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A Meteorologist's View of the Greenhouse Effect

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SUMMARY The greenhouse effect is a natural process in the atmosphere which keeps the earth's surface warm enough for human life. There are theoretical and observational reasons for believing that increasing atmospheric concentrations of the trace gases responsible for this surface warmth are leading to enhanced warming and other changes of global and regional climate. By modifying the meteorological models used for routine numerical weather prediction to incorporate the influences that are believed to be of most importance on decade to century and longer time scales, the climate research community are able to explore the possible impacts on global and regional climate of a range of possible future greenhouse gas emissions and concentrations. Despite many uncertainties, these provide the principal scientific basis for intergovernmental negotiation on the development of global strategies for averting or minimising adverse human impacts on climate and assisting national communities in planning to live with natural climate variability and possible future human-induced change.

1 INTRODUCTION

From the perspective of the meteorologist, the earths climate is ultimately the product of the radiation balance between the earth and the sun (Figure 1) with the detailed patterns of climate determined, inter alia, by the spherical shape of the earth (Figure 2), the distribution of land and sea and a range of physical chemical and biological processes in the atmosphere and oceans (Figure 3).

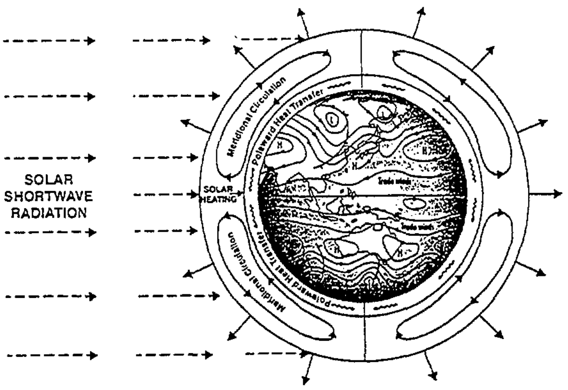

Figure 1 The earth-atmosphere system in radiative balance with space. The overall climate of the earth is determined by the planetary temperature which results from the balance between the incoming shortwave radiation from the sun (broken arrows) and the outgoing infrared radiation to space from the earth's surface and atmosphere (solid arrows). Because the solar heating in low latitudes greatly exceeds that at the poles, the atmosphere and ocean carry heat polewards and, in the process, generate the familiar patterns of weather and climate.

One of the most important of these physical processes in the atmosphere is the greenhouse effect. It is a well-understood natural process through which the absorption and re-emission of infrared radiation by a number of radiatively active trace gases (especially water vapour and carbon dioxide), keeps the earths surface some 70°C warmer than the atmosphere 10-15km above and approximately 33°C warmer than it would be if there were no such 'greenhouse' gases present. The mechanism of the greenhouse effect is shown schematically in Figure 4, including especially its role in determining the vertical profile of temperature with height in the atmosphere.

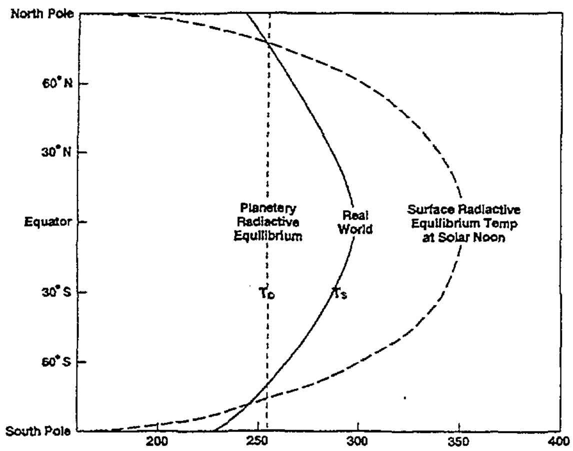

Figure 2 The role of the spherical shape of the earth in maintaining a temperature gradient between the equator and the poles. Because the sun is directly overhead at the equator (at the time of equinox), local radiation balance between the incoming solar radiation and the outgoing infrared radiation would produce radiative equilibrium temperatures of around 350K (>75°C) much hotter than the overall planetary radiative temperature of 255K (-18°C). The surface radiative equilibrium temperature at the poles on the other hand would approach absolute zero. In the real world, the very large equator-pole temperature differences that would result from local radiative equilibrium alone are greatly reduced by the poleward heat transfer by the circulation systems which they generate in the atmosphere and ocean.

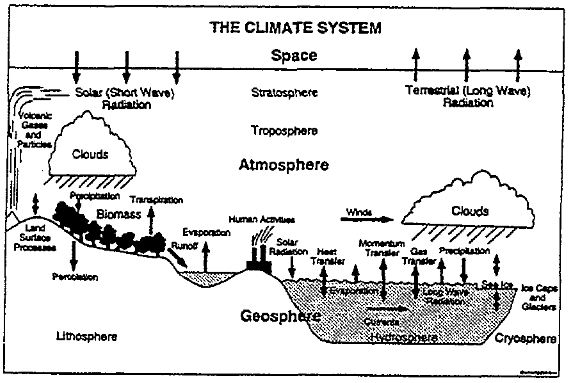

Figure 3 The earth-atmosphere-ocean climate system showing the main physical processes which are involved in the determination of climate. Of particular importance. are the atmospheric winds and ocean currents which are driven ultimately by the differences in solar heating between the equator and the poles; along with the exchange of sensible heat, water vapour. momentum and carbon dioxide and other trace gases between the atmosphere and ocean.

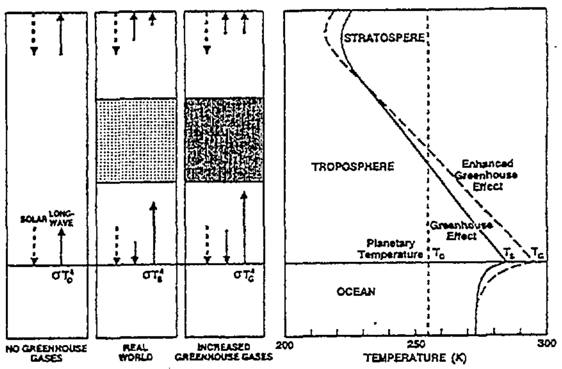

Figure 4 The greenhouse effect. In the idealised vertical slice through an atmosphere with no greenhouse gases (left panel), there is no interaction between the radiation and the atmosphere. The long wave infrared radiation (solid arrow) upward from the earth's surface (proportional to the fourth power of the surface temperature) just balances the incoming solar radiation (broken arrow) and the temperature of the surface stabilises at the planetary radiative temperature To. In the real atmosphere which contains radiatively active trace gases (second from left), the solar radiation at the surface is supplemented by the downward longwave radiation from the greenhouse gases in the atmosphere and the earth's surface must heat up (to the temperature Ts) to radiate enough infrared energy upward to restore balance - leading to the vertical temperature profile through the atmosphere shown as the solid curve in the right hand panel. If the concentrations of greenhouse gases are increased so that the downward longwave radiation from the atmosphere becomes even greater (third panel from left-denser hatching) radiative transfer theory suggests the likelihood of an enhanced greenhouse effect (broken curve in the right panel).

Although other processes, such as sensible and latent heat transfer, come into play, the greenhouse effect is a major influence in determining the vertical temperature structure of the atmosphere and thus in generating the horizontal pressure gradients that drive the winds of the daily weather systems and which average out, over time, to give the well known patterns of climate (which is usually characterised in terms of long-term averages, variability and extremes) over the globe.

2 AN ENHANCED GREENHOUSE EFFECT?

Although the possibility of human enhancement of the natural warming effect of the greenhouse effect had been elaborated by the Swedish scientist Svante Arrhenius (1) more than a century ago, it was not until the 1950s that routine observations of the atmospheric concentrations of carbon dioxide got underway and revealed an upward trend, since shown to be increasing rapidly from levels that had prevailed for the last one thousand years (indeed, much longer) and found also with other atmospheric greenhouse gases including methane and nitrous oxide (Figure 5) as well as a range of non-naturally occurring greenhouse gases such as the chlorofluorocarbons.

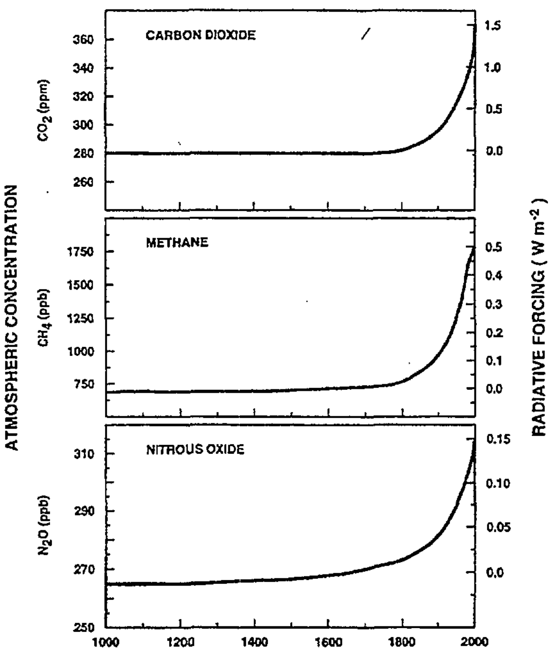

Figure 5 The observed increases of carbon dioxide, methane and nitrous oxide over the past one thousand years in parts per million (ppm) by volume for carbon dioxide and parts per billion for the others. The effect that the increased concentrations should have in decreasing the longwave radiative heat loss to space (which is linked to the stronger downward radiation to the surface in the middle panel of Figure 4) is shown on the right of the figure in watts per square metre.

The major scientific question that this posed for the meteorological community world wide through the 1960s, 70s and early 80s was whether the expected enhancement of the natural greenhouse effect was actually leading to warmer surface temperatures around the globe or whether some other factors were coming into play to suppress the expected warming. As it happened the fact that the best estimates of global mean surface temperature (Figure 6) showed no significant warming trend from the 1940s to the early 80s led some scientists to speculate on the possibility that, after more than ten thousand years of interglacial warmth and for other reasons, the earth may be about to plunge into a new ice age (Figure 7).

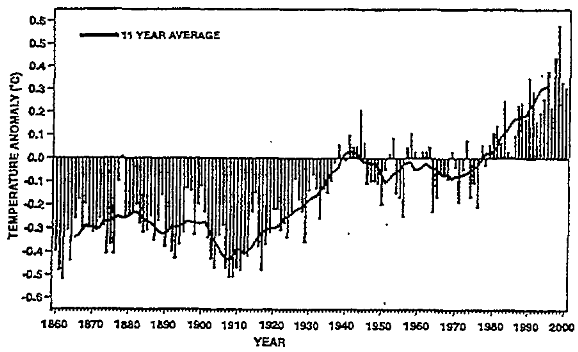

Figure 6 Annual and eleven-year average global mean temperatures from 1860 to 2000 shown as departures (°C) from the 1961-90 climatological normal. Note that from the 1940's to the late 1970's a slight global cooling trend was evident in the observed data.

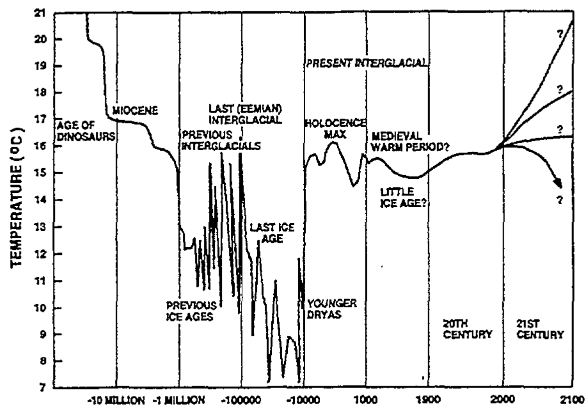

Figure 7 A schematic summary of the temperature history of the earth showing also a selection of possible climate futures through the twenty-first century. Note that, except for the twentieth and twenty-first centuries, the time scales for all the preceding time periods are shown collapsed by successive powers of ten.

Although the accelerated warming trend evident in the global mean surface temperatures since the early 1980s could be partly (or even completely) natural in origin, a large number of detection and attribution studies carried out over the past decade has lead to the conclusion that most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations.

3 MODELLING OF CLIMATE

The meteorologist's principal tool for determining future weather and climate is the numerical model. This involves formulating the equations governing the physical behaviour of the atmosphere and ocean for each of a vast number of grid points over the globe and solving them numerically on powerful computers. In the case of numerical forecasting of daily weather patterns, the role of processes in the ocean is relatively minor and, because of the influence of what is popularly referred to as 'chaos', all predictability runs out by around day 10. In the case of climate simulation, the influence of the ocean becomes of paramount importance and the governing equations must be solved in coupled form for the complete atmosphere-ocean system (Figure 8).

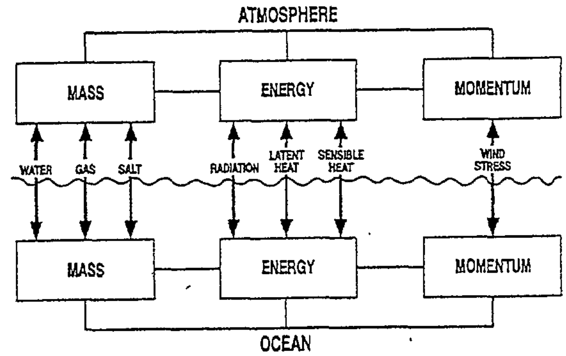

Figure 8 Schematic representation of the structure of a general circulation model for simulating (and potentially predicting) the behaviour of the global climate system.

The great challenge presented to the meteorological community by scientific and media speculation, in the early 1980s, on the prospects of a future greenhouse-warmed world was how to use the increasingly powerful and sophisticated general circulation models to provide governments with useful information for decision making as to whether to try to avert or minimise the potential greenhouse warming (and such other changes as it might bring to global climate) or whether to begin to plan to adapt to whatever changes might occur - recognising (and this recognition has not extended far beyond the meteorological community) that the enhanced greenhouse signal would almost certainly, for many decades, be quite small relative to the normal natural variability of climate on seasonal to interannual and longer time scales.

The basic difficulty centred not so much on the inadequacies of the climate simulation models as on the fact that the input to the models, the atmospheric concentrations of the greenhouse gases through the twenty-first century and beyond, will depend on presently unknown future socio-economic influences such as population growth, the development of new energy technologies, and in fact, on national and international policies for addressing the greenhouse issue itself. The conclusion of most of the meteorological/climate science community was that their contribution to international public policy development was best handled through the use of a range of alternative scenarios of greenhouse gas emissions so that policy makers could be informed of the likely climate implications of the alternative greenhouse gas emission futures. The basic philosophy of this approach is shown in Figure 9. Importantly, the meteorological community chose to identify the output of their models for the range of greenhouse gas input scenarios as projections rather than predictions of future climate.

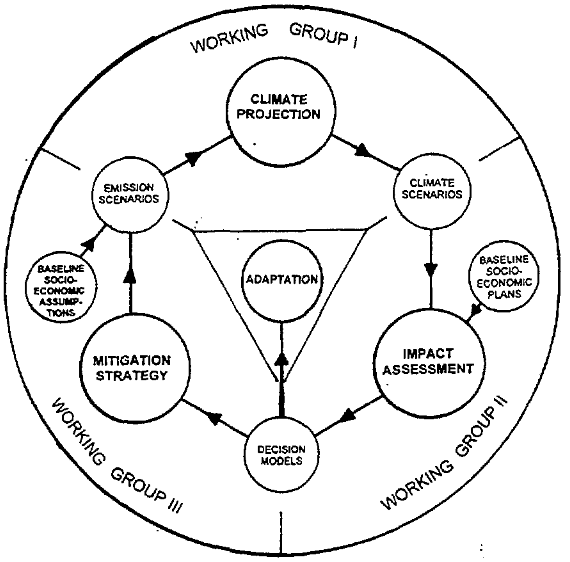

Figure 9 The IPCC methodology for using greenhouse gas emission scenarios as input to biogeoghemical and physical climate models to produce projections of alternative climate futures for use in impact sensitivity studies as an aid to decision making on the optimum balance between the complementary strategies of mitigation and adaptation.

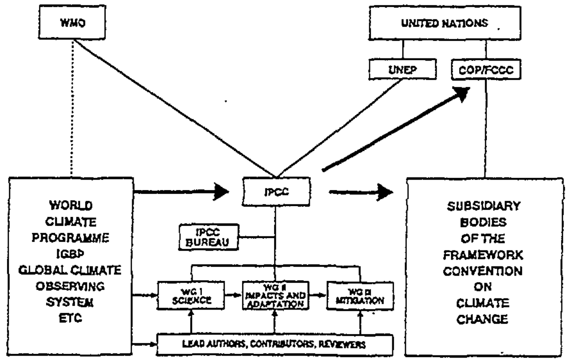

Figure 10. The Intergovernmental Panel on Climate Change (IPCC) as an interface between the international climate research effort under the World Meteorological Organization (WMO) World Climate Programme and other international research programs and the political processes of the United Nations (UN) Conference of the Parties to the Framework Convention on Climate Change (COP/FCCC).

4 THE IPCC

In 1987, the Congress of the World Meteorological Organization (WMO) decided to invite the United Nations Environment Programme (UNEP) to cosponsor the establishment of an Intergovernmental Panel on Climate change (IPCC) as a mechanism for taking stock of all the scientific literature on climate change and providing balanced objective scientific advice to governments on the state of knowledge, at any point in time. The IPCC process has generated a series of comprehensive assessments of the science, impacts and mitigation literature over the past decade via an intergovernmental structure of three working groups (WG) underpinned by a large contingent of Lead Authors and Reviewers drawn from the active research community (Figure 10).

The IPCC has just completed its Third Assessment Report (TAR). A summary of the climate science (Working Group I) component of the report is provided by Zillman (2). The main findings of the TAR (IPCC (3)) in respect of the state of the science were, in summary :

- An increasing body of observations gives a collective picture of a warming world and other changes in the climate system;
- Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate;
- Confidence in the ability of models to project future climate has increased;
- There is new and stronger evidence that most of the warming observed over the last 50 years in attributable to human activities;
- Human influences will continue to change atmospheric composition throughout the twenty-first century;
- Global average temperature and sea level are projected to rise under all IPCC SRES (Special Report on Emissions Scenarios) scenarios;
- Anthropogenic climate change will persist for many centuries; and
- Further action is required to address remaining gaps in information and understanding.

By way of illustration of the findings of the IPCC TAR regarding future climate to the end of the twenty-first century, Figures 11 and 12 present a range of emission scenarios for carbon dioxide (Figure 11 (bottom)) leading to corresponding concentrations (top) and projections of global mean temperature and sea level rise (Figure 12). It is important to note that the temperature and sea level estimates are strongly scenario dependent (including scenarios for the offsetting effect of various possible aerosol concentrations through the twenty-first century) but that the uncertainties of the climate models also add significantly to the uncertainty of the climate projections.

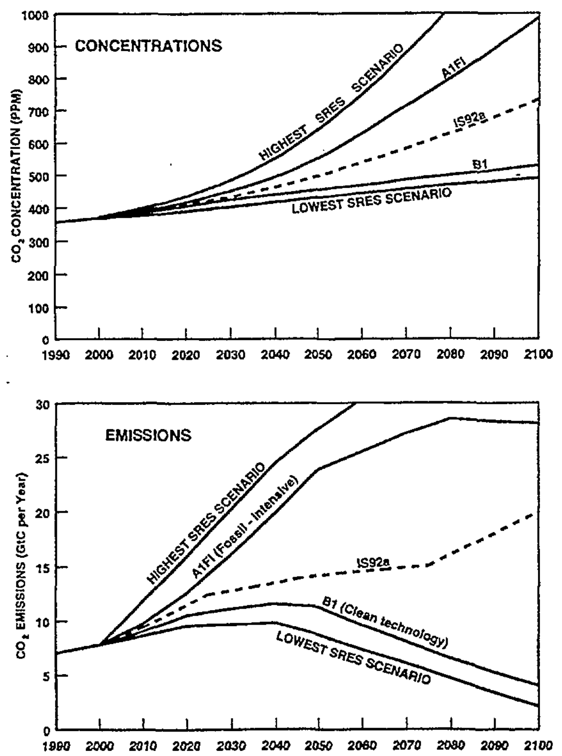

Figure 11 A simplified representation of the range of carbon dioxide emission scenarios (bottom) and the resulting atmospheric concentrations (top) used by way of illustration in the IPCC TAR. The A1FI and B1 are the highest and lowest, respectively, of the six 'illustrative' IPCC SRES (Special Report on Emissions Scenarios) scenarios. The envelope of all 35 SRES scenarios is also shown. IS92a refers to one of the most frequently quoted of the scenarios used in the IPCCs Second Assessment Report 1995.

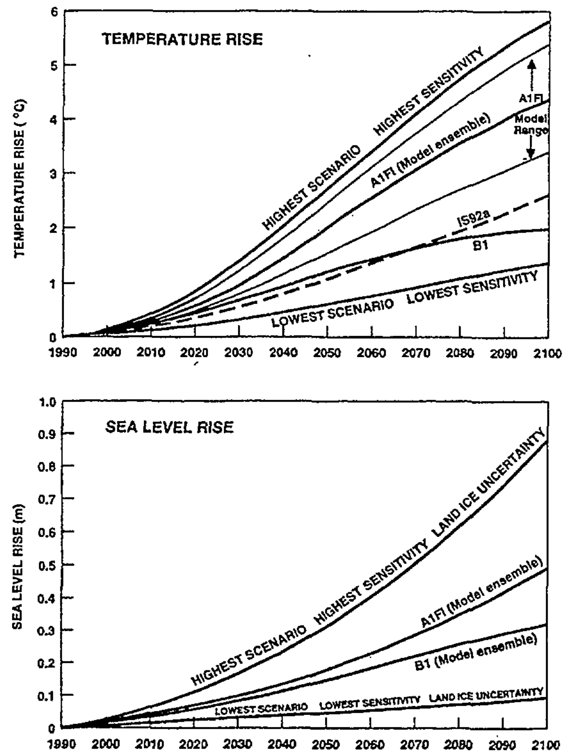

Figure 12 The global mean temperature rise (top) and sea level rise (bottom) projected by climate models for the emission scenarios illustrated (for carbon dioxide only) in Figure 11. The A1FI projections are illustrated for a climate sensitivity (equilibrium warming for doubled carbon dioxide) of 2.8°C (solid line) as well as for a range of climate sensitivities from 1.7° to 4.2°C. The B1 and IS92a estimates are shown for the mean sensitivity of 2.8°C.. The envelope of the temperature and sea level projections for all SRES model scenarios and all sensitivities is also shown.

5 CONCLUSIONS

While the greenhouse effect is a well understood meteorological process, the detailed implications of its enhancement by human induced emissions of greenhouse gases in terms of possible long term changes in global and regional climate remain uncertain and controversial. The meteorological community sees its role, working in collaboration with the various other disciplines involved in climate science, impacts assessment and strategy development, through the IPCC and other mechanisms, as primarily one of providing the best policy-relevant but value-neutral scientific advice that it can based on its rapidly advancing scientific understanding of the mechanisms of the global climate system. The recently completed IPCC Third Assessment Report provides the most up-to-date and comprehensive information currently available on the greenhouse effect and its implications. It also identifies what are currently seen as the major remaining areas of uncertainty.

6 REFERENCES

1 Arrhenius, S, 1896. On the influence of carbonic acid in the air on the temperature of the ground. Philos. Mag., 41, 237-276.

2 Zillman, J. W. 2001. The IPCC Third Assessment Report on the Scientific Basis of Climate change. Australian Journal of Environmental Management, 8, 43-59.

3 IPCC, 2001s : Climate Change 2001 : The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Nouguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press Cambridge, United Kingdom and New York, NY, USA, 881pp.