atmosphere, but also on the rate at which this emission occurs. This is due to the time-dependent absorption of CO_2 in the ocean (the largest CO_2 reservoir in the carbon cycle system). Up to the present, about half of the CO_2 emitted into the atmosphere has remained in the atmosphere, while the remainder has been absorbed by the oceans. This air-borne fraction of approximately 50 % is reproduced also by the two scenarios (a) and (b), which represent 4 % and 2 %

exponential-logistic growth extrapolations of the past CO_2-emission curve. The zero growth rate scenario (c) and the decreasing emission scenario (d), however, yield significantly lower air-borne fractions. The lower emission rates lead therefore not only to a smaller total amount of CO_2 released into the atmosphere, but also to a significantly smaller fraction of the total input which has remained in the atmosphere.

This additional bonus is due to the slow transfer of CO_2 into the main CO_2 reservoir in the deep ocean. If a small increment of CO_2 is introduced into the atmosphere, the carbon system adjusts to a new equilibrium in which the CO_2 increment is ultimately partitioned between the atmosphere and the ocean in the ratio 0.15 : 0.85. However, this asymptotic chemical equilibrium is attained only in the course of several hundred to a thousand years, after the additional CO_2 has penetrated into the deep ocean. For the zero growth rate and decreasing emission rate scenarios (c), (d) the equilibrium air-borne fraction of 15 % can nevertheless be asymptotically approached. However, for the exponential growth rate scenarios (a), (b), the large deep-ocean reservoir is unable to keep up with the continually increasing input, and a significantly higher air-borne fraction is maintained.

The time constant for CO_2 storage in the deep ocean, which controls the air-borne fraction, depends rather sensitively on the rate of deep-water formation. This occurs in today's oceans in the high-latitude regions of the North Atlantic and the Southern Ocean (particularly in the Weddel Sea). Numerical simulations with ocean general circulation models have demonstrated that relatively small changes in the air-sea heat transfer or surface evaporation and precipitation distributions, which together with the wind field drive the global ocean circulation, can significantly modify the rate of deep water formation in these areas. Maier-Reimer and Mikolajewicz (1989), for example,were able to explain the sudden resurgence of the ice sheets during the brief Younger Dryas interruption of the last post-glacial warming approximately 11,000 years ago by a rapid change in the Atlantic circulation triggered a reduction of deep-water formation in the North Atlantic through the influx of light surface melt-water from the ice sheets. Simulations with coupled ocean-atmosphere models suggest that a similar reduction in the rate of deep-water formation could be induced by the surface ocean warming in high latitudes accompanying a general global warming. This would seriously impede the ability of the ocean to transport CO_2-saturated surface water into the deep ocean.

This feedback process within the coupled ocean-atmosphere-carbon cycle system could lead to a potentially serious global warming amplification which has not been considered in past non-interactive carbon cycle and climate change simulations. It underscores that the prediction of future atmospheric CO_2 concentrations should not be treated separately from the prediction of future climate change: an integrated coupled ocean-atmosphere-carbon cycle model is clearly needed. Simulations with such a model are currently being planned in Hamburg.

6. Impact of climate models on the construction of Global Change and Global Environment and Man (GEM) models

Let me return to the beginning. What inferences can be drawn from the general structure of climate models which I have tried to briefly review for the construction of extended global change models and integrated GEM models outlined in Fig.1 ?

Perhaps the most important conclusion is that the climate system encompasses a broad spectrum of natural time scales. The response of climate to anthropogenic forcing cannot be treated, even to first approximation, as an equilibrium response problem. The anthropogenic input is inherently time dependent, and the climatic response characteristics are strongly dependent on the form of this time dependence. Since the socio-economic system also contains a broad spectrum of natural time scales, a GEM model must from the outset be conceived as a time-dependent, dynamic system.

A second important result is that the predictions of climate model simulations are always characterised by a finite band of uncertainty. This is the case even if the input (for example in the form of an assumed emission gas scenario) is regarded as precisely defined. Thus the input into a socio-economic model provided by a climate (or global change) model, and the resulting costs computed as output by the socio-economic model and used further downstream again as input to the cost-minimizing sector of the GEM model (cf. Fig. 1) must be regarded as probabilistic rather than deterministic. Since the socio-economic and cost-minimization model sectors will, also contribute their own uncertainty bands, the problem of minimizing the 'total cost-to-mankind function' must necessarily be formulated as a statistical optimization problem. From the point of view of formal mathematics the statistical cost minimization problem is fortunately no less well-defined than a deterministic optimization problem.

However, significant research work is clearly still needed before a reasonably realistic GEM model can be formulated which can be used as the basis for such an optimization procedure. We should nevertheless not lose sight of the ultimate goal of applying climate models together with socio-economic impact models in a general decision analysis and policy definition framework, even while struggling with the complex intricacies of global climate models. it should provide the guiding principle for our long-term climate modelling strategy.

In conclusion, I should like to emphasize that despite the many uncertainties in the quantitative details of present climate predictions - on which this summary has naturally focussed - and despite the present lack of adequate models to assess the socio-economic impacts of the predicted climate change, there exists no serious doubt within the scientific community that the predicted global warming is real, that the estimated orders of magnitude of the predicted climate change are reliable and that if no corrective measures are adopted we may expect within the next 100 years the warmest climate ever experienced in the history of mankind. It would be unwise to delay remedial action only because our predictions today - and in the foreseeable future - must be qualified with finite uncertainty bounds. We cannot afford to wait for the perfect GEM model before making political decisions. Policy and model development should be pursued as parallel, interactive, iterative processes.

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