SR-79-2A

A SYSTEMS STUDY OF ENERGY AND CLIMATE

J. Williams
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Prepared for
the United Nations Environment Programme

EXECUTIVE SUMMARY

March 1979

PREFACE

This is the final report of a study on energy systems and climate (Project Number: FP/0700-75-02(717)), which was supported by the United Nations Environment Programme (UNEP) for a period of three years (January 1976 - December 1978) and carried out within the IIASA Energy Systems Program in collaboration with scientists from national and international institutions. The overall objectives of the project were to investigate the impacts of energy supply sources on weather and climate and to integrate the findings on these impacts into our study of energy systems. Thus this report discusses the impact on climate of three energy supply sources which could be developed on a large scale during the next 50 years: solar and nuclear energy and fossil fuels.

ACKNOWLEDGEMENT

This study was made possible by a research grant from the fund of the United Nations Environment Programme (UNEP) covering the time period 1.1.1976 - 31.12.1978 with a total amount of U.S. $300,000 (UNEP Project Number: FP/0700-75-02 (717)). The project was carried out by IIASA in close cooperation with the United Nations Environment Programme.

During this period many individuals and institutions contributed to the project and it is appropriate here to express thanks to all of these.

The study of the impact of waste heat on the atmospheric circulation was made possible through an agreement reached between W. Häfele of IIASA and B.J. Mason, Director-General of the United Kingdom Meteorological Office, to use the atmospheric circulation model developed at the Meteorological Office. A. Gilchrist contributed much guidance to the interpretation of the results of the model experiments and the assistance of P. Rowntree and J. Walker, also of the Meteorological Office, is likewise gratefully acknowledged. The Kernforschungszentrum Karlsruhe (FRG) supported our computer requirements and R. Kuhn supervised the computer runs of most of the experiments (Experiments 72, 90, 96 and 01 were performed at the Meteorological Office computer center).

The Workshop on Carbon Dioxide, Climate and Society was cosponsored by the World Meteorological Organization and the Scientific Committee for Problems of the Environment, with the major financial support coming from the grant from UNEP.

A joint project between IIASA and the Stanford Research Institute International was established to investigate the impact of solar thermal electric plants on regional meteorological conditions and this work was carried out under the supervision of C. Bhumralkar.

The following people have actively contributed to the research described in this report: C. Bhumralkar[1], H. Flohn[2], A. Gilchrist[3], H.R. Grümm[4], W. Häfele[4], G. Krömer[4], R. Kuhn[5],

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[6]National Center for Atmospheric Research, Boulder, U.S.A, and IIASA.

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[8]Lawrence Berkeley Laboratory, California, U.S.A., and IIASA.

EXECUTIVE SUMMARY

The overall objectives of this project, supported by the United Nations Environment Programme, were to investigate the impacts of energy supply sources on weather and climate and to integrate the findings on these impacts into IIASA's study of energy systems.

The IIASA Energy Systems Program has considered scenarios for future energy demand[1], which suggest that the order of magnitude of demand 50 years from the present will be 24-40 TW, compared with about 8 TW now. To supply energy to satisfy this magnitude of demand, three large-scale sources are available: solar and nuclear energy and coal. Realistically one can expect a combination of these sources supplying the total energy requirement. These energy systems could influence climate through ejection of waste heat, by changing concentrations of atmospheric constituents or by large-scale changes in the characteristics of the earth's surface. Although we have given some consideration to local meteorological effects of certain energy conversion systems, the emphasis of this project has been on regional and global climatic impacts.

CO_2

The impact of increasing atmospheric CO_2 concentrations is perceived as the greatest risk at the present time. Observations already show that this concentration is increasing and it is accepted that part of this increase is due to the addition of CO_2 to the atmosphere by the combustion of fossil fuels; it is also argued that some of the increase is due to destruction of tropical vegetation. In order to assess the future atmospheric CO_2 concentration and its implications, three models are required. An energy model is used to estimate the future use of fossil fuels and thus the input of fossil fuel CO_2 into the atmosphere. The proportion of CO_2 that remains in the atmosphere is then given by a model of the carbon cycle, which describes the sources and sinks of carbon and the transfers between reservoirs. The effects of an increased CO_2 concentration can then be assessed using a climate model. At the present time uncertainties must be attached to the results of each of these models so that the future use of fossil fuels and implications thereof can not be reliably predicted. Nevertheless the model results can be used to assess the magnitude of the problem. Model studies within this project showed that:

[1]Detailed description of these scenarios and of the entire program will be given in the forthcoming book of the IIASA Energy Systems Program, "Energy in a Finite World: A Global Systems Analysis".

1) with an energy strategy in which energy consumption reaches a level of 30 TW by the year 2050 with energy being largely supplied by solar and nuclear sources after the year 2000, then the atmospheric CO_2 concentration is modeled to reach a maximum of 400 ppmv in about 2020 and the mean surface temperature change is *less than* 1^0C. *On the other hand,*

2) if the energy consumption reaches 50 TW in 2050 and the supply is entirely from fossil sources, then the atmospheric CO_2 concentration is modeled to be about 800 ppmv by the year 2050, giving *a mean surface temperature change of about* 4^0C.

In recent years, much concern has centered on the CO_2 issue. It appears that there are many uncertainties in our knowledge of the carbon cycle and of the impacts of an increase in atmospheric CO_2 concentration on global and regional climate. The IIASA Workshop on Carbon Dioxide, Climate and Society reviewed these topics and discussed the implications of our knowledge and lack of knowledge for decision making for energy policy. It was concluded that:

1) mankind needs and can afford a period of between 5 and 10 years for vigorous research and planning to narrow uncertainties sufficiently to be able to decide that a major change in energy policy is required. Because of uncertainties in knowledge of both the carbon cycle and the climate system,

2) it is *premature* at this time to implement policy measures requiring the *reduction* of fossil fuels. However,

3) policies that *emphasize* the use of fossil fuels *are equally unjustified* at present and it is most important to maintain flexibility in energy supply policies at this time.

WASTE HEAT

On a global basis the total amount of heat released by mankind's activities is only slightly more than 10^{-4} of the solar energy absorbed at the earth's surface. An extreme projection of 20 billion people with an average per capita demand of 20 kW would lead to a total heat release of about 0.5% of the solar energy absorbed, which could give rise to a surface temperature increase of 1^0C if one considers the energy balance of the global system. However, energy consumption is not and will not be distributed evenly over the surface of the earth and it is the concentration of waste heat release in certain areas which has the potential to alter global climate patterns. This potential could be realized with a total waste heat release less than that in the extreme projection above.

The maximum amount of electric power generated currently at a single thermal power station is about 3000 MW and the atmospheric effects of heat dissipation rates are not serious problems. It is suggested however that *waste heat release from power parks generating 10,000-50,000 MW would increase cloudiness and precipitation in the area and possibly act as a trigger for severe weather.*

The impact of waste heat on global climate has been studied using a numerical model of the atmospheric circulation. Within the IIASA Energy Systems Program and in cooperation with the U.K. Meteorological Office a series of experiments has been carried out with the atmospheric circulation model developed by the Meteorological Office, to investigate the sensitivity of the atmospheric circulation to large amounts of waste heat released at point sources in ocean areas. One reason for considering such point sources is that with a waste heat input of 150-300 TW, a significant response of the simulated atmospheric circulation was only likely if the input was concentrated in a small area. In addition, one may give some technological meaning to such point sources. The concept of energy islands has been considered within the IIASA Energy Systems Program in terms of the necessity of "embedding" energy systems within the atmosphere, hydrosphere, ecosphere and sociosphere.

Five experiments were made with the Meteorological Office model to look at the impacts of point sources of waste heat input of a total of 150 or 300 TW. These high amounts of heat input were used because earlier experiments elsewhere had also used 300 TW and because input of large perturbations ensures a significant response in the simulated atmospheric circulation. *It was found that* the response of the simulated atmospheric circulation is not just in the area of heat input, but large coherent changes are found on a hemispheric scale. The response varied according to the location, amount and method of heat input. A further experiment has investigated the response to 300 TW waste heat input distributed over six continental regions in the northern hemisphere. *In this case the response is* comparable to that when the heat input is concentrated at only two energy parks, with large coherent areas of change in the sea level pressure and 500 mb height fields and the distribution of temperature in the lowest atmospheric layer.

The results of such experiments must be viewed with a recognition of the model shortcomings, such as absence of a coupled atmosphere-ocean system, poor treatment of clouds, hydrological and subgrid scale processes. *The results suggest that waste heat is a "non-problem" on a global scale, in that it is unlikely to perturb the global average climate state in the foreseeable future.* However, when extremely large amounts of heat (on the order of 100 TW) were inserted in special modes, such as point souces, significant changes in the atmospheric circulation could be determined. *With an energy consumption level of 24-40 TW there appears to be little or no ground for global concerns regarding the climatic impact of waste heat release.*

SOLAR ENERGY

A number of solar energy conversion systems could be developed on a large enough scale to contribute significantly to an energy supply of about 30 TW and these are solar thermal electric conversion (STEC), photovoltaic (PV), ocean thermal electric conversion (OTEC), biomass and solar satellite power (SSP) systems.

The possible climate impact of the large-scale deployment of solar energy systems has received little attention. A workshop was held at IIASA which discussed the physical characteristics of the systems, assessed their impact on boundary conditions of the climate system and discussed the climatic implications of such impacts.

Large-scale deployment of STEC systems would lead to regional changes in the surface heat balance, surface roughness and hydrological characteristics. The STEC systems do not really change the magnitude of the net heat flow from the surface to the atmosphere but the mechanism of transfer is changed; the significantly lower heat release from the surface is compensated by a release of waste heat from cooling towers upon energy conversion. Although no specific studies of the potential climate impact of large-scale changes in hydrological characteristics due to STEC and PV systems have been made, model and observational studies indicate that *large-scale changes in surface wetness can significantly influence climate.*

OTEC systems use the vertical temperature gradient in the ocean to generate electricity. Climatic impacts could be caused by the lowering of the ocean surface temperature or by interference with ocean current dynamics. Both observational and model studies indicate that ocean surface temperature anomalies could influence climate. Further impacts of OTEC systems could arise because of the upwelling of water, through albedo changes, for example, but these have not been investigated in detail.

A preliminary study has been made of the possible impact of a hypothetical 1000 km^2 STEC power park in Southern Spain on regional meteorological conditions. This work, carried out in conjunction with the Stanford Research Institute International, used a two-dimensional model of meteorological conditions. The results of two pairs of model integrations suggest that for the particular configuration of a STEC power park considered, the effects, due to the changes in the surface energy balance and the input of waste heat at wet cooling towers, are such that in the summer the cloudiness which develops in the normal sea breeze situation, occurs earlier in the day and persists more in the presence of the STEC park. In the winter it appears that the prevailing wind is strong enough to prevent meteorological impacts due to the STEC park.

PARTICULATES

The release of particles and other gases due to energy conversion has also been considered. It seems that most anthropogenic particles exist over land where they are formed and are sufficiently absorbing to cause a warming of the earth-atmosphere system. However, no quantitative evaluations of the interactions of particles with the radiation field and with condensation/precipitation process are available due to the lack of observed data on the nature and distributions of the particles and lack of models which can account for all the interactions and feedbacks.

RESILIENCE

Work has also been carried out within the project on resilience and *dynamical systems theory and their applications to climatology*. Resilience has been described as "ability of systems to absorb changes in the values of state variables, driving variables and parameters and still persist". The mathematical expression of this concept of resilience is through the global theory of non-linear dynamical systems. Climate is also a non-linear dynamical system and therefore applications of this theory to climatology have been investigated. An ultimate goal of such investigations at IIASA and elsewhere is the derivation of a shortcut to the determination of time averages in meteorological models. Further work has included studies of limit cycles and time averages and studies of simple (zero-order) climate models using catastrophe theory.

CONCLUSIONS

In order to devise energy policies which take into account the climate constraints, more detailed information on the climate impacts will be required--in particular, model results showing regional changes to be expected from different perturbations and scenarios of possible future climatic states. In this regard it is clear that many uncertainties still exist regarding the many feedbacks within the climate system and thus it appears that even basic theoretical research and observational studies are required in order that prudent energy policies, in which energy-climate interactions are considered, can be devised and used.

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SR-79-2B

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G. Krömer

Prepared for
the United Nations Environment Programme

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1. GENERAL STATEMENT OF THE PROBLEM AND AIMS OF THE PROJECT

The overall objectives of this project, supported by UNEP, were to investigate the impacts of energy supply sources, including coal, nuclear and solar, on weather and climate and to integrate the findings on these impacts into IIASA's study of energy systems.

World primary energy consumption in 1975 was at an average rate of about 8 TWyr/yr, or 8 TW (1 TW = 10^{12}W). The share of oil and gas in this total was about 5.3 TW, with oil from the Middle East amounting to nearly 1.4 TW. Growth in energy demand is stimulated by many factors; predominant among these are the world population growth, the development of less developed countries and the continued industrialization in developed countries. The most important stimulus for energy growth in the future will probably result from efforts to reduce the differences between developed and developing countries.

The IIASA Energy Systems Program has considered scenarios for future energy demand[1]; the scenarios are defined in terms of population, economic growth and primary and final energy demand for seven regions of the world. Consideration of these energy demand scenarios suggests that the order of magnitude of energy demand 50 years from the present will be 24-40 TW, compared with about 8 TW now.

In addition to demand, it is necessary to consider supply of energy. Most of the present supply is from fossil fuels (coal, oil and gas) and in the future, in addition to these sources of energy, non-conventional fossil fuels such as secondary and tertiary oil recovery, high-cost low-grade coal, tar sands and oil shales must be taken into account. A second supply source is nuclear energy conversion, which at present largely comes from the light water reactor but fission and fusion breeder reactors are potential future sources. Hydropower and localized renewable energy sources (biogas, wind, "soft" solar and tides, for example) represent supply sources which, although important on local and regional scales have been considered to make only small contributions to a global energy supply of 24-40 TW. A third energy supply source which could, however, be developed on a large scale during the next 50 years is "hard" solar energy conversion, where solar energy

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[1]Detailed description of these scenarios and of the entire program will be given in the forthcoming book of the IIASA Energy Systems Program, "Energy in a Finite World: A Global Systems Analysis".

is converted to electricity, methanol, hydrogen or another secondary energy carrier at large-scale centralized facilities.

Thus, in considering the impact of energy systems on climate, with reference to a projected demand in the year 2030 of 24-40 TW, the impact on climate of the large-scale depolyment of three energy supply sources (nuclear, fossil fuel and solar) must be considered. These energy systems influence climate through the ejection of waste heat, by changing concentrations of atmospheric constituents or by large-scale changes in the characteristics of the earth's surface.

Climate is a complex, non-linear system with many feedback processes between the components. It is the potential of energy systems to interfere with natural climate processes to produce global climatic changes that has received increasing attention. It should be emphasized, however, that it is not the possibility of a globally-averaged climate change which is the central issue but rather the inevitable regional shifts in climatic patterns, which would result from a perturbation of the climate system. Although we have given some consideration to local meteorological effects of certain energy conversion systems, the emphasis of this project has been on regional and global climatic impacts. This emphasis is a natural outcome of the global approach of the IIASA Energy Systems Program.

Before the present project began, work had started within the Energy Systems Program to investigate the impact of the release of large amounts of waste heat from one or more energy parks on the general atmospheric circulation. The proposal for the project contained the following tasks:

TASK 1: Use of global circulation model and follow-up on numerical experiments already performed by

- (a) further analysis of significance of results of model experiments
- (b) a gradual waste heat release in the model
- (c) comparison by the use of at least one further circulation model.

TASK 2: Use of regional models in particular view of

- (a) upper limits for dry cooling towers
- (b) local changes of rainfall patterns
- (c) heat effects of a megalopolis
- (d) albedo changes due to solar power plants.

TASK 3: More specific investigations

(a) brackets for CO_2 increase in the atmosphere

(b) brackets for dust.

TASK 4: Effects on polar regions.

The work completed within Task 1 is reported in Section 3 of this report. Considerable attention was paid to the evaluation of the statistical signficance of the differences between model experiments and a methodology for such analysis was adopted. A total of 6 model experiments was made to look at the impacts of various scenarios of waste heat release and these were compared with three model control cases. For all of this work, the model developed at the Meteorological Office of the United Kingdom was used. No experiments with further models were made within the project, largely in view of financial and personnel limitations. However, the results of this work have been compared with those from studies made with other models elsewhere and examples of such comparisons are given in Section 3.

Within Task 2, a survey was made of the results of regional meteorological models used to investigate the effects of cooling towers on atmospheric conditions including rainfall patterns and this work is summarized at the beginning of Section 3. In addition to a consideration of the regional effects of a megalopolis, the question of the global climatic impacts of waste heat release fom megalopolitan areas has been addressed by the use of experiments and both of these topics are also considered in Section 3 of this report. Lastly, a model of regional meteorological conditions has been used in collaboration with the Stanford Research Institute International to investigate the impacts of surface energy balance changes due to a 1000 km^2 solar thermal electric power plant (Section 4).

Within Task 3 considerable attention was paid to the subject of carbon dioxide. Firstly a model of the carbon cycle was used to look at the impact of different energy strategies on the atmospheric CO_2 concentration and thus on the global average surface temperature. Secondly, a detailed study was made of possible climate scenarios for a future man-made warming. Thirdly, a workshop of more than 100 scientists from 17 different countries was convened to consider three main aspects of the carbon dioxide problem. All of this work on carbon dioxide is reported in Section 2 of this report. The question of the impacts of dust and other man-made gases on regional and global climate is discussed in Section 5 of the report.

Task 4, considering the effects on polar regions, has not been considered on its own as a topic, but within each of the evaluations of the impacts of different energy supply sources, the polar areas receive attention. In particular, the polar areas have received considerable attention in the discussion of the impacts of increasing atmospheric CO_2 concentration as described in several of the papers in the proceedings of the workshop.

The organization of this report does not however describe the work done in the above tasks in that order, but rather divides the work into a number of subject areas which evolved as a response to the general structure of the overall IIASA Energy Systems Program. Thus the next section (2) considers all of the work done within the systems study on energy and climate in connection with the carbon dioxide issue. Section 3 describes all of the work which considered the impact of waste heat. The impacts on regional and global climate of a number of solar energy conversion systems are considered in Section 4, the material for which is derived from the proceedings of another workshop held under the auspices of the project and also from model studies. Section 5 presents a review of the impacts of particles and man-made gases on global climate. The applications of dynamical systems theory to climate, a topic developed at IIASA, with the systems study of energy and climate is discussed in Section 6.

The conclusions of this systems study of energy and climate are presented in Section 7 and it is at this point that reference can also be made to the rest of the Energy Systems Project, especially with regard to the intercomparison of the different energy supply sources and implications for energy policy decision making and, indeed, future research. Finally, the material which has been (or is in the process of being) published during the course of this project is listed in the Appendix.

2. CARBON DIOXIDE

2.1. Introduction

Figure 2.1 shows the trend in the concentration of atmospheric CO_2 at Mauna Loa Observatory, Hawaii, for the period 1958-1974 (Keeling et al., 1976b; Baes et al., 1976). Superimposed upon a seasonal oscillation of about 6 ppm there is a secular increase in the concentration from about 315 ppmv at the beginning of the period to about 332 ppmv at the end. The concentration of atmospheric CO_2 has been measured at the South Pole virtually continuously since 1957 (Keeling et al., 1976a) and this record also shows a secular increase in concentration. Shorter CO_2 records from other stations and aircraft data substantiate the rates of increase observed at Hawaii and the South Pole.

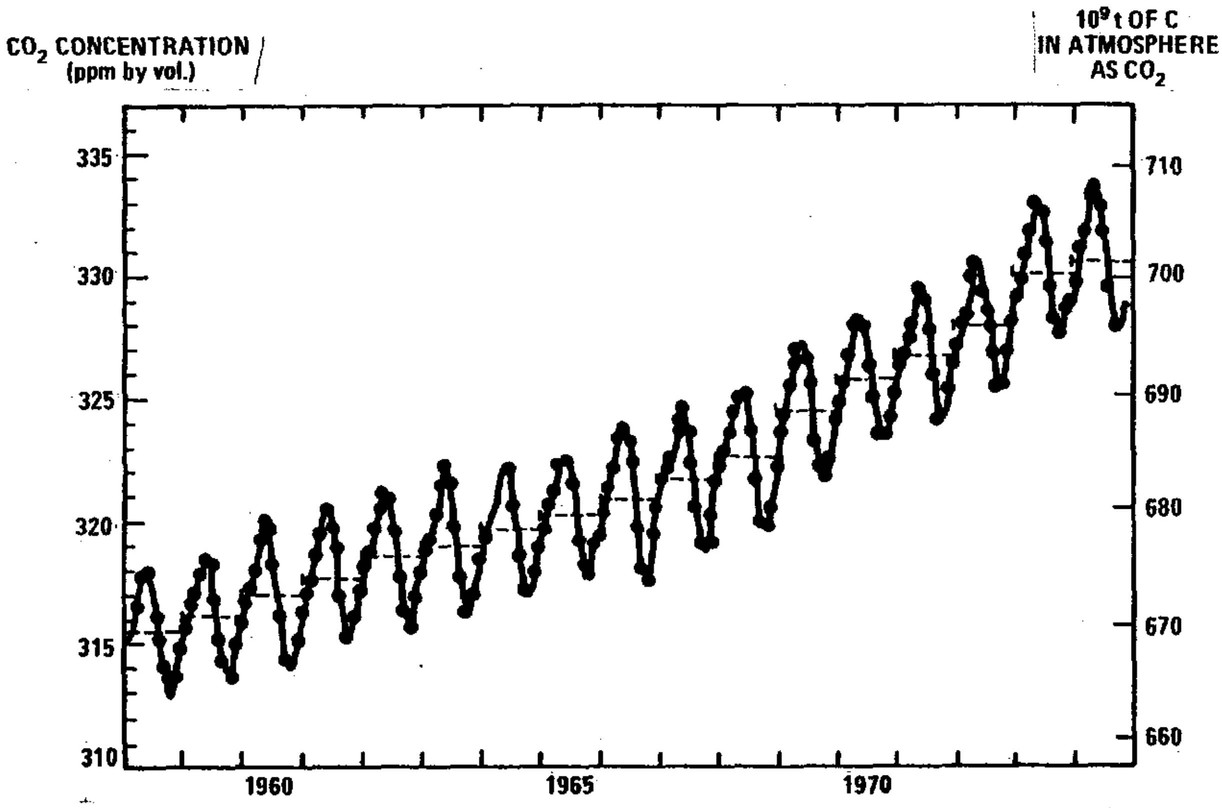

Figure 2.1. Atmospheric carbon dioxide concentration at Mauna Loa observatory
Source: 1958-1971 data from Keeling et al.(1976) 1972-1974 data from Baes et al. (1976).

It is accepted that part of the observed increase is due to the addition of CO_2 to the atmosphere by the combustion of fossil fuels; it is also argued that some of the increase is due to destruction of tropical vegetation.

The concern over the observed increase of atmospheric CO_2 concentration and potential future increases arises because of the physical properties of the gas. CO_2 is a trace gas in the atmosphere. It is relatively transparent to incoming short-wave solar radiation but is a strong absorber of long-wave radiation coming from the earth's surface, particularly in the wavelength band around 15μ. Part of the reemitted long-wave radiation is downward to the earth's surface, so that CO_2 warms the earth's surface. This has been called "the greenhouse effect", although the analogy is not a perfect one since the greenhouse keeps the surface warm by preventing sensible heat escape. There are other atmospheric trace gases which exert a similar effect; in particular, water vapor and man-made chlorofluoromethanes. An increase in atmospheric CO_2 concentration would, all other factors constant, lead to an increase of the earth's surface temperature. Observations and models of the climate system must be used to assess the implications of an increase in atmospheric CO_2 concentration.

The "CO_2 problem" as it has often been called, has basically three aspects. Firstly, we are concerned with the carbon cycle, that is, a description of the sources and sinks of carbon and the transfers of carbon between the atmospheric, biospheric and oceanic reservoirs. Only with a detailed knowledge of the biogeochemical carbon cycle can we hope to predict future levels of atmospheric CO_2 concentration. Given that atmospheric CO_2 concentration will reach a certain level in the future, the second aspect of the CO_2 problem is to discuss the impact of this CO_2 on climate and thus on the environment, including such areas as agriculture and the ice caps. In particular we are concerned not so much with the question of changes in global average temperature, but with regional changes of temperature, rainfall and other climatic variables. The third aspect is then a discussion of what the present knowledge (and lack of knowledge) about the first two points implies for decision making concerning energy strategies.

Within the Subtask on Energy and Climate each of these aspects has been considered in some detail. Firstly, a model of the carbon cycle, developed by F. Niehaus of the Joint IAEA-IIASA Research Project, has been used to assess the impacts of different energy strategies on the atmospheric CO_2 concentration. Secondly, Professor H. Flohn of the University of

Bonn prepared a detailed consideration of the possible climatic consequences of a man-made global warming. Thirdly, a workshop was held at IIASA in February 1978, in cooperation with the United Nations Environment Programme, the World Meteorological Organization and the Scientific Committee on Problems of the Environment to consider and report on each of the above outlined aspects of the CO_2 problem. Each of these activities is outlined in more detail below.

2.2. The Effects of Different Energy Strategies on the Atmospheric CO_2 Concentration and Climate

In order to assess the future atmospheric CO_2 concentration and its implications, three models are required. An energy model is used to estimate the future use of fossil fuels, and thus to estimate the input of fossil fuel CO_2 into the atmosphere. The amount of the fossil fuel CO_2 that remains in the atmosphere can then be given by a model of the carbon cycle, which considers the reservoirs of carbon and the transfers between them. The effects of the atmospheric CO_2 concentration on climate can then be assessed using a climate model. To the results of each of these models must be attached an uncertainty, such that the future use of fossil fuels and the implications thereof can not be predicted. The model results can only be used at the present time to assess the magnitude of the problem.

A preliminary assessment of the time scale of interaction between energy strategies and the atmospheric CO_2 concentration was made at IIASA by W. Häfele and W. Sassin (see W. Häfele et al., 1976). It was assumed that there would be a population growth from today's 4 billion to 12 billion and that provision must be made for an average per capita energy consumption of 5 kW. It was further assumed that oil and gas would be consumed at first and coal thereafter. Taking a scenario where 200% additional CO_2 is considered as a limit, the use of coal was found to be curtailed to 20% of the world's coal resources assumed at present. Figure 2.2 shows the implications of these assumptions when different energy growth rates are considered. At a growth rate of 4.5% the limit of 200% increase of CO_2 is reached just beyond 2030; at a growth rate of 2% the limit is reached only 42 years later. This result shows that, within the limits of the assumptions made, the reaching of some imposed limit on fossil fuel consumption is fairly insensitive to technological/economic considerations.

An example of the combined use of an energy model, a carbon model and the results of a climate model is given in the study of Niehaus and Williams (1978), which again shows the range of the CO_2 problem. The model of the carbon cycle has been described by Niehaus (1976, 1977). Exchange rates

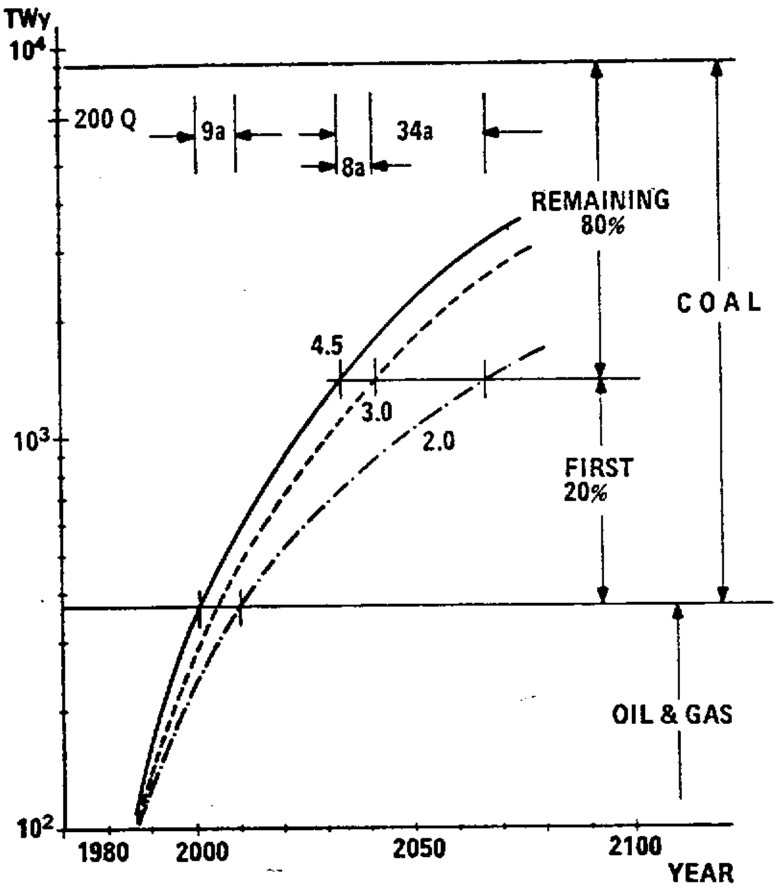

Figure 2.2. Fossil energy reserves and cumulated energy consumption. Source: Häfele et al (1976).

of carbon and ^{14}C are simulated between eight reservoirs. The global surface temperature response was assumed from the study of Manabe and Wetherald (1967), which gives an estimate of the average global temperature change of about 2.4°C for a doubling of atmospheric CO_2 concentration.

Most of the scenarios, used within this particular study, for future energy consumption were derived using a global energy model developed by Voss (1977). The latter model considers the dynamics of population growth, interactions between investments, labor and industrial production, the process of capital stock growth, environmental costs, raw materials and the dynamics of substitution of primary energy carriers.

The verification of the carbon model has been described by Niehaus (1976) and Niehaus and Williams (1978). The results of three hypothetical energy strategies will be discussed here. Others have been described by Niehaus and Williams (1978).

Figure 2.3 shows a hypothetical scenario for energy consumption based on a "35 TW Reference Supply Scenario for 2030", which has been described by Häfele and Sassin (1977). The energy consumption in 1975 is assumed to be 7.5 TW of which 0.45 TW is used for non-energetic purposes. The growth rate in energy consumption is assumed to be 3.5% in 1975 decreasing smoothly to 1% by the year 2030 and thereafter. The consumption of oil and gas for non-energetic purposes is 6% of energy demand in 1975 increasing to 11% by 2030 and constant thereafter. It is assumed that the consumption of oil, coal and gas reaches a constant level in the year 2030, such that the annual consumption of coal is 8.06 TW, of gas is 3.52 TW and of oil is 3.47 TW.

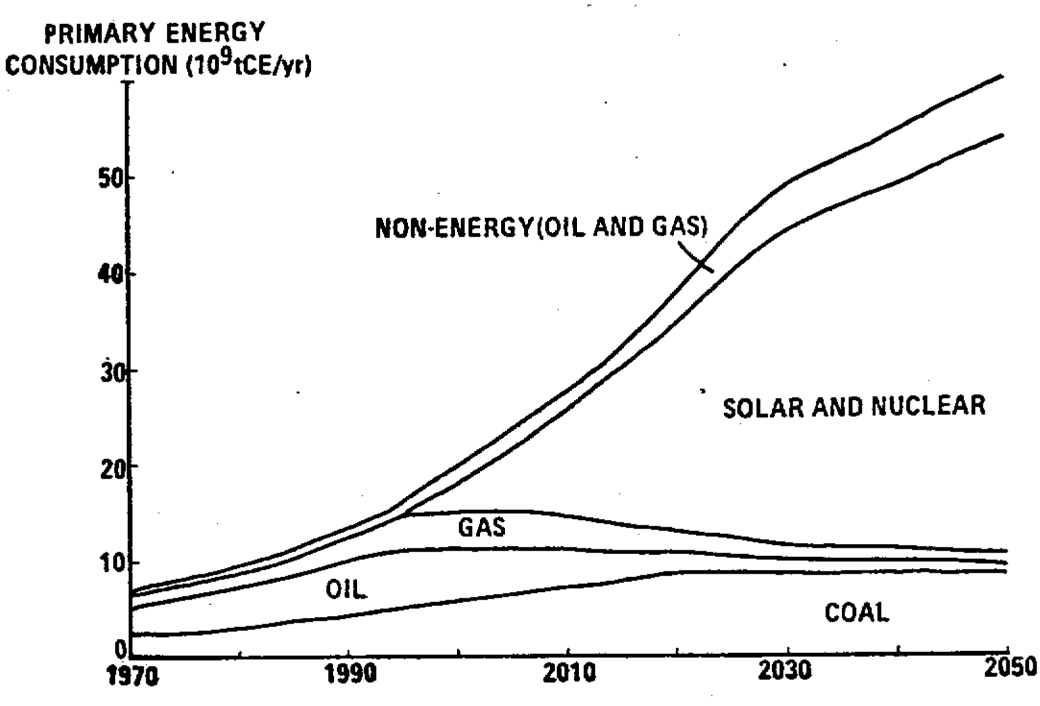

Figure 2.3. Energy strategy for the hypothetical 35 TW Reference Scenario. Source: Williams (1978).

Figures 2.4 and 2.5 show energy strategies, in which the energy model of Voss was used to decide on the distribution of energy supply as a function of time while the total amount of energy was based on estimates given by Riedel (1977). In

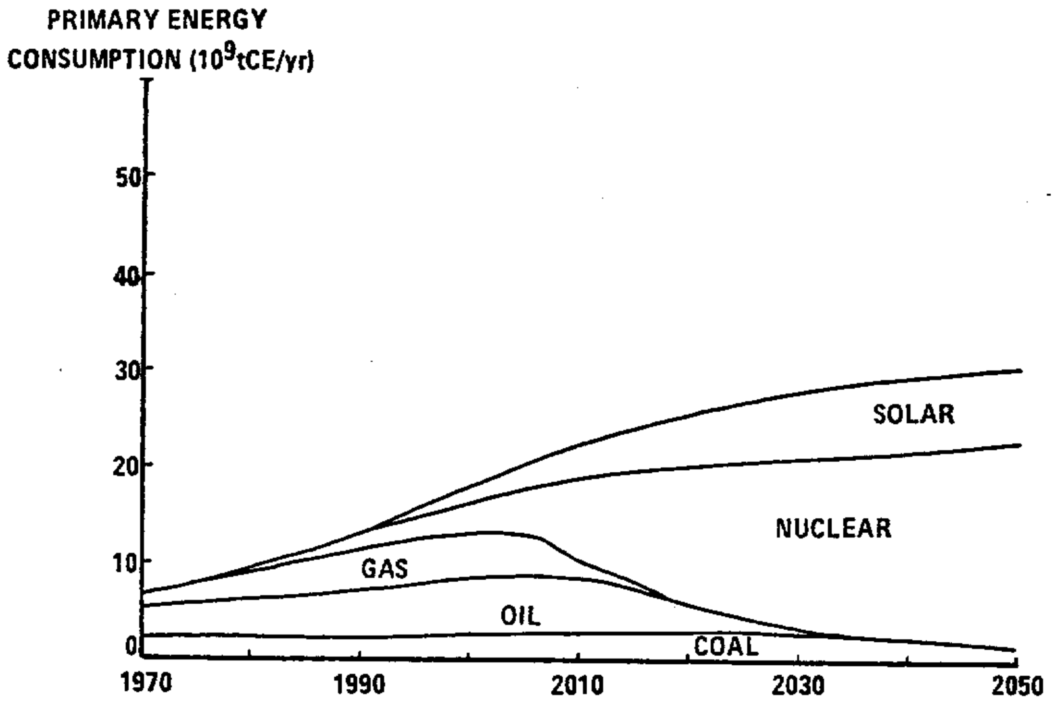

Figure 2.4. 30 TW hypothetical energy strategy with nuclear and solar. Source: Williams (1978).

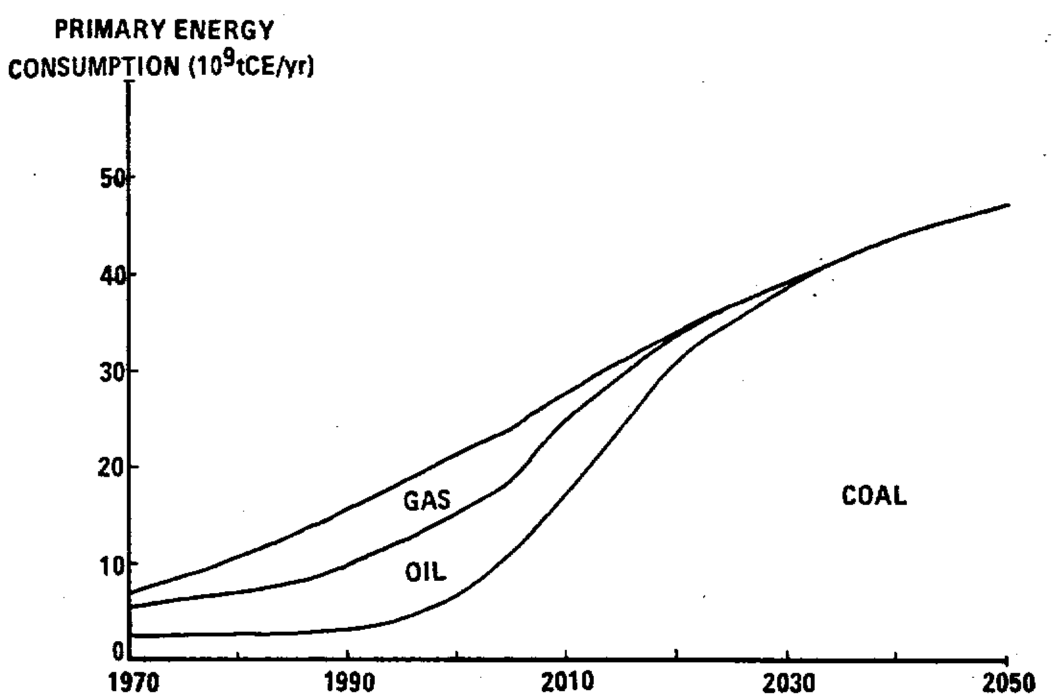

Figure 2.5. 50 TW hypothetical fossil fuel energy strategy. Source: Williams (1978).

Figure 2.4 it is assumed, after Riedel (1977), that energy consumption levels out at 30 TW and that nuclear and solar energy contribute significantly to the energy supply. In Figure 2.5 the energy consumption is assumed to level out at 50 TW and no nuclear and solar energy are used.

Figures 2.6, 2.7 and 2.8 show the atmospheric CO_2 concentrations given by the carbon model for the above three strategies together with CO_2 emissions implied by the strategies and the estimate of global surface temperature change corresponding to the atmospheric CO_2 concentration.

For the 35 TW strategy (Figure 2.6) the emissions of CO_2 reach a constant level at about the year 2000; the atmospheric CO_2 concentration continues to increase, reaching a level of about 510 ppmv in 2050 and the corresponding mean temperature increase is about 1.7°C.

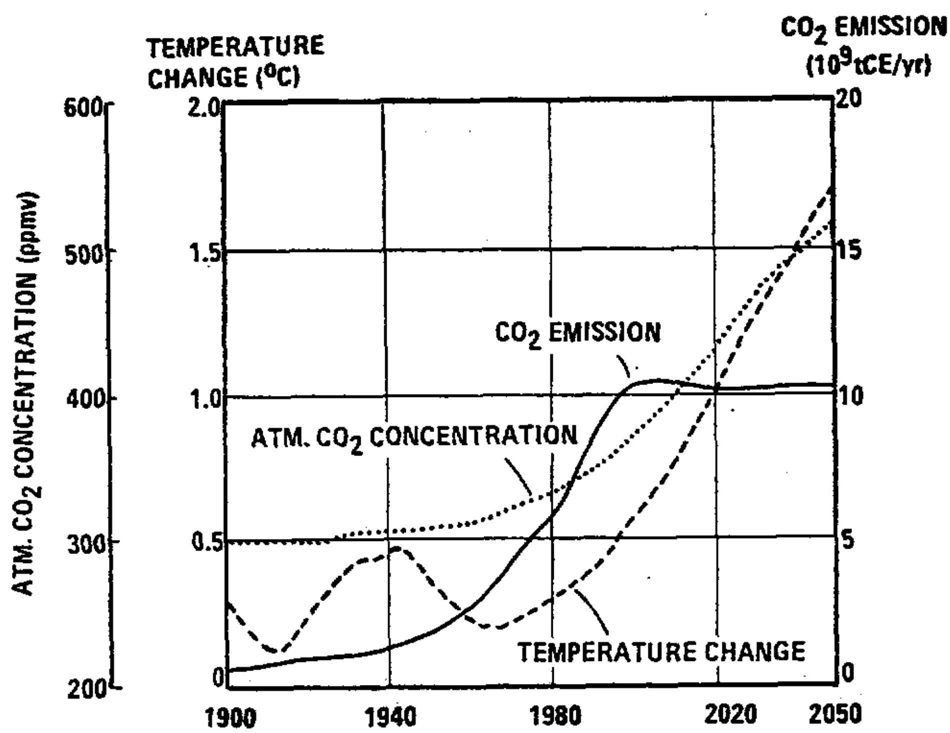

Figure 2.6. CO_2 emissions, atmospheric CO_2 concentration and temperature change for 35 TW hypothetical Reference Scenario energy strategy. Source: Williams (1978).

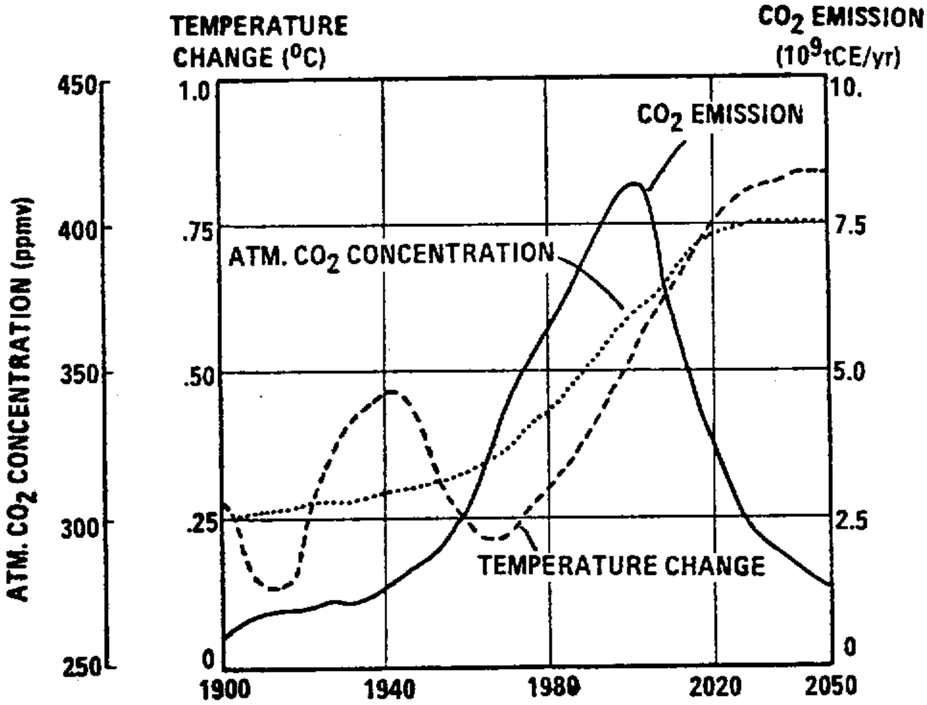

Figure 2.7. CO_2 emissions, atmospheric CO_2 concentration and temperature change for hypothetical 30 TW solar and nuclear energy strategy. Source: Williams (1978).

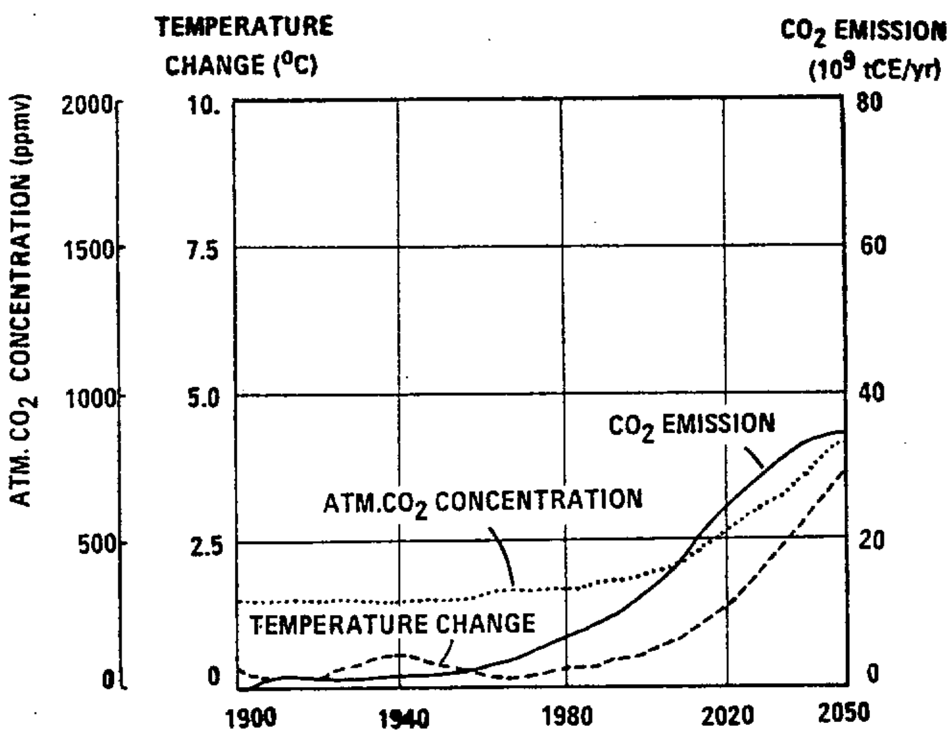

Figure 2.8. CO_2 emissions, atmospheric CO_2 concentration and temperature change for hypothetical 50 TW fossil fuel energy strategy. Source: Williams (1978).

For the 30 TW strategy with solar and nuclear energy, Figure 2.7 shows that the emissions of CO_2 peak at about 2000 and the concentration of atmospheric CO_2 reaches a maximum of 400 ppmv in about 2020. The largest mean surface temperature change associated with this strategy is therefore less than 1°C.

For the 50 TW strategy which considers only fossil fuel consumption the emissions of CO_2 increase until 2050, reaching a value 3.5 times as large as that in the hypothetical 35 TW Reference Scenario by the year 2050. The atmospheric CO_2 concentration reaches about 800 ppmv in 2050, implying a mean surface temperature increase of about 4°C.

The results of the models have many limitations. For example, we have only considered the mean surface temperature change as derived from a one-dimensional radiative-convective model, whereas we know that the climate system is highly complex and that the surface temperature changes in the year 2050 as shown in Figures 2.6-2.8 are only indicators of the scale of response to the change in atmospheric CO_2 concentration. Likewise, the carbon model has considered that the biosphere acts as a sink for CO_2, being allowed to grow to 110% of its initial size as a result of the increasing atmospheric CO_2 concentration. As pointed out above, because of such uncertainties in the model results, the latter can only be used at the present to indicate the possible magnitude of the problem. In this regard, the results of the three hypothetical energy strategies described above show that, if the ultimate level of energy consumption is limited to 30 TW and nuclear and solar energy conversion are relied on, the climatic effects are small since the mean surface temperature change was computed to be less than 1°C. If the use of fossil fuels increases to levels as shown in the 35 TW Reference Scenario, then the climate effect increases, with a mean surface temperature change of more than 1.5°C. If only fossil fuels are used and if the ultimate level of energy consumption is assumed to be 50 TW, then the climate change by 2050 is considerably larger, with a mean surface temperature change of about 4°C.

2.3. Possible Climatic Consequences of a Man-Made Global Warming

As mentioned above, although the impacts on globally averaged temperature of a doubling of the atmospheric CO_2 concentration have received considerable attention, the regional changes of temperature and rainfall and other climatic variables are of more concern when the social, political and environmental issues are being considered. In the absence of climate models which can reliably predict these regional changes other approaches have also been taken. Kellogg (1978) has suggested that one way to find out what a warmer earth might be like is to study a time when the earth itself was warmer than it is now. As Kellogg points out, such a time existed about 4000 to 8000 years ago, a period referred to as the Altithermal.

Professor Flohn of the University of Bonn contributed to the Subtask on Energy and Climate by preparing a detailed review of the possible climatic consequences of a man-made warming. This work will be published as a IIASA research report (Flohn, 1979). Flohn has emphasized that other gases released by man's activities also have a greenhouse effect. In particular, the impacts of N_2O, CH_4, NH_3 and chlorofluoromethanes should not be neglected. The model study of Wang et al. (1976) has shown that a doubling of the atmospheric concentrations of N_2O, CH_4 and NH_3 would give global average surface temperatrue increases of 0.7 K, 0.3 K and 0.1 K respectively.

Flohn has considered the possible time scale of a global warming due to the greenhouse effect of CO_2 and other man-made trace gases, which have been considered in a combined greenhouse effect (CGE). The impact on mean surface temperature of the greenhouse effect was assumed from the model studies of Augustsson and Ramanathan (1977). Thus instead of referring to the atmospheric CO_2 concentration, Flohn considers a virtual CO_2 content, expressed as ppm*, which is the actual CO_2 content plus the CO_2 amount which represents the effect of additional trace gases. Table 2.1 shows the temperature increase corresponding to different values of the virutal CO_2 content using the constant cloud top altitude version of the model of Augustsson and Ramanathan (1977).

The values in the first column of Table 2.1 are in brackets because these refer to the case in which trace gases contribute twice as much to the greenhouse effect as does CO_2 and this is considered to be unrealistic. Taking the most conservative case, that CO_2 contributes 67% of the greenhouse effect and trace gases 33% (third column), then Flohn used the CO_2 growth rate model of Zimen et al. (1977), to derive the figures illustrated in Figure 2.9. With a growth rate of 3.5-4% per year, the "level of perception" of a warming (when the warming reaches 0.5 K, according to Flohn) will be reached between 1990 and 2000. Even when the CO_2 growth rate is reduced to 2% this level is reached around the year 2010. Similarly a 1 K warming is found in about the year 2000 for an annual CO_2 growth rate of 4%. When this growth rate is reduced to 2%, the 1 K warming occurs around the year 2040.

Table 2.1. Estimated increase of near-hemispheric temperatures and equivalent changes of the virtual (ppm*) and real (ppm) CO_2 content, both estimated from the Augustsson and Ramanathan model.

	Temperature increase[1]		Virtual CO_2 content	Contribution of real CO_2 to combined greenhouse effect (CGE) 33%	50%	67%
CTA	+ 0.5°K	(perception of warming)	400 ppm*	(346)	360	374 ppm
	+ 1.0°K	(Medieval warm phase)	490	(376)	405	432
	+ 1.5°K	(Holocene warm phase)	580	(406)	450	492
	+ 2.0°K	Eem interglacial period	670	(435)	495	555
	+ 2.5°K	Eem interglacial period	760	(465)	540	615
	+ 4.0°K	Ice-free Arctic Ocean[2]	1150	(560)	740	878
CTT	+ 0.5°K		365 ppm*	(335)	342	350
	+ 1.0°K		420	(353)	370	386
	+ 1.5°K		475	(371)	398	422
	+ 2.0°K		530	(390)	426	458
	+ 2.5°K		590	(409)	455	498
	+ 4.0°K		780	(465)	555	630

[1] Augustsson and Ramanathan model

[2] Budyko model

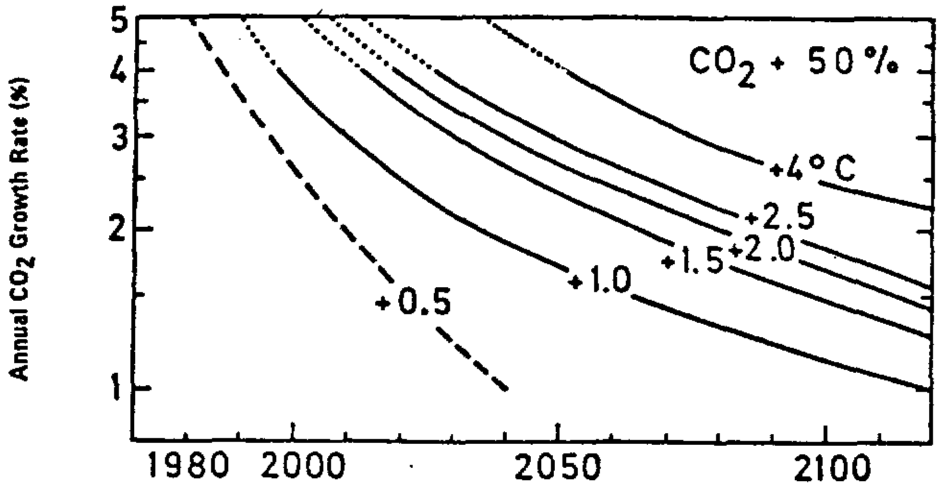

Figure 2.9. Sample of curves representing different temperature thresholds, derived from CTA version of the Augustsson and Ramanathan model plotted as a function of time and the initial CO_2 growth rate.

An extension of the approach taken by Kellogg (1978) has been made by Flohn, who has considered further evidence for past climatic regimes as scenarios for a man-made warming. Flohn suggests that the "level of perception" of a warming is when the global surface temperature increase is 0.5 K, which possibly was the case in the earlier decades of the present century. A warming of 1 K would be equivalent to the early Middle Age warm epoch, occurring about 900-1100 AD. A warming of 1.5 K would be equivalent to the postglacial warm period, referred to above as the Altithermal, which Flohn dates as about 5500 to 6500 years before present. A warming of 2-2.5 K would be equivalent to the last interglacial period, referred to as the Eem and dated about 125,000 years before the present. Lastly Flohn considers a scenario of a 4 K warming in which case the Arctic is assumed to be ice free. Recent data suggest that the Arctic Ocean has not been ice free in the past 2.3 million years. Flohn has made a detailed survey of the climatic conditions during each of these periods, but does also ask the question: Can climatic history repeat itself?

This question is of major importance, because, for example, two boundary conditions which existed during the Altithermal period have basically changed. Firstly the presence of limited and shallow but not negligible permanent ice sheets in eastern Canada during the Altithermal gave an asymmetry to the circulation which would not occur today. Secondly, since the Altithermal, the climatic boundary conditions have been increasingly changed by man-triggered desertification effects. Because of these changes, Flohn has concluded that, for example, along the northern margins of the Old World arid belt, no substantial increase of rainfall should be expected. At the southern flank some increase might be possible, if (as expected) the intensity of the subtropical anticyclones weakens together with their displacement towards higher latitudes. Flohn likewise points out that because of man-made desertification effects, reconstruction of the natural vegetation cover, under present population pressure, might be delayed by several decades until a reliable long-term increase of rainfall could be achieved.

2.4. IIASA Workshop on Carbon Dioxide, Climate and Society

This workshop, cosponsored by UNEP, the WMO and SCOPE was convened in Baden in February 1978 to contribute towards the study of the climatic constraints associated with CO_2 produced by combustion of fossil fuels. The first two days of the workshop were spent in reviewing present knowledge on the carbon cycle, the climatic and environmental effects of an increase in atmospheric CO_2 concentration and on the implications of this knowledge (or lack of knowledge) for energy strategy decision making. During the second two days, three working groups met to discuss the problems further and to produce a list of major issues that were covered, an evaluation of our present knowledge on the three aspects of the CO_2 problem and recommendations. The proceedings of the workshop (Williams, 1978) contain a virtually complete record of the workshop, including review papers and papers submitted for discussion in the working groups.

The first working group considered the questions of the sources and sinks of CO_2 and the possibilities of predicting future levels of atmospheric CO_2 concentration given a knowledge of the fossil fuel input. CO_2 circulates between the atmosphere, oceans and biosphere and models are required to represent the exchanges of CO_2 between these reservoirs. It turns out that our confidence in existing models of the carbon cycle is considerably less now than it was 10 years ago. But nevertheless, the working group concluded that reasonable predictions of the level of atmospheric CO_2 concentration can be made for a period of 20-30 years using the existing models. The major uncertainty in these predictions is not in the role of the oceans but in the magnitude and direction of the net fluxes between the biosphere and atmosphere. The working group considered data indicating apparent insignificance of forest fires and a number of changing land-use practices as sources of CO_2 but found further support for the idea that *tropical forest clearing is a significant source of* CO_2. However, it was felt that if there has indeed been a net global deforestation this has in part been *compensated by regrowth patterns* in areas cut over past decades.

The second working group addressed the impact of increasing atmospheric CO_2 concentrations on climate and environment. A large part of the discussion centered on the use of models of the climate system to study the effect of doubling the CO_2 concentration. A variety of one-dimensional, globally averaged models have been used and the group considered that this kind of calculation has been refined to the point that, accepting a 25% uncertainty, a doubling of CO_2 concentration gives a 2-3°C surface temperature increase, depending on how clouds are treated in the models. However these figures are calculated under carefully specified constraints on the behavior of the rest of the climate system. The group therefore also considered the use of expensive (time and money consuming) general circulation models, which simulate the three-dimensional atmospheric circulation and consider more of the feedbacks in the climate system. These models still have shortcomings, since, for example, they do not consider the coupling of the atmospheric and oceanic circulation. But, as the group pointed out, statements about global average temperature trends are of little value to planners and policy makers, who need to know what the *regional* changes in seasonal temperature and *rainfall* are going to be.

At the moment the complex models are not sufficiently developed to reliably answer these questions, but it can be stated that some of the regional changes will be much greater than the global average and that they will be both positive and negative with regard to temperature and precipitation. Model results already suggest that there will be more rainfall, because the warmer atmosphere causes more evaporation from the oceans, and this increase will show up in areas affected by monsoonal circulations and some midlatitude regions. *But* there will probably be places where rainfall decreases because of altered large-scale circulation patterns. Since our present socio-economic system is tuned to present climatic conditions, large-scale climatic changes, especially those affecting the production of food, can be expected to have many repercussions.

The third working group considered the implications for energy policy decision-making of the CO_2-climate questions. *It was judged that mankind needs and can afford a time window of between 5 and 10 years for vigorous research and planning to narrow the uncertainties found in almost every aspect of the CO_2 issue sufficiently to justify a major change to energy policies which can be more responsive to the CO_2 problem than one which allows the continued reliance on abundant and inexpensive fossil fuels.*

The group discussion centered on the question: What are the tolerable rates of burning fossil fuel? It is clear that to maintain a rate of fossil fuel use at or below a certain "tolerable" level, while maintaining hope within the impoverished masses of the world, will require extremely careful planning and the ability to deploy inexhaustible energy sources effectively. The aspirations and energy requirements of the developing world will play a major role in determining the rates of fossil fuel use on a global scale.

In considering the above question the working group derived five policy statements, which together reflect the importance of flexibility in determination of energy policies.

- Quantitative estimates of the rates of increase of atmospheric CO_2 concentration and of other molecules which absorb long-wave radiation and of the resulting global and regional climatic changes are not only uncertain but are likely to remain so for most of the next decade. *It is therefore premature to implement at this time policy measures which require reduction in the use of coal* and other fossil fuels. Present knowledge is sufficient to require detailed study of alternative energy supply systems but does not yet warrant a policy of curtailment of fossil fuel use.

- On the other hand, *policies which emphasize the use of coal, because of its great abundance, in preference to non-CO_2-producing energy supply systems are equally unjustified.* Such policy decisions can become difficult and very costly to reverse. Emphasis on coal at the expense of either hard or soft solar, nuclear (including the breeder), nuclear and/or solar-methanol systems appears to be unreasonable in view of the possible CO_2 consequences. *The maintenance of great flexibility in energy supply policies at this time is necessary.*

- *Environmental impact assessments of escalating energy use must be performed* with greater depth than in the past and on a scale commensurate with the potential importance of the problem.

- It would be highly desirable *to devise energy supply systems that allow ready environmental amelioration.* This concept requires that energy systems are non-polluting (or very nearly so) or that undesirable effects are easily mitigated (at acceptable cost and energy expenditure).

  Non-polluting systems include (1) a solar or hydroelectric hydrogen economy, (2) the IIASA 35 TW Scenario fueled largely by synthetic methanol manufactured at large energy parks with nuclear or hard solar energy supply, or (3) a very highly decentralized solar energy supply system, which, however, is unlikely to provide sufficient energy to maintain the global economy at a satisfactory level.

Systems which allow easy mitigation include those employing *short-time recycling of carbon through the atmosphere.* Biomass as fuel with prompt and rapid regrowth is one example. Stripping CO_2 from exhaust stack systems and even from the atmosphere itself is technically feasible and the manufacture of synthetic methane or methanol (as in the IIASA scenario) from the carbon thus obtained would be an effective "short recycling time system". It is also possible to "store" CO_2 in the living biomass by planting more trees, or in the deep oceans by locating and using areas of sinking ocean waters or in old oil and gas wells. These techniques may prove costly in either money or time, but quantitative tradeoffs may prove either favorable or necessary. Another possibility is in the area of climate modification or control, e.g. controlled modification of the albedo.

- *No less important than efforts to maintain an appropriate energy supply are those to reduce energy demands.* With carefully developed procedures, energy demands can be reduced on a global scale without causing unacceptable changes in the global economic well-being.

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3. WASTE HEAT

3.1. Introduction

Fossil fuel, nuclear and some (proposed) solar energy conversion power plants release heat because the energy conversion efficiencies are less than 100% (typically close to 30% for electric power plants). In addition, as it is used, virtually 100% of the energy finally ends up as a heat addition to the environment. This chapter describes the findings of the project on the impact of waste heat on climate.

The usual starting point for any discussion of waste heat has been a discussion of natural energy densities, that is, the amount of heat or energy in the climate system, as a point of comparison with man-made energy densities.

The incoming solar radiation amounts to $\sim 1360\ Wm^{-2}$. Taking into account the fact that the solar energy intercepted by the earth's disk is spread rapidly (by a rotating earth) over the entire earth's surface (which has four times the area of the earth's disk), it can be calculated that the global average solar irradiation is $\sim 340\ Wm^{-2}$ and the global average solar energy absorbed by the earth's suface is $\sim 160\ Wm^{-2}$.

Kellogg (1977) estimates that on a global basis the total amount of heat released by all of mankind's activities is roughly 0.01% of the solar energy absorbed at the surface. Such a small fraction must have a negligible effect on the total heat balance of the earth. Taking an extreme projection of a population of 20 billion with a per capita energy requirement of 40 kW, the total rate of heat release would be about 1% of the solar energy absorbed at the earth's surface. Global energy balance climate models suggest that a 1% increase in the heat available to the system would increase the mean surface temperature by $2^{0}C$ (although it has been suggested that this could be in error by a factor of 2 because of uncertainties in the models).

However, the use of the global average conditions is misleading since the atmospheric and oceanic circulations are driven by *differential* heating of the globe, primarily in latitude zones although there are also longitudinal differences because of the continent/ocean distribution and thermal-orographic effects. Heat release from mankind's activities will not be evenly distributed over the earth's surface but will be concentrated in certain areas. The impact of the heat release could occur on a local scale if the energy density is comparable with natural energy densities, but also on a global scale if it is large enough to influence the temperature gradients, which drive atmospheric and oceanic motions.

3.2. The Impact of Power Plants on Local Climate

As pointed out by Moore (1976), there are three choices for heat ejection from power plants: heat release to the earth's surface, referred to as once-through cooling using lake, river or ocean water; evaporative release, using wet cooling towers; sensible heat release, using dry cooling. The climatic factors likely to be affected by waste heat release from power plants are: the surface temperature, which could increase above ambient; cloudiness, which could increase; and precipitation, which could also increase. The effect of waste heat depends on the climatic character of the region in which the waste heat release occurs.

Koenig and Bhumralkar (1974) have listed potential problems associated with power plant cooling towers as:

- Restriction of sunlight caused by visible plume;
- Deposition of detrimental chemicals in cooling waters onto surrounding areas;
- Restriction of visibility by visible plumes reaching the ground (fogging);
- Increase or change in the spatial and temporal pattern of precipitation;
- Initiation of severe weather such as tornadoes and thunderstorms.

The first three effects have been extensively investigated and are basically local meteorological effects on the scale of the power plants themselves. The fifth problem is addressed in the next section.

Table 3.1 lists observed atmospheric effects of power plants as compiled by Hanna (1978). With regard to the impact on precipitation, there are some reports of observed precipitation enhancement. Kramer et al. (1976) report that during the winter of 1975-76 snowfall was observed from plumes of large natural draft cooling towers. Similarly snowfalls downwind of cooling towers have been reported by Culkowski (1962) and Ott (1976). On the other hand, Martin (1974) reports a study of local weather records near a 2000 MWe power station with eight natural draft cooling towers. For the four years of operation of the power station, it was concluded that emissions had not affected the values of total rainfall, hours of bright sunshine, or incidence of morning fog recorded by stations at distances of 4 km or more from the power plant. Landsberg (1977) suggests that the difference in precipitation due to emissions from present day power plants is small enough that it can be found to be significant only during special case studies of short time and space scale.

Table 3.1. Observations of Atmospheric Effects of Power Production Facilities

Effect	Source	Time Scale	Space Scale
$1-5^{\circ}$ Surface temperature increase	St. Louis urban area	Seasonal	50 km
10-30% Precip. increase	St. Louis urban area	Seasonal	100 km
10 cm Snowfall	Amos Power Plant Charleston, W. Va.	Few hours	50 km
1 cm Snowfall	Gaseous Diffusion Plant Oak Ridge, In.	Few hours	10 km
0 Rain	Power Plants in England & Oak Ridge Gaseous Diffusion Plant	Monthly & Annual Average	100 km
40% Increase in ground fog	Oak Ridge Gaseous Diffusion Plant	Case studies over several seasons	1 km
Salt drift deposition equal to that within 1 km of the area	Chalk Point Power Plant	Few hours	1 km
Chromate drift deposition not sufficient to harm plants	Oak Ridge Gaseous Diffusion Plant	Few days	1 km
Small to medium stratus or cumulus clouds	Any large power plant	Few hours to a few days	1-10 km
Small whirlwinds	Keystone Power Plant & Dresden Power Plant	Few minutes	100 km
Slight cloud & precip. increases due to pollutants	Kraft Paper Mill, Wash.	Few hours	100 km
	LaPorte, Ind.	Annual average	100 km

Weber (1978) describes a study of the impact of a nuclear power plant with a once-through cooling system and one with mechanical draft cooling towers on the average air temperature in the vicinity of the plants. The latter produce 1100 MWe and 700 MWe repsectively. It is concluded that on the basis of the data available and the analyses made so far there has been no detectable average increase in temperature at meteorological stations near either of the power plants.

Hanna and Gifford (1975) point out that the maximum amount of electric power currently generated at a single power station is about 3000 MWe. As shown by the brief review above and discussed by Hanna and Gifford (op. cit.), the atmospheric effects of current heat dissipation rates are not serious problems, especially beyond the scale of the power station, provided that efforts are made to design the facility such that downwash is eliminated, drift is minimized and plume rise is maximized. It is found that fog formation and drift deposition are generally localized and that although clouds are observed, no significant changes in rainfall in areas of study have been detected. However, concern has been expressed over the possible climate impact of "power parks", releasing much more heat than present power plants and this problem is discussed in the next section.

3.3. The Impact of Power Parks on Local and Regional Climate

Several recent studies have addressed the impact of proposed 10,000-50,000 MW power parks on climate (Rotty, 1974; Rotty et al., 1976; Hanna and Gifford, 1975; Koenig and Bhumralkar, 1974; Bhumralkar and Alich, 1976). The effects of such large releases of heat can be assessed by analogy with effects of comparable sources of heat and moisture, such as islands heated by solar radiation, urban-industrial complexes, forest fires and phenomena such as volcanoes. Model studies are also reported. Table 3.2, from Hosler and Landsberg (1977) compares estimates of man-made and natural energy releases. It appears that a 20,000 MW power park might produce effects of the same magnitude as St. Louis, Chicago or the island of Aruba. Also, the energy release from such a power park is of the same order of magnitude as some "mesoscale" atmospheric phenomena.

Koenig and Bhumralkar (1974) found from model experiments that a 36,000 MWe power plant proposed for Louisiana would cause perturbations to the temperature and moisture field (3-4^{0}C rise over 6 km, 1-2 g/kg increase of water vapor mixing ratio) large enough to initiate convection (and, therefore, cloudiness and rainfall). Koenig and Bhumralkar also concluded that the downwind modification of the cloudiness and rainfall would be more consistent and visible in the case of an energy park than for an urban heat island. Bhumralkar and Alich (1976) have also modeled the effects of waste heat from a proposed 36,000 MWe power park and found that significant weather modification could occur. Hosler and Landsberg (1977) describe some model results of Deaven which show the effects of a 20,000 MWe power park. Hosler and Landsberg (op. cit.) suggest

Table 3.2. Comparison of man-made and natural energy releases

Heat Source	Area (sq. km)	Approximate MW Equivalent Input to the Atmosphere
St. Louis	250	16,100
Chicago	1,800	52,700
Aruba	180	35,000
One-megaton nuclear device (heat dissipated over 1 hour)		1,000,000
20,000-MW power park	26	40,000
Cyclone (1 cm of rain/day)	10×10^5	100,000,000
Tornado (kinetic energy)	10×10^{-4}	100
Thunderstorn (1 cm of rain/30 min)	100	100,000
Great Lakes snow squall (4 cm of snow/hour)	10,000	10,000,000

that a three-dimensional process of the magnitude indicated in the two-dimensional model results would give formation of a vortex flow and that inclusion of moisture effects would result in additional instability.

Hanna and Gifford (1975) indicate that the heat release from an energy park could act as a thunderstorm "triggering" mechanism, especially in areas where thunderstorms are naturally frequent; the parks could also cause development of large clouds and whirlwind activity and increase precipitation in frontal systems. As pointed out by Hanna (1978) a potential problem is the concentration of vorticity by large buoyant plumes. Hanna reports that at currently operating power stations visible vortices have occasionally been observed, for example a small whirlwind associated with the cooling tower plume at the Keystone, Pennsylvania plant is reported. Everett and Zerbe (1977), are referred to by Hanna (1978) as having observed small waterspouts occasionally over the Dresden cooling pond. Vortices are also reported from other experiments and over large wildfires and it is suggested that as the output from power plants exceeds 10,000 MWe the incidence of whirlwinds can be expected to increase, because they are more prevalent when the magnitude and area of the buoyant source increase.

The results of model and analogue studies and comparisons with natural phenomena suggest that the principal effects of the release of large amounts of waste heat from power parks would, on the local and regional scale, be significant changes in cloudiness and precipitation with an increase in the probability of severe weather.

3.4. Impact of Waste Heat on Global Climate

This section considers the possible impact of large amounts of waste heat release (from the large-scale deployment of any of the energy conversion systems) on climate. The study was made possible through an agreement reached between the Meteorological Office (Bracknell, U.K.) and IIASA to use the Meteorological Office general circulation model in a series of experiments, to investigate the impact of waste heat on the simulated atmospheric circulation.

The impact of waste heat on simulated atmospheric circulation has previously been studied by Washington (1971, 1972) and Llewellyn and Washington (1977). Washington (1971) investigated the response of the National Center for Atmospheric Research (NCAR) general circulation model (GCM) to the addition of 24 Wm^{-2} over all continental and ice regions. There was, on the average, a 1-2 K increase in surface temperature with an 8 K increase over Siberia and northern Canada.

Washington (1972) considered a per capita energy usage of 15 kW, a population of 20 billion, and a heat input distributed according to present-day population density. It was concluded, however, that the thermal pollution effects were no greater than the inherent noise level of the model.

Penner (1976) has used the Budyko (1969) global energy balance equation to investigate the effect on global surface temperature of a world population of 10 billion with a per capita energy consumption of 20 kW. Penner found a mean global temperature rise of 0.27 K (0.44 K between 15^0N and 60^0N). With an energy consumption of 5 kW per capita for the same population, the computed temperature rise between 15^0N and 60^0N was 0.11 K.

3.4.1. The experiments

The model. The Meteorological Office general circulation model has been described by Corby et al. (1972). It has five levels in the vertical, equally spaced in terms of the vertical coordinate σ (pressure (p)/surface pressure (p_*)). The horizontal resolution is 3^0 in the latitudinal direction and the spacing of the grid points along lines of latitude gives approximately the same resolution in the longitudinal direction. The version of the model used in this study includes only the northern hemisphere. Prescribed conditions include the earth's orography, the solar heating rates, sea-surface temperature and ice cover. The temperatures of the land surface are computed from a surface heat balance equation, assuming a heat capacity for the land. A simplified hydrological cycle is considered, in which condensation is assumed to occur when the relative humidity of the air exceeds 100%. The effects of small-scale convective motions are parameterized.

Each experiment was run for 80 simulated days with prescribed conditions maintained at their January climatological values. The results for the last 40 days were taken for analysis. Three control integrations were available in the Meteorological Office for estimating the model's January climatology and its inherent variability. The control integrations are described in more detail by Rowntree (1976), who designates them C3, C4 and C6.

Scenarios of the experiments. The GCM experiments were designed to study the impact of ocean energy parks on simulated climate. The concept of large-scale energy parks determined the scenarios selected. As illustrated in Figure 3.1, three parks, each designated by a letter, have been used. The heat inputs and combination of parks in the five GCM experiments are listed in Table 3.3.

Table 3.3. The combination of energy parks and heat input in five GCM sensitivity experiments

EX	Energy Parks	Heat Input	Remarks
01	A & C	1.5×10^{14} W at each park	Total heat input 3×10^{14} W
02	B & C	1.5×10^{14} W at each park	Total heat input 3×10^{14} W
03	A only	1.5×10^{14} W	Total heat input 1.5×10^{14} W
04	A & C	$.75 \times 10^{14}$ W at each park	Total heat input 1.5×10^{14} W
05	A & C	1.5×10^{14} W at each park	Heat added to "ocean box" below each park rather than directly to atmosphere

The energy parks cannot be simulated realistically because the area involved is too small to be properly represented within the grid structure of the model. Also, a realistic scenario would include the spread of heat by ocean currents and, therefore, require a linked atmosphere-ocean model. The area of each park was made equal to that of four grid boxes (i.e., 4.4×10^5 km^2), this being the smallest area that seemed likely to produce acceptable results. This representation is an approximation which, it was hoped, would retain the essential features of the meteorological problem.

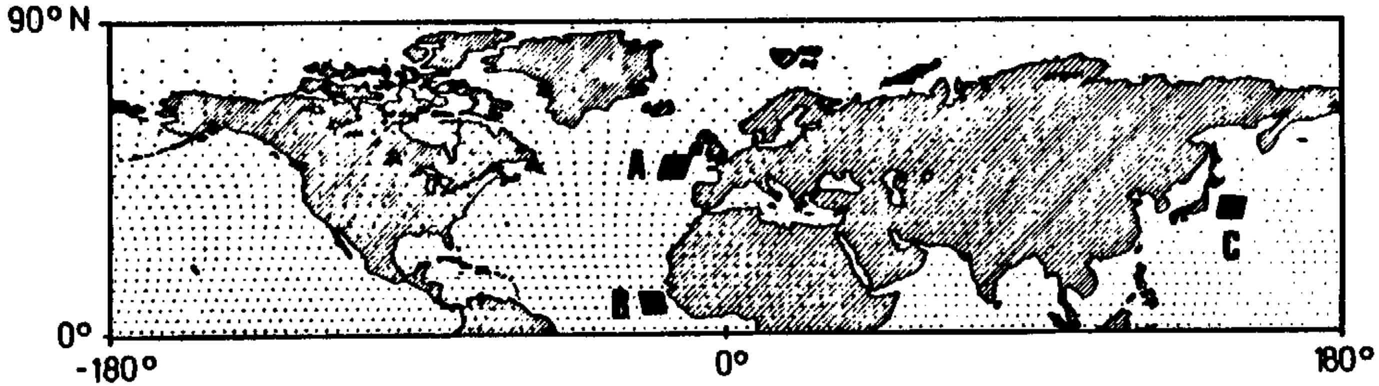


Figure 3.1. Location of the three energy parks, designating each park by a letter:

A	49.5°N,	12.0-16.5°W;	46.5°N,	14.0-18.5°W
B	10.5°N,	21.0-24.0°W;	7.5°N,	20.5-23.5°W
C	37.5°N,	146.0-150.0°E;	34.5°N,	145.5-149.5°E

In experiments EX01 to EX04, the waste heat was inserted directly into the atmosphere in sensible heat form by adding 375 Wm^{-2} (187.5 Wm^{-2} in EX04) to the sensible heat exchange between the air and the earth's surface at the four grid points. In EX05, an "ocean box" of 10 m depth was considered below the two energy parks; the surface temperature, constant in EX01-EX04 and the control cases, was computed from the same energy balance formulation as for land points, but assuming an effective heat capacity of 4.18×10^7 Jm^{-2} K^{-1}. In EX05, therfore, the added heat was released to the atmosphere in both sensible and latent forms.

3.4.2. Results

Estimation of inherent variability of the model. An important aspect of the analysis of the results of GCM prescribed change (sensitivity) experiments is to determine how much of the difference from control integrations is due to the prescribed change and how much is a result of the model's inherent variability. Chervin et al. (1976) used a significance test based on Student's t-statistic. Although, as pointed out by Laurmann and Gates (1977), this method does not address a number of important statistical questions, it has been used in this study. Recognizing problems in the purely statistical approach, however, emphasis has been placed here on studying the similarities among experiments that have common features. That is, the results of successive experiments after the first have been examined with an *a priori* expectation of certain responses which are physically realistic. The evidence of consistent responses in accordance with the a priori expectation is strong evidence of their reality and lessens the need for dependence on a purely statistical analysis.

The inherent variability of the Meteorological Office GCM was estimated by computing the standard deviations of 40-day means, S_{40}, from the three control cases that were available. The statistical significance of the results may then be judged from

$$r = \frac{|\Delta|}{S_{40}} ,$$

where Δ is the difference at a grid point between the 40-day mean of a meteorological variable in a prescribed change experiment and the average of the three control experiments. r has a Student's t-distribution. Values of r greater than 5.0 are statistically significant at the 5% level. That is, if r is greater than 5.0 at an individual grid point, there is a 95% chance that the difference is significant and caused by the prescribed change.

Sensible and latent heating at energy parks. Figure 3.2a shows the sensible heat input to the atmosphere at the mid-latitude Atlantic park (park A in Figure 3.1) and at surrounding points in each of the energy park experiments. No waste heat was added at this park in EX02. In EX01, EX03 and EX04, the total heat input differs only slightly from the amount of waste heat; the heat was inserted in an area where the atmosphere is normally stable and, therefore, where heat exchange values are small in the control integrations. By contrast, in EX05, the sensible heat input is less than half of the waste heat input. However, as shown in Table 3.4, the latent heat flux from the surface is greater in EX05 than in the other experiments at park A. In addition, as discussed in detail later, a marked increase of precipitation directly over the energy parks in EX05 implied the release of an additional average 83 Wm^{-2} of sensible heat at park A (as compared with the control cases). In EX01-EX04, there is no large increase in precipitation over park A and thus no additional sensible heat input. Figure 3.2b shows the difference in sensible heat input from the average of the control integrations in the vicinity of park A. Local changes in the meteorological variables have tended to offset the waste heat input by reducing the sensible heat exchanged at the surface, but the magnitude of this effect is not more than about 15%.

Table 3.4 **Latent heat flux at energy parks ($W\ m^{-2}$) 40-day means averaged for four grid points of each energy park**

Experiment	Park A	Park B	Park C
Average of controls (C)	116	160	170
EX01-C	-62	-5	+136
EX02-C	+3	-90	-48
EX03-C	-25	-11	-21
EX04-C	-9	+1	-3
EX05-C	+235	+2	+240

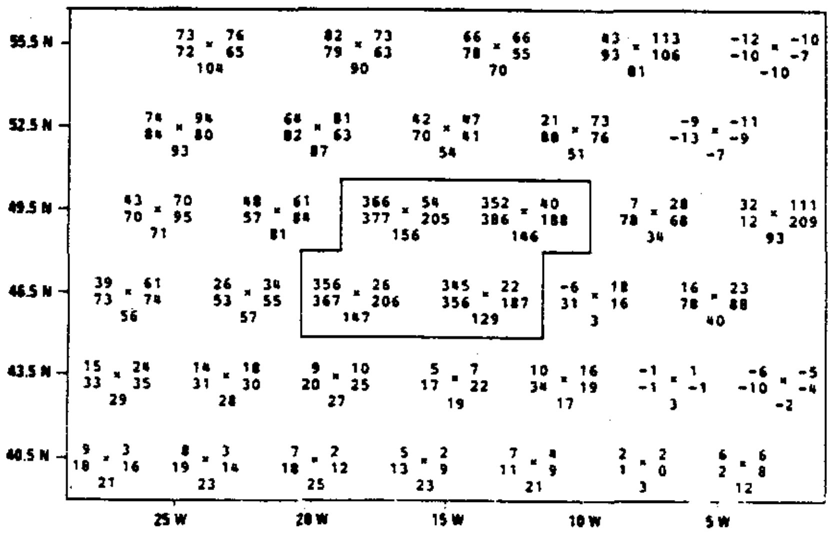


Figure 3.2a. Sensible heat values (in Wm^{-2}) in the vicinity of the midlatitude Atlantic energy park (park A). Averages for days 41-80. Values in the top line at each grid point are for EX01 (left) and EX02 (right). Values in second line at each grid point are for EX03 (left) and EX04 (right). Values below are for EX05.

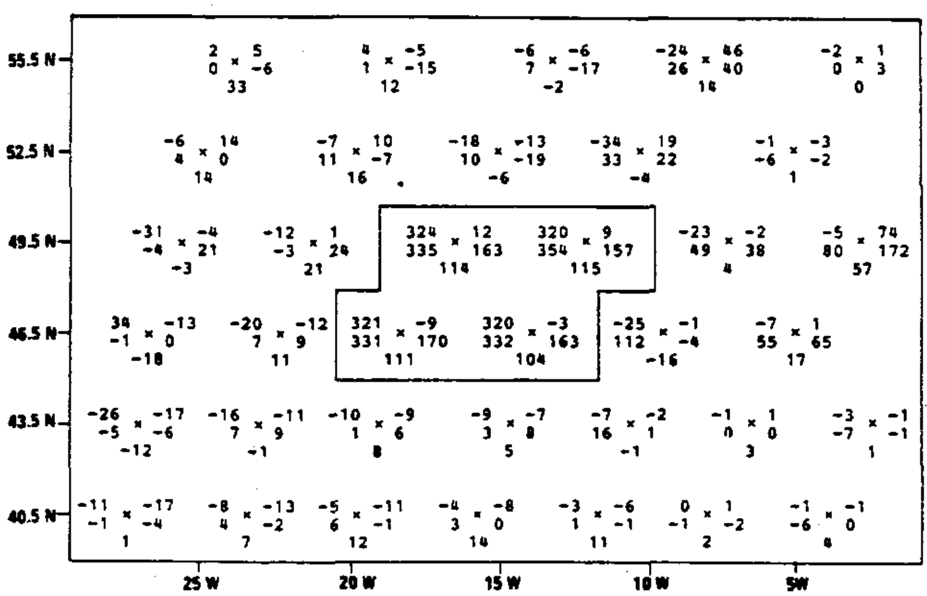


Figure 3.2b. As in Figure 3.2a but for *differences* between energy parks experiments and average of control cases.

The total sensible heat flux and differences from the control cases for the Pacific energy park (C) are given in Figures 3.3a and 3.3b. The total input is greater than the waste heat input in most cases, due to a positive contribution from surface exchanges at the park. In the vicinity of the park there are large sensible heat fluxes due to the cold air flowing off the Asian continent over the relatively warm ocean. Figure 3.3b shows that there are considerable differences among the experiments at park C. In EX01, the total heat input is larger than the waste heat input at all four grid points, while in EX02 it is less. In EX04, the sensible heat input is greater than the waste heat input, but not by as large a margin as in EX01. In EX05, the total sensible heat input varied substantially among the grid points, but on the average it is about the same as in EX04; i.e., less than half of the waste heat input. As for park A, however, the latent heat flux in EX05 from the surface is also increased at park C, and a precipitation increase directly over the energy park adds a further 26-133 Wm^{-2} (averaging 81 Wm^{-2}) to the atmosphere.

Table 3.4 shows the differences between the latent heat flux in the energy parks experiments and the average of the control cases averaged for each energy park. In EX05, the latent heat flux at parks A and C increased by about 240 Wm^{-2}. That is, during days 41-80 of EX05, 375 Wm^{-2} were added to the ocean box beneath each energy park, the latent heat flux at the surface was about 351 Wm^{-2} (park A) and 411 Wm^{-2} (park C), while the sensible heat flux was about 145 Wm^{-2} (park A) and 210 Wm^{-2} (park C). Over both parks (and generally not over the surrounding grid points), however, the precipitation increased and thus much of the latent heat was converted directly to sensible heat input to the atmosphere. At both park A and park C the average sensible heat release due to condensation over the energy park is 171 Wm^{-2} (40-day mean).

Table 3.4 shows a major difference between the response of EX01 and that of EX02 and EX04 at the Pacific energy park. In EX01, in addition to the enhancement of the sensible heat flux at park C, there was an enhancement of the latent heat flux which did not occur at any of the other energy parks in the experiments without an ocean box. Unlike EX05, however, the latent heat flux at park C in EX01 was not converted immediately to sensible heat by condensation; the precipitation increase was downstream where the sensible heat input was about 50 Wm^{-2} greater than in the control cases, as a result of increased precipitation. This heat input possibly contributed to maintaining the sea level pressure decrease downstream of park C.

Suface temperature changes at energy parks in EX05. As described in Section 3.4.1 in EX05, 375 Wm^{-2} were added at the four grid points of the two energy parks (A and C) to an ocean box. Figure 3.4 shows the surface temperature, latent heat and sensible heat fluxes for the average of the four grid points at each park for each of days 41-80.

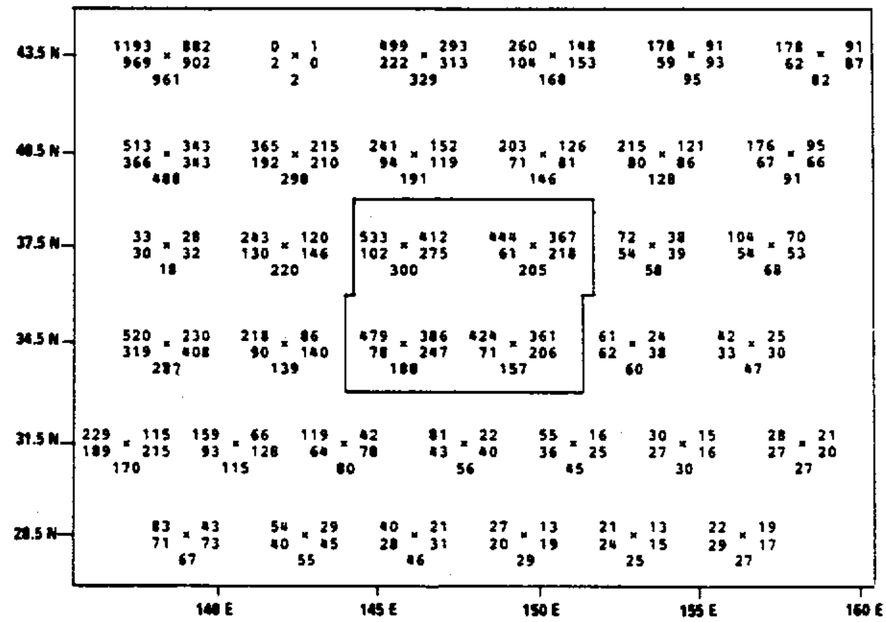


Figure 3.3a. As in Figure 3.2a but for midlatitude Pacific energy park (park C)

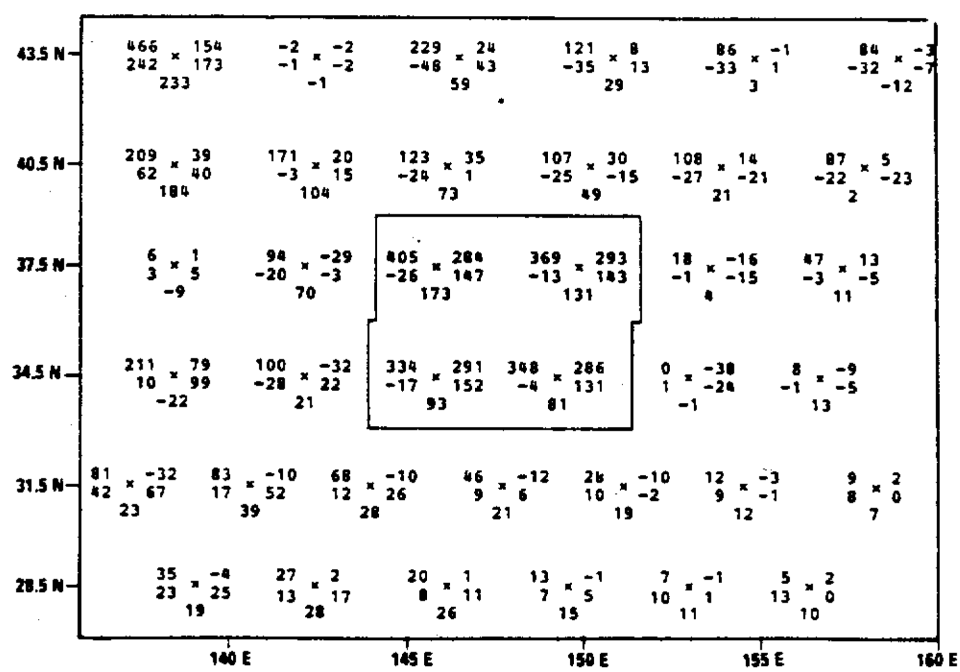


Figure 3.3b. As in Figure 3.2b but for midlatitude Pacific energy park (park C)

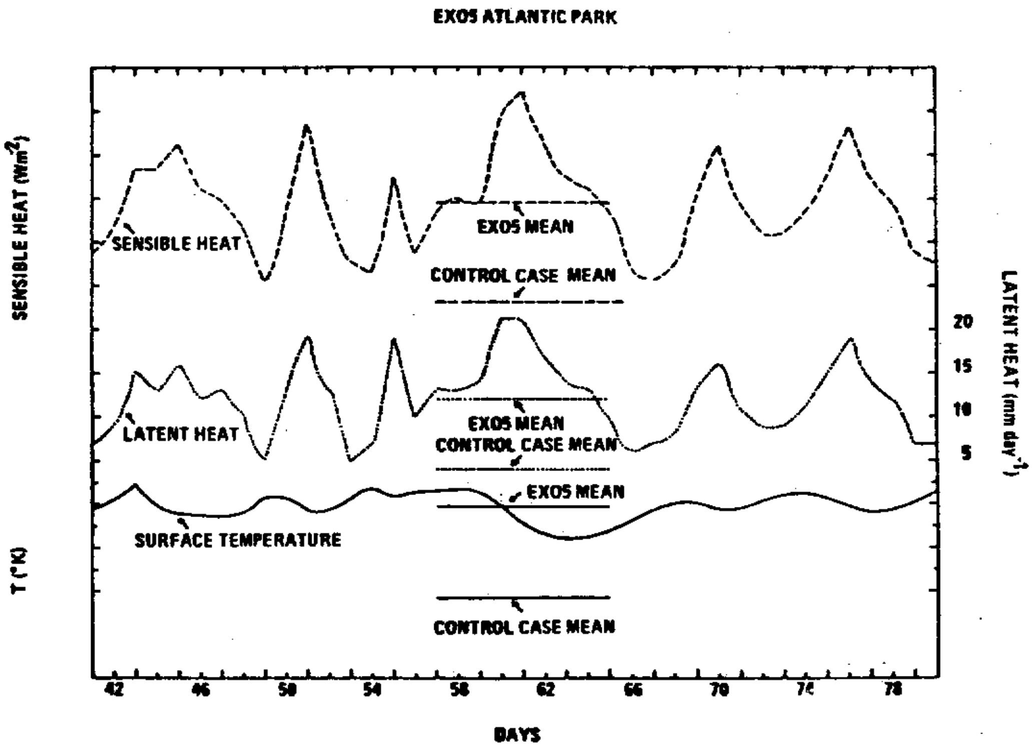


Figure 3.4a. Sea-surface temperature (K), latent heat flux (Wm^{-2}), and sensible heat flux (Wm^{-2}) for the average of the four grid points in park A for each of days 41-80 in EX05. 40-day mean values for EX05 and the average of the control cases are also shown.

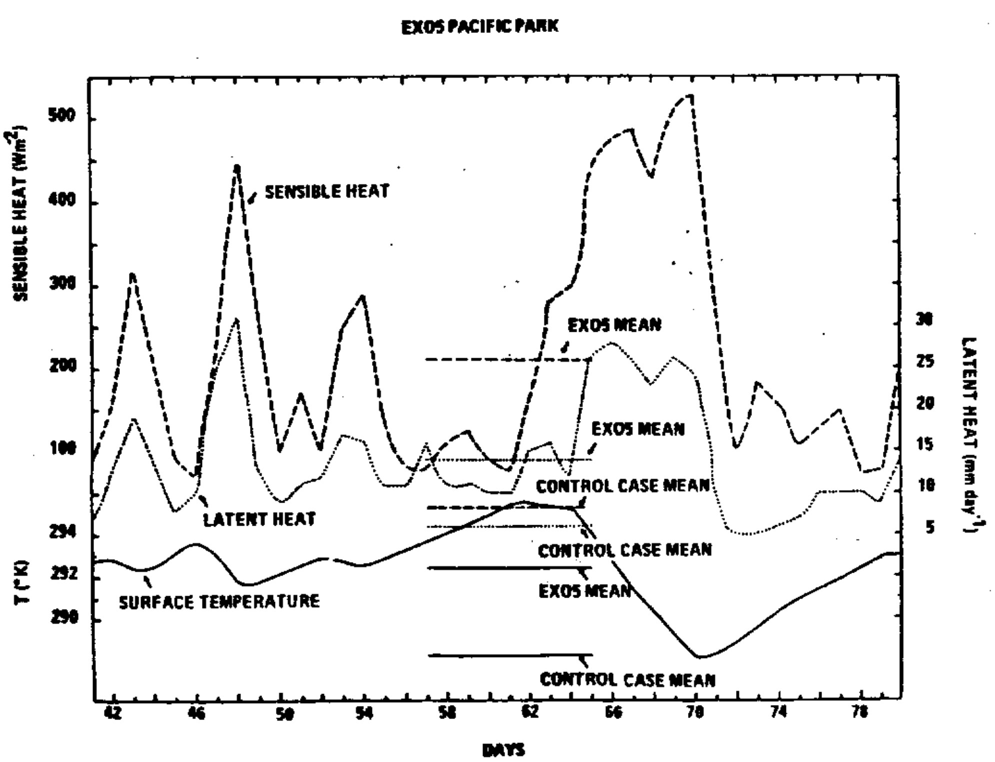


Figure 3.4b. As in Figure 3.4a but for park C.

At park A, the sea surface temperature is about 4 K higher than in the control cases and the sensible and latent heat fluxes from the surface increased. The largest variations from mean values of these variables occur between days 58 and 66. Examination of the u and v components of the wind shows that the cooling of the sea surface temperature between days 58 and 66 and associated increase in sensible and latent heat flux from the surface occurred when the surface wind flow became northerly, in contrast to the southerly flow before this period.

At park C, the fluctuations around the means are much larger. The sea surface temperature again is increased about 4 K compared with the control cases. The large increases in the sensible and latent heat fluxes from the surface and consequent lowering of the sea surface temperature between days 60 and 70 is a result of a change of the surface wind flow from easterly (off the Pacific) before the period to westerly (off the continent).

At both energy parks, therefore, the sea surface temperature in EX05 increased by about 4 K on the average. Figure 3.4 shows that there were no apparent long-term trends in the sea surface temperature, but that the temperature fluctuated depending on the direction of flow of the surface wind. Thus, when the SST at park C was about 7 K higher than the average in the control cases (day 62), an atmospheric circulation pattern was established which caused it to cool down to the control case mean value.

Longitudinal differences in sea level pressure and 500 mb height. Figures 3.5-3.8 show the longitudinal distributions of differences in sea level pressure and 500 mb height between the control cases and the energy parks experiments. The differences are averaged for two lines of latitude in each figure.

For the lines of latitude which pass through park A (Figure 3.6), it is seen that there is a fairly consistent response to the heat input at park A in all of the experiments. In the Atlantic-European sector, in EX01, EX03, EX04 and EX05, there is a relative ridge in the 500 mb height and sea level pressure at 30-50^{0}W and a relative trough at 10-30^{0}E. These features can also be seen further north (Figure 3.5) and further south (Figure 3.7) for EX01, EX03 and EX05. Mostly there is evidence of a westward shift with height of the relative ridge and trough.

Figure 3.6 shows also that, in the vicinity of park A, the response in EX01 and EX03 (where the heat input was 375 Wm^{-2}) was greater than in EX04 (heat input of 187.5 Wm^{-2}). Moreover, the response in the experiments with the larger heat input extends further to the north and south. These points tend to confirm that the relative trough and ridge are a significant response and not merely random variations of the model. The results of EX05 are unexpected, however, in that, although the sensible heat input is much less than in EX01, the amplitude of

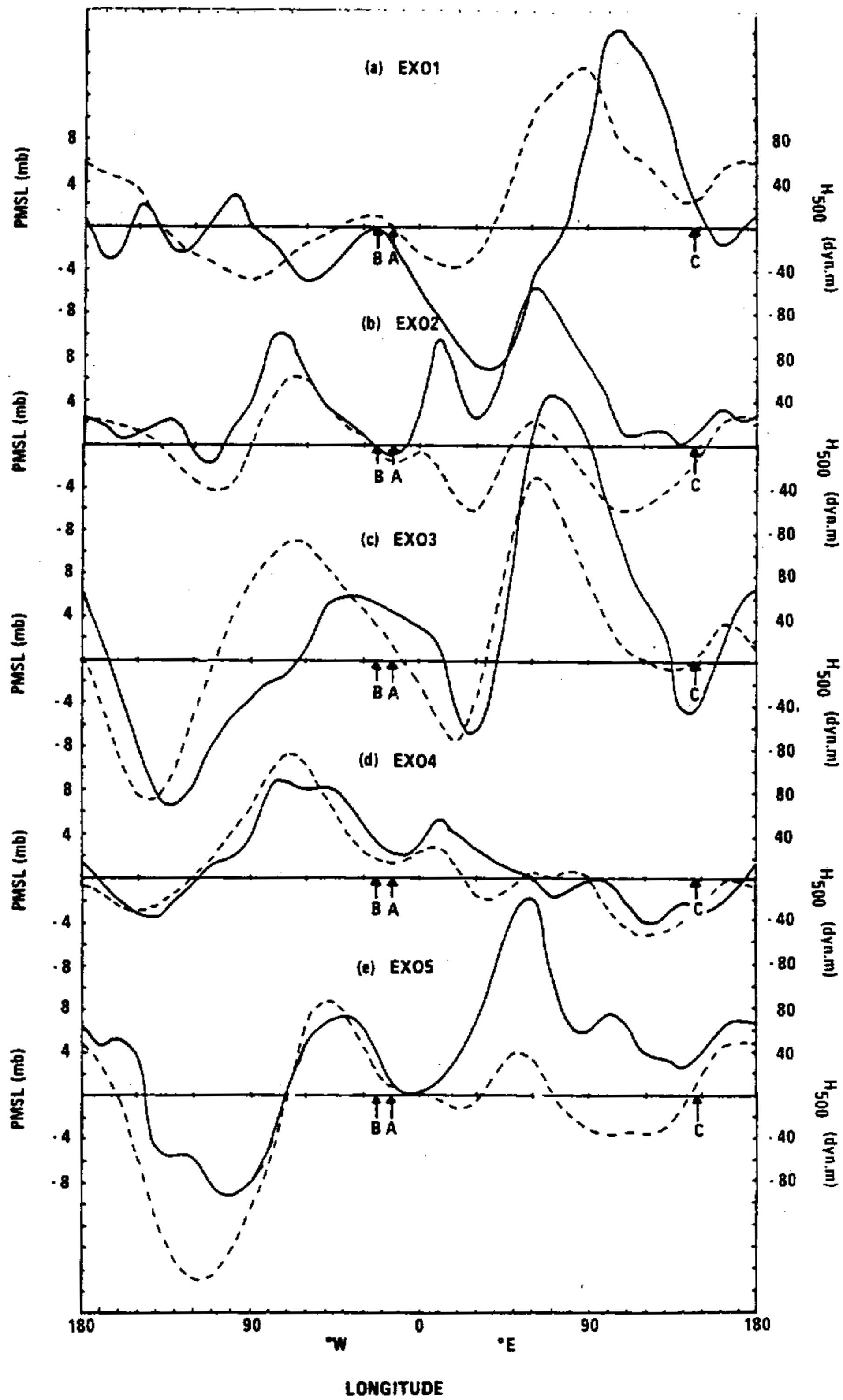


Figure 3.5. Longitudinal distribution of differences in sea-level pressure and the height of the 500 mb surface between the energy parks experiments and the average of the control cases. Values are averages of days 41-80 and for 61.5°N and 58.5°N.

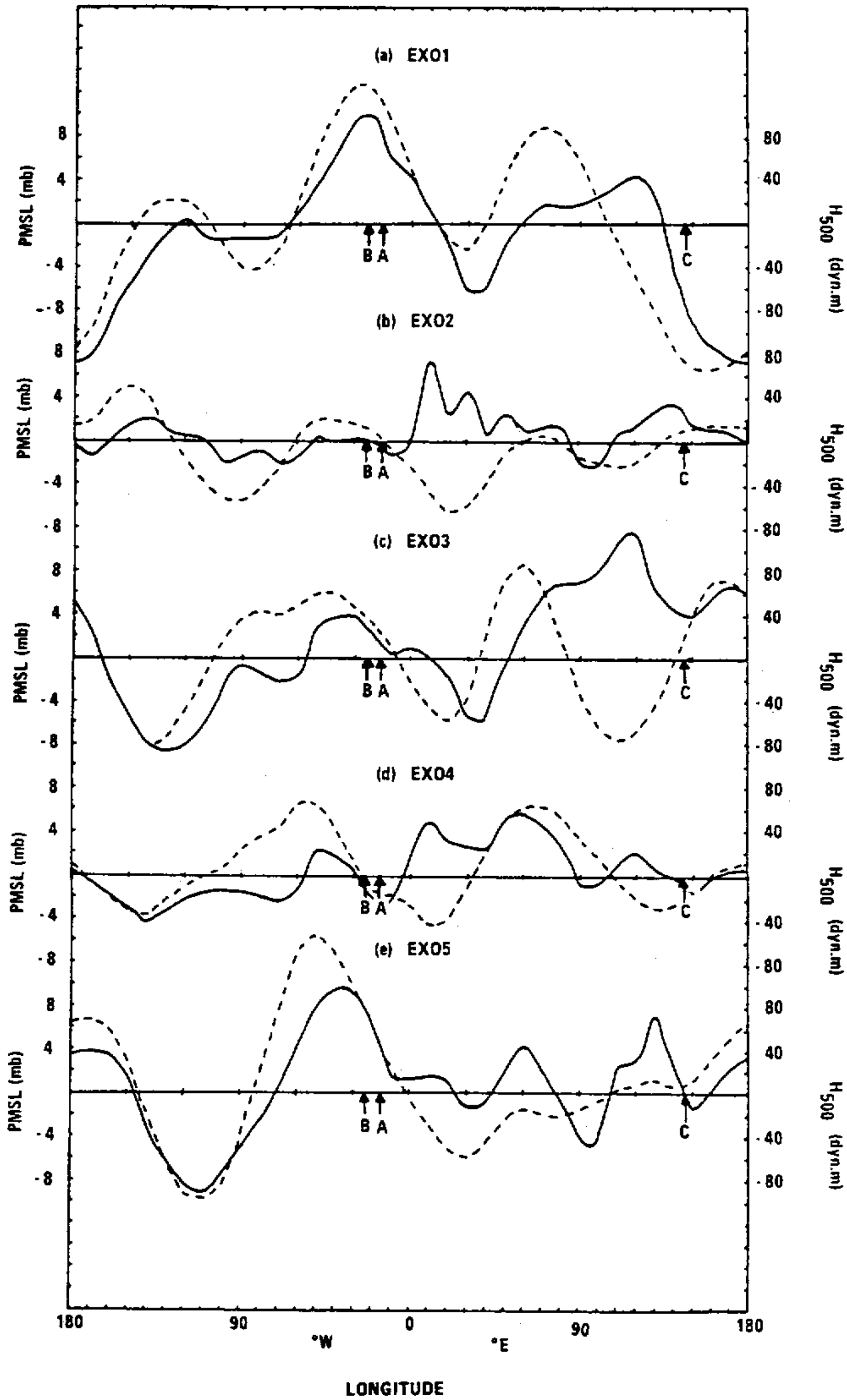


Figure 3.6. As in Figure 3.5 but averages of 49.5°N and 46.5°N.

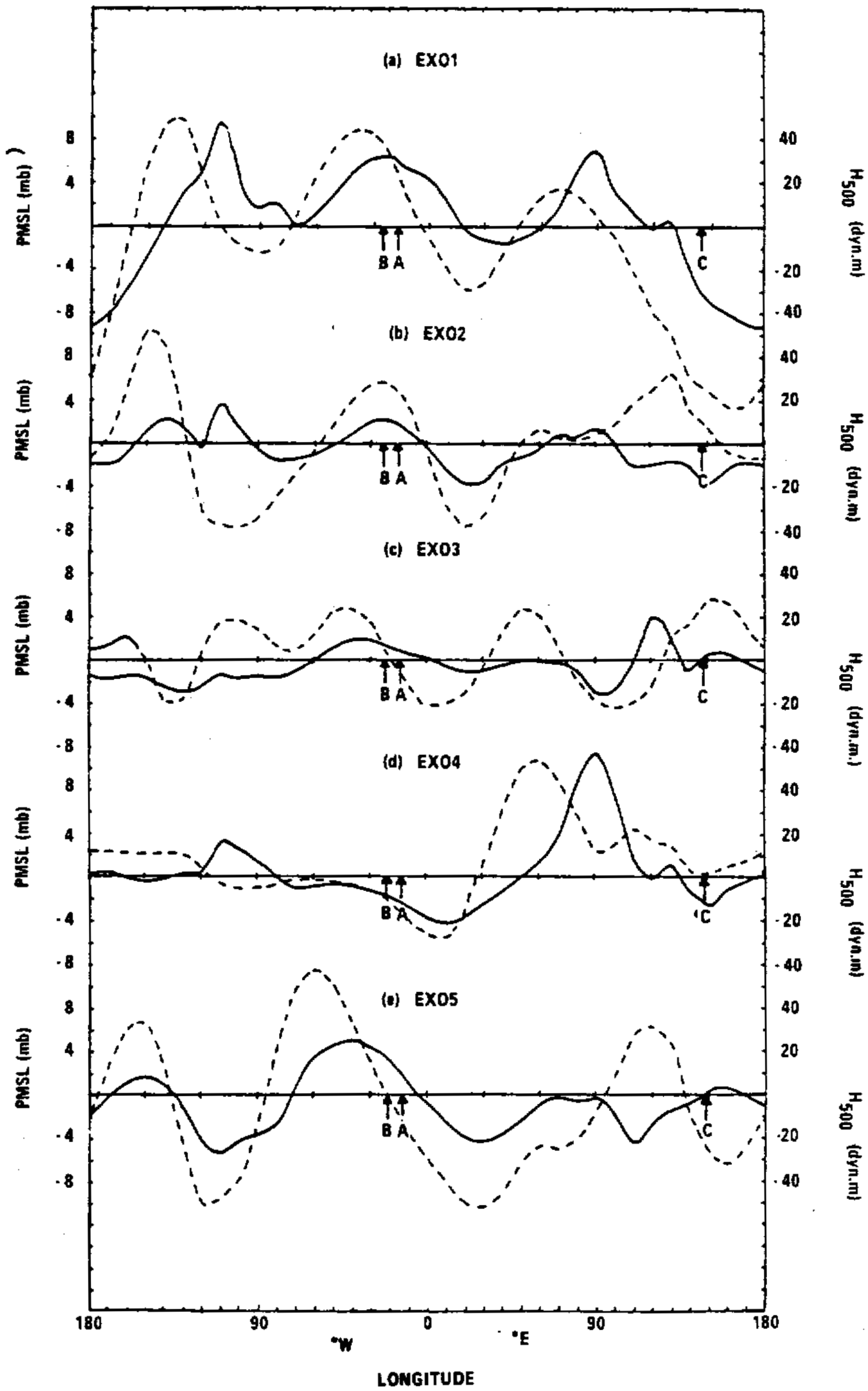


Figure 3.7. As in Figure 3.5 but averages of 37.5°N and 34.5°N.

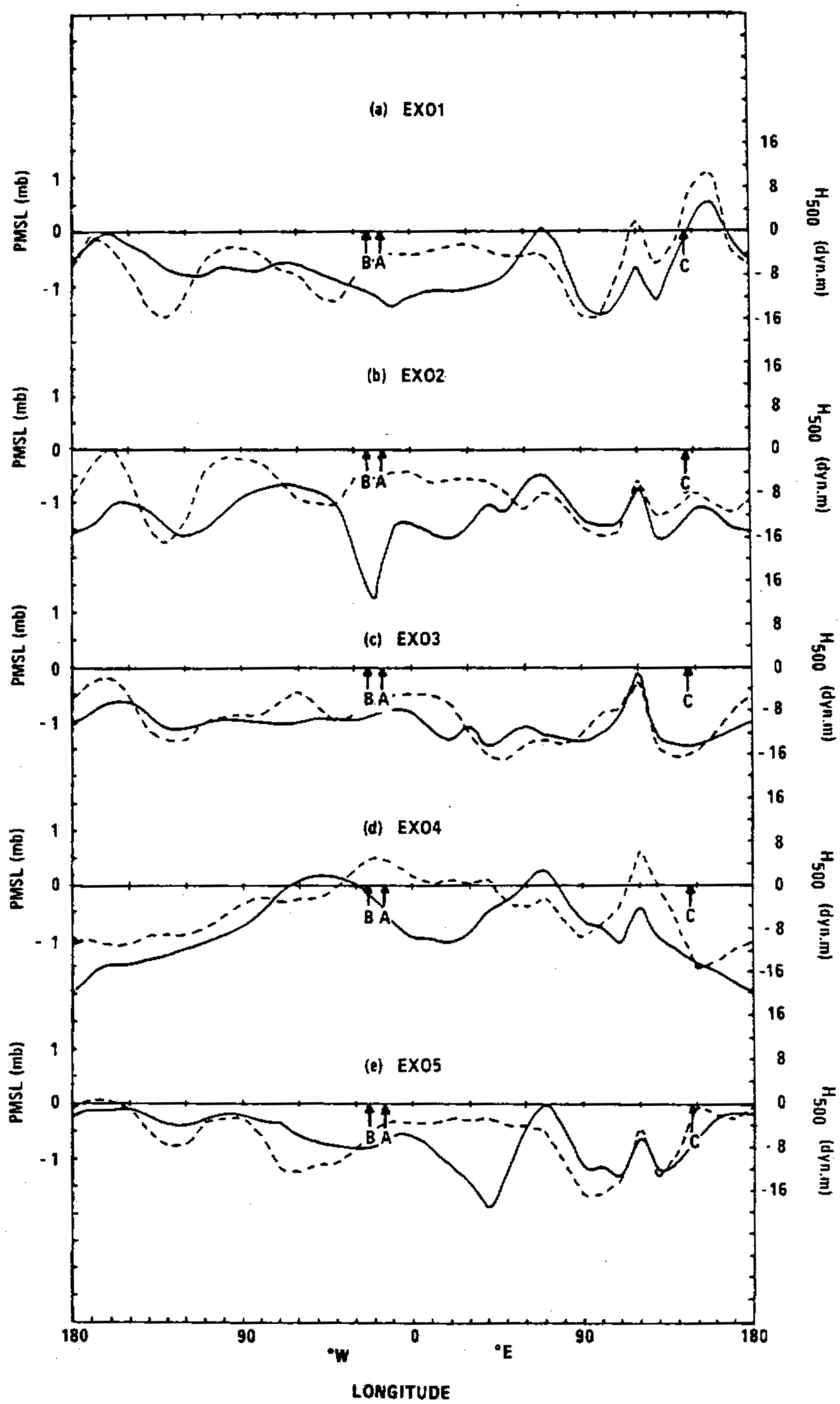


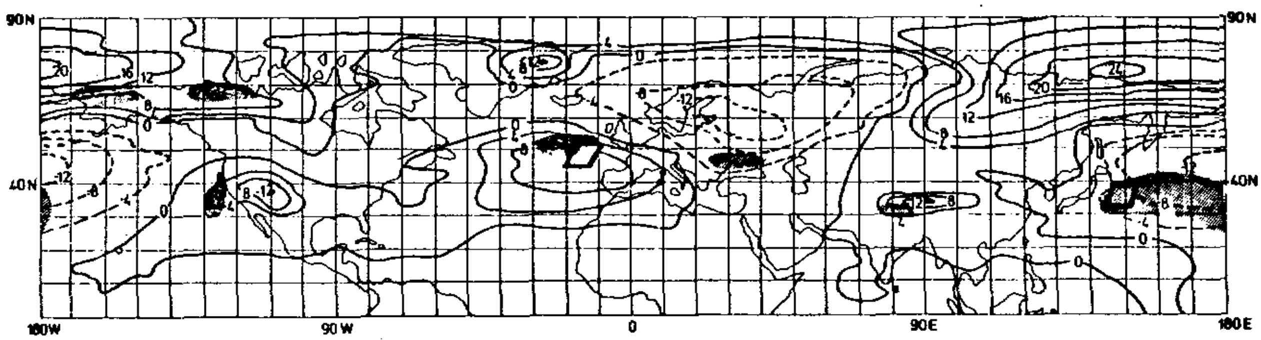
Figure 3.8. As in Figure 3.5 but averages of 10.5°N and 7.5°N.

the ridge over park A is greater. However, the enhanced evaporation at park A in EX05 (Table 3.4) leads to a total heat input greater than in EX01. Also, as discussed above, the increased precipitation at the park is equivalent to an additional average of about 80 Wm^{-2}. EX05 is closer to being a conventional sea surface temperature anomaly experiment than the other energy parks experiments, yet the response is much larger than might be expected from the results of Rowntree (1976) and Kutzbach et al. (1977), for example. However, the anomaly in EX05 is in the eastern midlatitude Atlantic and the impact of SSTAs in these locations have not been investigated. A possible explanation for the unexpectedly large response is that anomalies in the eastern Atlantic, where the normal variance of surface temperature is low, have a relatively large impact, perhaps because the depression tracks are altered most readily by changes some distance downstream from the main developmental region.

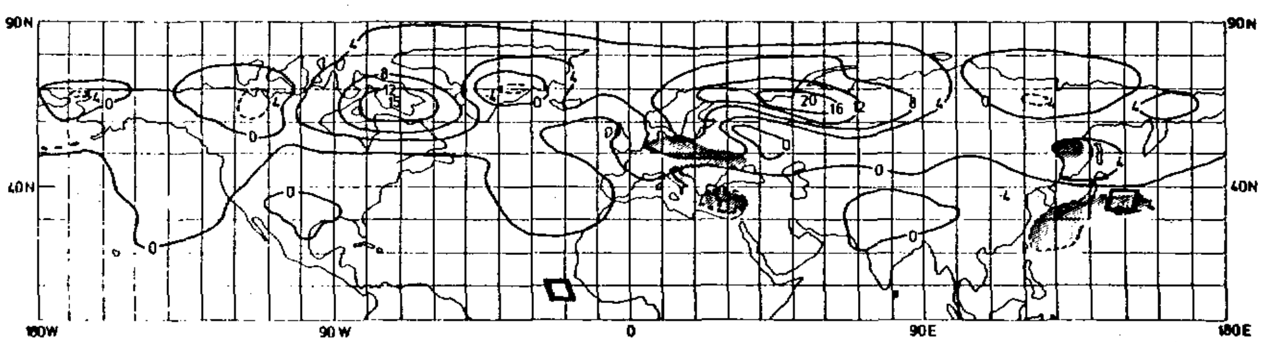
In contrast, it is difficult to discern a consistent response to the heat input at park C. As already noted, the circumstances at this park are very different from those at park A. Waste heat is inserted where the heat input is naturally very large and very variable. At the latitude of the park (Figure 3.7) there is a tendency for downstream ridging between 180°W and 120°W in EX01, EX02 and EX06, but this response is limited in horizontal extent and does not occur at higher latitudes. The largest response to the heat input in park C occurs in EX01, where a large relative trough occurs over and downstream of the heat input.

At higher latitudes (61.5°N-58.5°N, Figure 3.5), the differences in both sea level pressure and 500 mb height tend to be larger than noted elsewhere. In particular, large changes are found over the area between 60°E and 150°E. However, as will be shown below, this area is one of high model variability and, therefore, the large changes may not be significant. In tropical latitudes (10.5°N-7.5°N, Figure 3.8) the differences of both mean sea level pressure and 500 mb height are negative in all but a very few instances. Examination of differences in this latitude band from individual control cases, rather than from the average control cases, shows that the differences between only one of the control cases and each of the energy parks experiments are dominantly negative. That is, the sea level pressure and height of the 500 mb surface are much higher in one of the control cases in tropical latitudes than in the other two control cases. For the latter, differences from the energy parks experiments are both positive and negative. The occurrence of large variability among the control cases in tropical latitudes, as reflected in Figure 3.8, can also be seen in the maps of the geographical distribution of differences (Figures 3.9 and 3.10). At park B in EX02, there is a sharp pressure decrease directly over the area of heat input but no related response in the 500 mb height field.

(a)



(b)



(c)

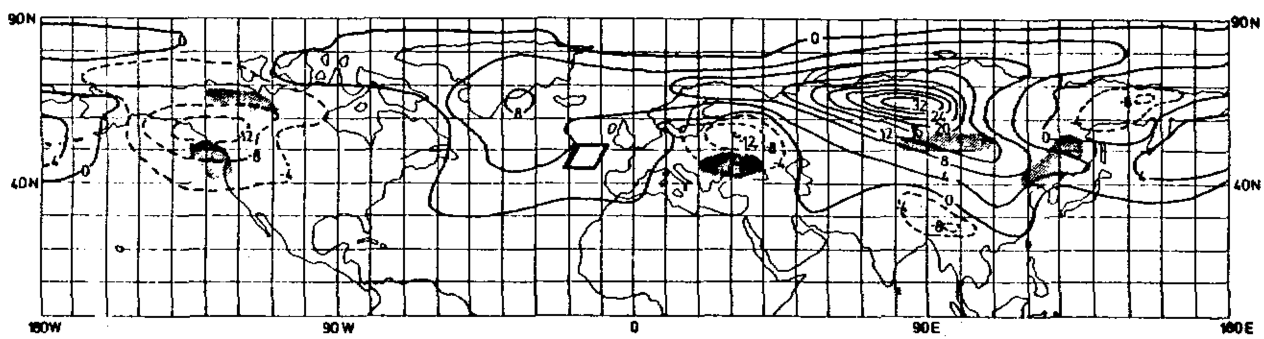
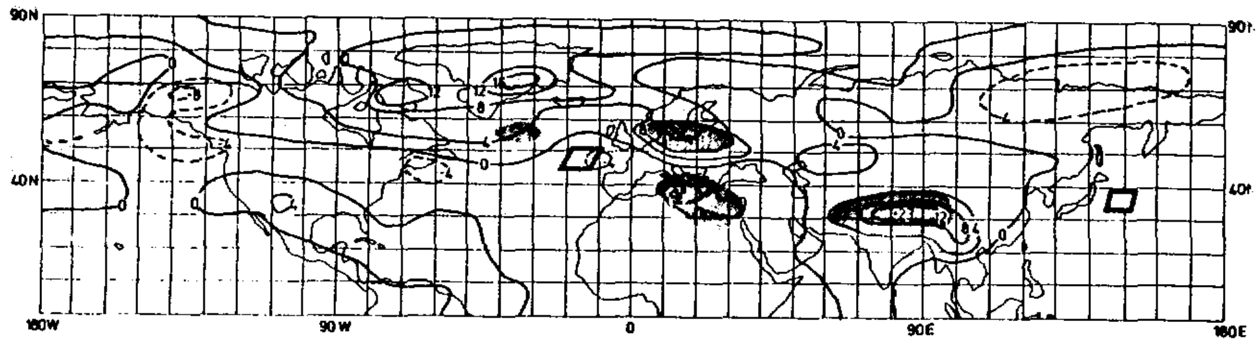


Figure 3.9. Geographical distribution of the differences in 40-day mean sea level pressure between energy parks experiments and the average of the three control cases. Shaded areas show where the ratio, r, is greater than 5.0 based on an estimate of model variability using 40-day means.
(a) EX01, (b) EX02, (c) EX03, (d) EX04, (e) EX05.
Units: mb.
(continued)

(d)



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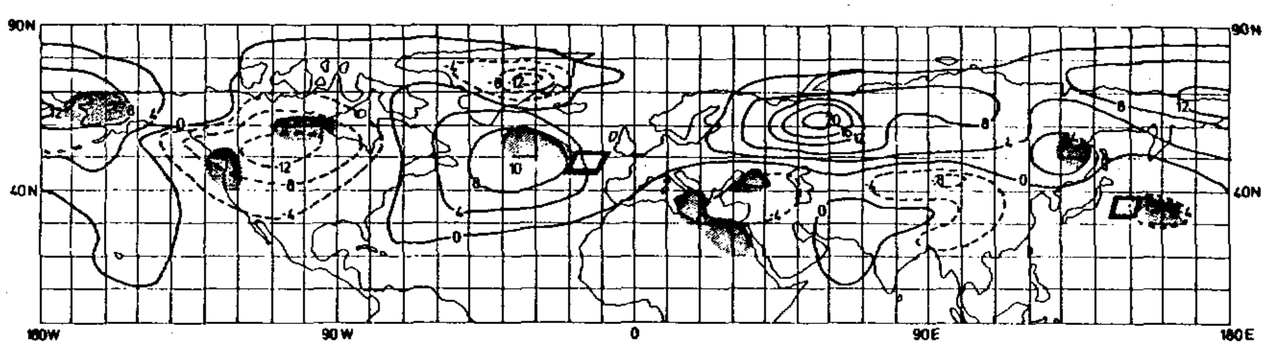
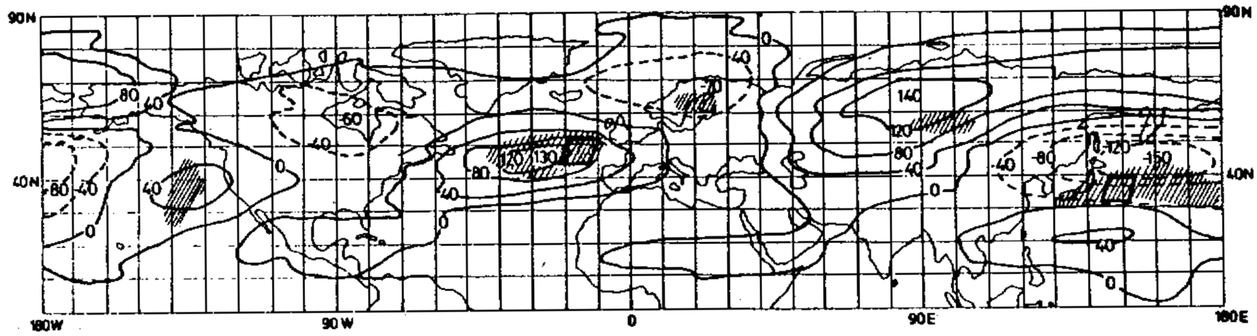


Figure 3.9. Geographical distribution of the differences in 40-day mean sea level pressure between energy parks experiments and the average of the three control cases. Shaded areas show where the ratio, r, is greater than 5.0 based on an estimate of model variability using 40-day means.
(a) EX01, (b) EX02, (c) EX03, (d) EX04, (e) EX05.
Units: mb.

(a)



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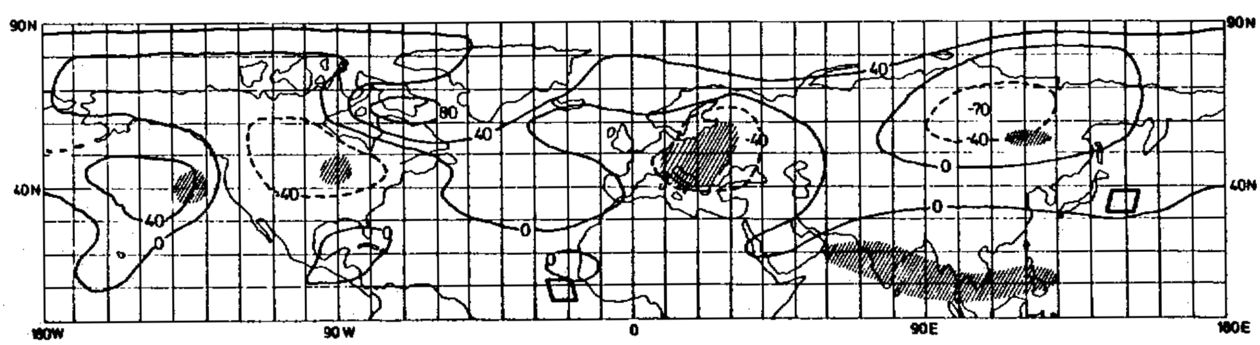


(c)

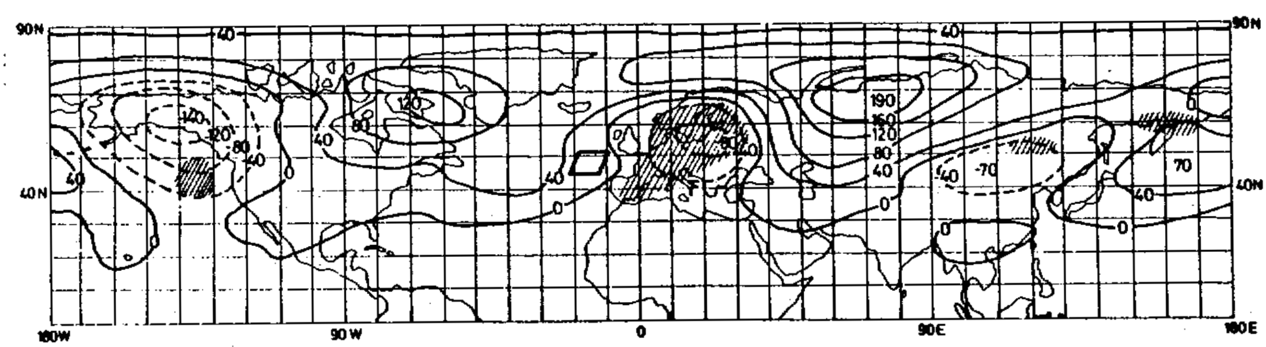
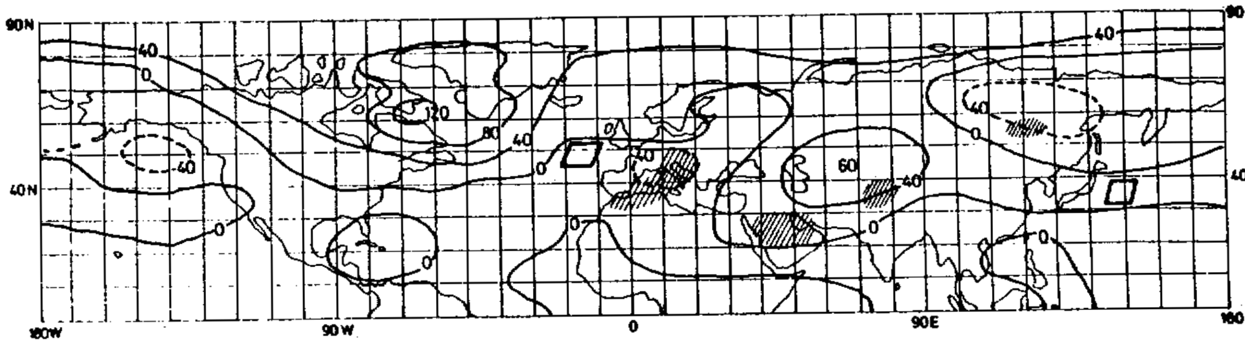


Figure 3.10. As in Figure 3.9 but for height of the 500 mb surface.
Units: dyn.m.
(continued)

(d)



(e)

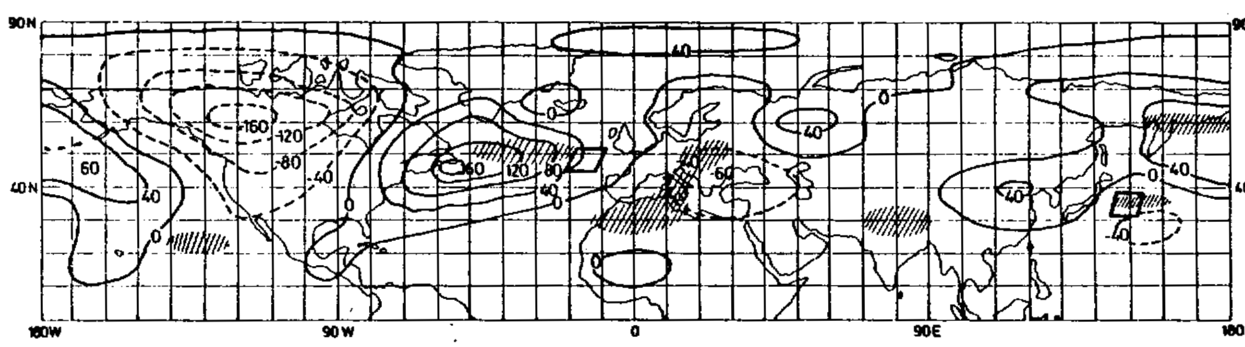


Figure 3.10. As in Figure 3.9 but for height of the 500 mb surface.
Units: dyn.m.

Changes in the distribution of sea level pressure and 500 mb height. Figure 3.9a-e shows the geographical distribution of the difference in 40-day mean sea level pressure between the energy parks experiments and the average of the three control cases. Areas where the signal-to-noise ratio is greater than 5.0 are shaded. The geographical distribution of 500 mb height differences are shown in Figure 3.10a-e. Harmonic analysis of the differences in sea level pressure and 500 mb height has been made for three latitude lines. The results of the analysis are given in Tables 3.5 and 3.6 for waves 1-4.

In EX01, several large areas of sea level pressure change are found. The sea level pressure increase over and upstream of park A and the decrease over and downstream of park C are on a much larger spatial scale than the area of an energy park.

The differences in 500 mb height in EX01 show that, in the vicinity of the waste heat input, the 500 mb height changes correspond very closely to the sea level pressure changes. At 500 mb, there are essentially three major relative ridges and troughs. Some of these features have maximum intensity at about 45°N and others at about 60°N. In the harmonic analysis (Table 3.6), this shows up as a wave 3 response whose phase does not change much with latitude, and a wave 1 response which, although accounting for the largest percentage of the variance from the zonal mean, changes phase by approximately π between 31.5°N and 58.5°N.

The changes in sea level pressure in EX02 (Figure 3.9b), which considered waste heat input at parks B and C, are neither as large nor as coherent in middle and high latitudes as in EX01. The heat input made at one tropical location produced a limited response in the immediate vicinity (Figure 3.8). The 500 mb height changes in EX02 are also generally smaller than those in EX01. The largest values are in high latitude continental regions, where the inherent variability of the model is also highest. However, downstream from park C, there is an area of increased 500 mb height at 130-140°W, which is extensive and which, since it appears in all the experiments with the Pacific energy park (but not in EX03, which did not consider this park) may be a real model response.

Despite the generally small values shown in Figure 3.9b, the broad pattern in middle latitudes from the eastern Pacific to the middle of Asia, for EX02, shows some similarity with that of EX01. There is not enough evidence to determine whether this is a small but real response to heat input in the tropics, linking up with the response over the Pacific Ocean, or whether it is only a manifestation of the model's inherent variability. At 500 mb, the harmonic analysis at all three latitudes shows that wave 3 explains much of the variance from the zonal means of EX02. For the sea level pressure field, wave 3 explains more of the variance at 31.5°N, but at the other latitudes no wave is dominant.

Table 3.5 Amplitude (mb) and phase (longitude of first ridge east of Greenwich) for waves 1-4. Percent variance explained by waves 1-4. Computed for differences in sea level pressure field between the energy parks experiments and the average of the control cases. Harmonic analysis performed on 40-day mean differences for three latitude lines (58.5°N, 43.5°N, and 31.5°N)

	wave 1		wave 2		wave 3		wave 4		% total var.
Latitude 58.5°N									
EX01-CON	3.3	157°	5.6	112°	5.6	107°	1.6	12°	86
EX02-CON	1.8	33°	2.4	88°	2.5	61°	0.7	3°	55
EX03-CON	7.7	73°	5.1	112°	6.6	78°	4.2	80°	92
EX04-CON	4.6	322°	1.3	134°	1.3	47°	1.0	18°	88
EX05-CON	6.3	86°	1.4	92°	4.8	10°	2.2	31°	97
Latitude 43.5°N									
EX01-CON	6.3	347°	2.1	104°	4.9	109°	2.6	61°	94
EX02-CON	0.6	249°	1.0	2°	1.4	117°	1.7	53°	62
EX03-CON	4.1	89°	3.8	137°	0.8	101°	0.6	85°	88
EX04-CON	1.3	130°	1.2	84°	0.5	78°	1.1	67°	64
EX05-CON	2.0	311°	4.0	159°	2.5	82°	1.8	41°	91
Latitude 31.5°N									
EX01-CON	2.1	333°	1.9	95°	1.7	107°	0.5	53°	85
EX02-CON	0.6	290°	0.9	83°	1.5	96°	0.8	78°	66
EX03-CON	0.5	293°	1.1	164°	0.6	25°	1.2	42°	63
EX04-CON	0.8	118°	2.3	91°	1.1	87°	0.2	3°	62
EX05-CON	0.9	313°	0.3	136°	2.0	79°	0.8	42°	74

Table 3.6 Amplitude (dyn. m) and phase (longitude of first ridge east of Greenwich) for waves 1-4. Percent variance explained by waves 1-4. Computed for difference in height of 500 mb surface between the energy parks experiments and the average of the control cases. Harmonic analysis performed on 40-day mean differences for three latitude lines (58.5°N, 43.5°N, 31.5°N).

Latitude 58.5°N

	wave 1		wave 2		wave 3		wave 4		% total var.
EX01-CON	50	105°	14	90°	38	82°	14	75°	97
EX02-CON	21	258°	13	163°	33	64°	6	83°	77
EX03-CON	40	24°	57	107°	65	56°	35	72°	96
EX04-CON	44	304°	18	114°	23	52°	15	4°	93
EX05-CON	40	49°	59	158°	62	63°	11	32°	98

Latitude 43.5°N

	wave 1		wave 2		wave 3		wave 4		% total var.
EX01-CON	77	343°	29	73°	62	93°	21	58°	98
EX02-CON	22	172°	15	161°	30	88°	15	48°	92
EX03-CON	7	320°	16	160°	41	54°	28	66°	95
EX04-CON	13	111°	22	85°	24	64°	9	66°	94
EX05-CON	23	265°	48	141°	45	77°	21	28°	98

Latitude 31.5°N

	wave 1		wave 2		wave 3		wave 4		% total var.
EX01-CON	13	274°	17	71°	16	88°	12	43°	91
EX02-CON	0	234°	3	174°	12	89°	9	41°	54
EX03-CON	5	205°	5	79°	6	47°	6	51°	59
EX04-CON	5	52°	15	57°	9	64°	7	49°	87
EX05-CON	13	235°	17	106°	17	79°	41	24°	88

In EX03, which considered only park A, the magnitude of the sea level pressure change in the vicinity of the mid-latitude Atlantic park is in the same direction as in EX01. In both there is a pressure increase over and upstream of the park and a pressure decrease downstream. Further downstream, the two experiments differ, since EX03 has no Pacific energy park. The differences at 500 mb parallel those in the sea level pressure field. In midlatitudes (43.5°N), the harmonic analysis shows that the differences in sea level pressure contain a large wave 1 component, but, at 500 mb, wave 3 is larger.

The differences of sea level pressure in EX04 (Figure 3.9d) do not reproduce the geographical variation of EX01, which considered the same energy parks but had twice as much heat input. There are, however, large coherent areas of pressure change in EX04 and, in the vicinity of the parks themselves, the sea level pressure changes exhibit the characteristics of EX01 in having an increase upstream from the Atlantic park. At 500 mb, the differences downstream from the Atlantic park are similar to those in EX03, though weaker. Over the Pacific there are only small changes in the 500 mb height field in EX04, which are unlike those found in the other experiments which considered the Pacific energy park. In high latitudes, the differences in EX04 in both sea level pressure and 500 mb height exhibit a large wave 1 response. In middle latitudes, at 500 mb, waves 2 and 3 explain much of the variance from the zonal mean.

For EX05 (Figure 5.9e), the changes in sea level pressure are similar to those of EX01 in the vicinity of the energy parks, with a pressure increase over and upstream of park A and a pressure decrease over and downstream of park C. There are, however, big differences over North America. At 500 mb, the response in EX05 is like that in EX01 in general features, although with some variation in the intensities of the centers. In particular, the differences over North America, the Atlantic and European sectors are larger in EX05, while those over Asia are weaker. Harmonic analysis of the sea level pressure field shows that, in middle and high latitudes, wave 2 explains much of the variance from the zonal mean. At 500 mb, there is a large wave 3 response with the same phase at the three latitudes investigated. However, the differences in magnitudes of the large-scale features as described above lead to substantial contributions also in wave 2 (43.5°N and 58.5°N) and wave 4 (31.5°N).

With regard to the distribution of signal-to-noise ratio in the maps in Figure 3.9, for each of the experiments there are areas where the ratio is large enough to suggest that the results differ significantly from the control case ensemble. However, since the number of control cases considered is small, the ratio cannot be used as a definitive test of significance. As pointed out before, the aim of successive experiments has been to check particular consistent, physically realistic responses in the experiments rather than rely on statistical tests of significance. Nevertheless, for the sea level pressure field, it is notable that, in EX01, EX04 and EX05 (which each considered parks A and C), the signal-to-noise ratio is greater than 5.0 upstream and downstream of park A, providing statistical evidence supporting the view that the park produces a genuine (and similar in each experiment) response in the model. For the sea level pressure field, EX02 shows a smaller total area of large values of r than other experiments. For the 500 mb height field in EX01, r is greater than 5.0 in the vicinity of both energy parks and at three other locations where the response shows a relative ridge or trough. In each of the experiments which considered park A there is an area where r is greater than 5.0 in the region of 500 mb height decrease downstream from park A.

Changes in the distribution of precipitation. The geographical distribution of the differences in precipitation between the energy parks experiments and the average of the control cases (not illustrated) showed the largest changes in the tropics, where rainfall rates are greatest. In EX01 and EX04, significant values of the signal-to-noise ratio are found over and upstream of park A and not in the vicinity of park C. In the vicinity of park A a similar response was found in EX03. A decrease of precipitation in a band upstream of and near park A and an increase downstream in association with the trough are consistent with the average surface pressure changes. When the Atlantic park was situated in tropical latitudes, the major effect on the precipitation was to increase it immediately over the park. In neither EX01 nor EX04 did the Pacific energy park have a significant effect on the precipitation distribution in its vicinity, although an increase downstream of park C has been noted.

Table 3.7 shows the 40-day mean precipitation at the energy parks in each experiment and the average and standard deviation of the control cases. There was a significant decrease in EX01 at park A, but otherwise the changes at this park in EX03 and EX04 are rather small. In EX02, the enhancement of the precipitation over the tropical Atlantic energy park (B) demonstrates the difference in the response of the tropical atmosphere to a large input of heat in sensible form. In EX05, because the heat was inserted into the ocean box and an increase in the latent heat flux occurred at the energy parks, there is an increase in the precipitation rate at these locations.

Table 3.7 **40-day mean precipitation (mm/day) at energy parks (average for four grid points of each park)**

Experiment	Park A	Park B	Park C
Average of controls	5.35	2.66	5.46
Standard deviation of controls	0.24	0.79	1.16
EX01	2.97	2.06	5.02
EX02	5.07	20.20	4.43
EX03	4.77	2.44	5.47
EX04	5.52	1.37	4.35
EX05	10.38	3.87	10.36

3.4.3. Conclusions

The response of the simulated atmospheric circulation to the insertion of large amounts of waste heat at ocean energy parks has been investigated using five prescribed change experiments and three control cases of the Meteorological Office GCM.

Four experiments that included an energy park in the mid-latitude eastern Atlantic gave qualitatively similar results in the region surrounding the park. In each case, the flow at middle levels of the atmosphere became more anticyclonic upstream and cylconic downstream from the park. The amount by which the flow was changed and the latitudinal extent of the significant effect depended on the heat input, and for the smaller heat input used (0.75×10^{14} W) was small. The longitudinal extent between the positions of relative ridging and troughing was about 60-80^{0}, though this apparently depended in some measure on developments elsewhere in the hemisphere. Statistical evidence supports the view that the park produces a consistent response in the model.

One experiment included an energy park in the Atlantic off West Africa. In this case the atmospheric effects were mainly in the immediate vicinity of the park, with the heat input creating greatly enhanced rainfall.

The third location for an energy park was off the east coast of Japan, in the region of a pronounced climatological upper trough. In this instance, the various experiments showed considerable variation in response. In the first experiment, the effect of the energy park was to deepen the climatological trough and so, in combination with the eastern Atlantic changes, produce a large response in waves 1 and 3.

It is of interest to compare qualitatively the results of the energy parks experiments with those of GCM experiments to investigate the effects of sea surface temperature anomalies. In the latter, it has been found that, with anomalies of large horizontal extent in the tropics, significant atmospheric effects extend beyond the region of the anomalies themselves (e.g., Rowntree, 1972, 1976). When the anomalies are in middle latitudes, it is difficult to detect significant changes away from the anomalies (e.g., Kutzbach et al., 1977; Chervin et al., 1976). In the present experiments, this response is apparently reversed: when the heat is added as sensible heat to the atmosphere at small concentrated sources, the response of the atmosphere is greater when the heat input is in middle latitudes than when one of the point sources is in tropical latitudes. In the fifth experiment the waste heat was added to 10 m deep ocean boxes simulated at two middle latitude energy parks. When equilibrium was reached, the ocean temperature at the four grid points of each energy park was about 4 K higher than in the control cases and the sensible and latent heat fluxes increased. EX05 is closer to being a conventional SSTA experiment than the other energy parks experiments, yet the response is much larger than might be expected from the results of those with SSTAs in midlatitudes.

Overall, the energy parks experiments indicate that there is a possibility that the input of large amounts of heat could cause large, coherent changes in the atmosphere, not just over the areas of heat input but also elsewhere in the hemisphere. The response may vary according to the location, amount, and manner of heat input.

3.5. The Impact of Energy Consumption Areas on Climate

The experiments with the Meteorological Office GCM described in the last section were concerned with the impact of heat release at energy conversion sites (power parks for the production of electricity, methanol, hydrogen or other secondary enery carriers) on global climate. The experiments made by Washington (1971, 1972) considered the impact of waste heat input either uniformly distributed over all non-ocean areas or distributed according to present-day population density, with no distinction being made between the areas of energy conversion and consumption. This section considers the impact of waste heat release in the energy consumption areas, basically urban-industrial complexes, which on a large scale are referred to as megalopolises.

The energy balance of an urban area is influenced not only by the addition of heat due to energy consumption. Much of the urban area has a lower surface albedo (reflectivity) than natural or even cultivated vegetation that it replaces, leading to an increase in surface temperature. Secondly, building materials (brick, stone, concrete, asphalt, etc.) have a considerably higher thermal conductivity and heat capacity than vegetated surfaces. Hosler and Landsberg (1977) point out that these differences, together with the compaction of soil under roads and parking lots, mean that more solar radiation is absorbed and transferred to deeper layers and stored. This heat is then transferred back to the surface during intervals of net outgoing energy flux. The urban surface also modifies the transfer of latent heat into the atmosphere, with a much reduced evaporation. All of these factors contribute largely to the production of the urban heat island.

The release of heat by energy consumption may equal or exceed the amount of heat received from the sun, particularly in cold northern climates during winter. In major U.S. cities the heat production is 21-42 Wm^{-2} in summer and 174-209 Wm^{-2} in winter (Hosler and Landsberg, 1977). Table 3.8 adapted from the SMIC (1971) report shows the energy consumption density of several urban/industrial areas and compares this with the

Table 3.8. Energy consumption (EC) density, industrial and urban areas

	Area (km^2)	EC density (W/m^2)	Average net radiation (W/m^2)
Nordrhein-Westfalen	34,039	4.2	50
Same, industrial area only	10,296	10.2	51
West Berlin	234	21.3	57
Moscow	878	127	42
Sheffield (1952)	48	19	46
Hamburg	747	12.6	55
Cincinnati	200	26	99
Los Angeles County	10,000	7.5	108
Los Angeles	3,500	21	108
New York, Manhattan	59	630	93
21 metropolitan areas (Washington-Boston)	87,000	4.4	~90
Fairbanks, Alaska	37	18.5	18

Source: SMIC (1971)

average net radiation. The energy consumption in some areas already exceeds the net radiation in winter. The effect of cities on the weather is described by Landsberg (1975) and Changnon (1973), for example.

The urban influence on climate is already observable. Hosler and Landsberg (1977) point out that by the end of the century projections suggest that 81% of the population in developed nations and 51% of the world's population will live in urban areas (with a total population of about 6 1/2 billion compared with slightly more than 4 billion today). It is to be expected that there will be some large megalopolitan regions, which will be considerably warmer than surrounding rural areas, which will induce increased rainfall and possibly initiate severe weather. Because of the scale of these effects the possibility of a global response to these energy consumption areas must be considered.

Llewellyn and Washington (1977) discuss an experiment with the NCAR GCM, in which thermal pollution was added to an area extending from the Atlantic seaboard of the U.S.A. to the Great Lakes and Florida. It was assumed that the energy consumption for that region was equal to that presently found in Manhattan, i.e. 90 Wm^{-2}. Other regions of the globe were not modified. Temperature differences of as much as 12°C were observed in the vicinity of the anomalous heating but the heating had little effect above the surface layer.

Washington and Chervin (1978), using an improved version of the NCAR GCM, considered the same heat input as Llewellyn and Washington (1977) in both January and July experiments. A surface temperature change of 12°C over the area of heat input was found in the January experiment. Smaller but still significant changes, with a maximum of 3°C, were found in the July experiment. Significant changes in precipitation and soil moisture were also found in the prescribed change region. However, neither experiment produced any evidence of a coherent, statistically significant, downstream response over the Atlantic Ocean or Europe.

3.6. Model Studies of the Impact of Megalopolises on the Atmospheric Circulation

Following the lines of the latter series of experiments, this section describes an investigation of a scenario in which the waste heat release areas are distributed in a more realistic way only over continental areas rather than over the oceans as in the earlier IIASA studies. This approach avoids the heat being concentrated in small energy parks and might be considered as a compromise between Washington's and IIASA's earlier experiments.

3.6.1. The megalopolis experiment (MX01)

In this scenario the heat was released from six different regions in the northern hemisphere. The selected locations represent areas where a large population and/or energy consumption density could be expected in the future (Doxiadis, 1974; National Research Council, 1977; Keyfitz, 1977; Llewellyn and Washington, 1977). To be consistent with the previous experiments and for easy comparison with them, the same total amount of heat as in EX01, EX02 and EX05, namely 300 TW, was released from the 6 areas. As one might call this a "megalopolis" experiment we denote the energy consumption areas M1-M6. Table 3.9 gives the locations of the heat input and the amount of heat released at each location. Figure 3.11 shows the geographical distribution of the 6 areas. The size of the areas and their heat input were chosen in such a way that the heat released per square meter was the same for each grid point, namely 60 W.

Table 3.9. The megalopolis scenario

Area	Location	Heat released (TW)	Area size (km^2)
M1 (USA)	42^0N, 81.2^0W - 69.4^0W 30^0N, 87.1^0W - 76.5^0W	72 TW	12×10^5 km^2
M2 (EUROPE)	51^0N, 4.2^0E - 36.5^0E 45^0N, 5.7^0E - 36.1^0E	84 TW	14×10^5 km^2
M3 (SU)	54^0N, 71.4^0E - 86.2^0E 48^0N, 68.8^0E - 82.7^0E	36 TW	6×10^5 km^2
M4 (INDIA)	24^0N, 79.5^0E - 86.0^0E 18^0N, 78.0^0E - 84.4^0E	24 TW	4×10^5 km^2
M5 (CHINA)	36^0N, 111.2^0E-118.5^0E 24^0N, 109.4^0E-116.0^0E	48 TW	8×10^5 km^2
M6 (JAPAN)	36^0N, 132.8^0E-144.1^0E 33^0N, 133.0^0E-143.9^0E	36 TW	6×10^5 km^2
Total		300 TW	50×10^5 km^2

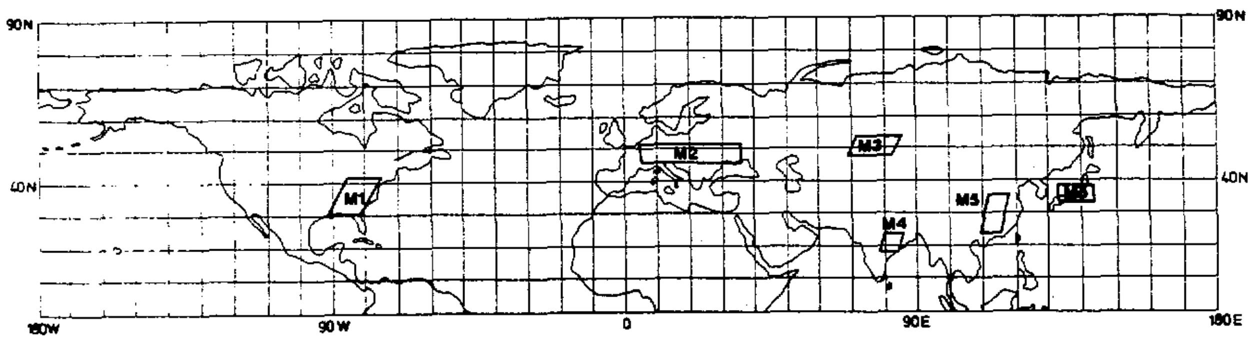


Figure 3.11. Locations of the energy consumption areas

The experiment was performed with the GCM of the U.K. Meteorological Office. In addition to the perturbed case, the same three control cases were used as in the previous investigations. These control experiments were run with the same version of the model and simulate unperturbed January climate. They differ from each other only as a result of small random differences in the inital conditions. The megalopolis experiment has also been performed with January boundary conditions. Each experiment is a simulation of 80 model days, and the results are generally described in terms of means of meteorological variables for days 41-80.

3.6.2. Results

Difference maps. In the following, maps showing the differences of meteorological variables between MX01 and the average of the control experiments are presented. The statistical significance of the results is considered applying the method described in Section 3.4.2.

Figure 3.12 shows the differences in 40-day mean sea level pressure between MX01 and the average of the three control cases. A big change occurs over an extended area covering eastern Siberia and most of Canada, its maximum being a 16 mb pressure increase over Alaska. The signal-to-noise ratio is greater than 5.0 over a large part of this area. The pressure increase also covers parts of the Pacific, as far south as 40^0N. The effect in the vicinity of the American megalopolis (M1) is a 4 mb decrease right over this area. Over the Atlantic there is a 12 mb pressure increase, which exceeds the model variability. A decrease is covering Greenland which, despite of its magnitude of 12 mb, is not significant. The European megalopolis (M2) has caused a big regional response. An 8 mb decrease occurs directly over the area and the ratio, r, is greater than 5.0 over middle Europe and the Mediterranean Sea. North of M2, a pressure increase occurs which increases further

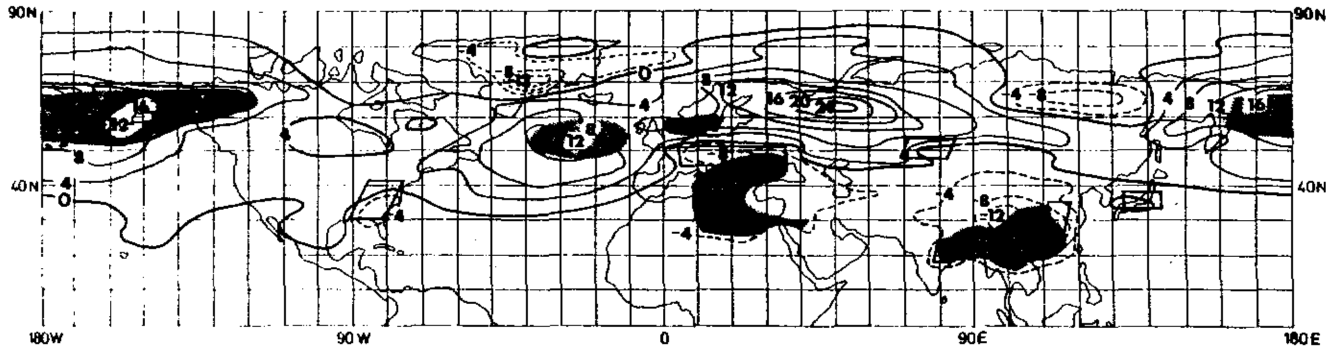


Figure 3.12. Differences between MX01 and the average of the three control cases in 40-day mean sea-level pressure. Shaded areas indicate where the signal to noise ratio is greater than 5.0 based on the standard deviation of the 40-day means.

east with a maximum of 24 mb over the western part of the Soviet Union. There is no change directly over M3, but a big decrease downstream of this area covers parts of Siberia. M4, M5 and M6 also cause big regional responses. Particularly south-east Asia is covered by a large pressure decrease with r being greater than 5 in a big part of this area. As a general result it can be said that in almost all 6 areas the heat input causes large regional pressure decreases. The total sum of changes in MX01 is comparable with those in EX01, the magnitude and locations of the individual changes, however, are different.

Figure 3.13 shows the differences in 40-day mean height of the 500 mb surface between MX01 and the average of the control experiments. The largest changes are found over the northern Pacific, the Atlantic and Siberia, where the ratio is also greater than 5.0. Comparison of the changes in the height of the 500 mb surface with those of the sea level pressure show interesting similarities. The sea level pressure increase over the Atlantic, western Siberia and Alaska, the decreases over the Soviet Union and the Mediterranean Sea can be found again at the 500 mb surface. The pressure response over the U.S.A., south-east Asia and Greenland, however, have no parallels in the height field.

Again, the response in the height of the 500 mb surface in MX01 is generally smaller than it is in EX01, but some of the changes are still of a similar or even higher magnitude compared to EX01.

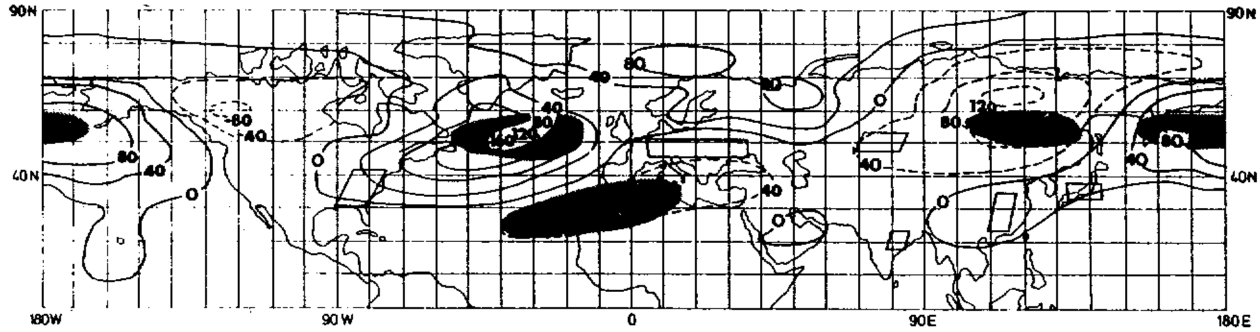


Figure 3.13. Differences between MX01 and the average of the three control cases in 40-day mean height of the 500 mb surface. Shaded areas indicate where the signal to noise ratio is greater than 5.0 based on the standard deviation of the 40-day means.

In Figure 3.14, the differences in 40-day mean temperature of the lowest atmospheric layer between MX01 and the average of the control cases are shown. Large changes occur mainly over the continents. There is a 10°C cooling over Canada and Siberia, which is clearly related to the increase of sea level pressure, with the ratio, r, being greater than 5.0 in parts of Siberia and over M3. A 6°C warming over Greenland, related to the decrease of sea-level pressure in this area, also has a high value of the signal-to-noise ratio. As in EX01-EX05 the temperature response in areas away from the heat input is forced by pressure response. There is again a large possibly significant impact in Europe with a maximum in a 4° warming over the megalopolis area. An 8°C increase over M5 and a 5°C warming over M1 exceed the model's inherent variability. Again, the big regional responses of the megalopolis areas should be noted. M1, M2 and M5 show large, possibly significant temperature increases which are also consistent with the fact that we are adding heat in these areas.

The geographical distribution of the differences in precipitation between MX01 and the average of the control cases (not illustrated) show the largest changes in the tropics. This has been found already in the previous experiments and has been explained there. One consistent response in the energy parks experiments was the similar pattern of precipitation differences in the vicinity of park A. There was a decrease of precipitation in a band upstream of park A and an increase immediately downstream.

This pattern can also be found in MX01 to some extent. There are increases in precipitation downstream of M1, M2 and M5 and southeast of M4. A decrease occurs over the Atlantic

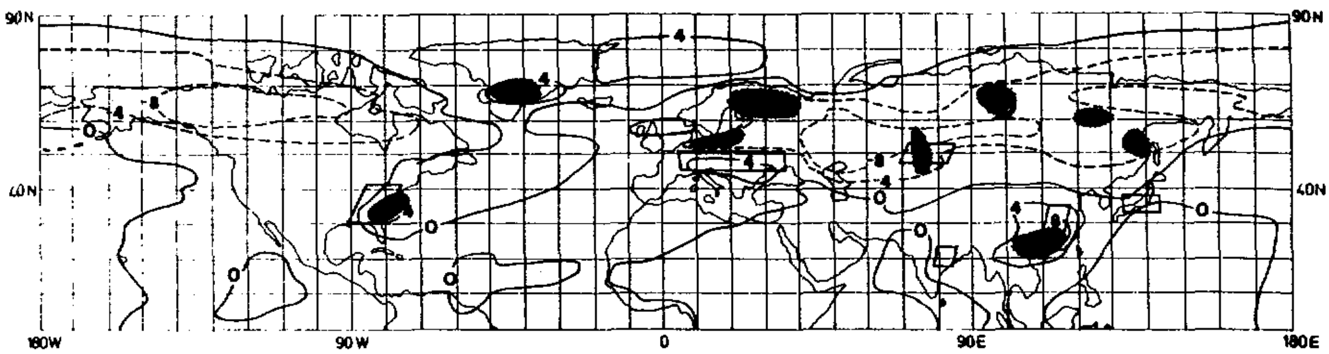


Figure 3.14. Differences between MX01 and the average of the three control cases in 40-day mean temperature of the lowest atmospheric layer. Shaded areas indicate where the signal to noise ratio is greater than 5.0 based on the standard deviation of the 40-day means.

upstream of M2 and an area upstream of M4. The impact of M4 and M5 on precipitation, however, must be considered with some caution because of the large inherent variability of the models precipitation in this area. As already observed in the previous experiments for park A, it is seen that the precipitation increase on the downstream side of M1, M2, M4 and M5 is somehow associated with the pressure decrease in these regions. On the upstream side of the mentioned areas, the pressure changes can not be consistently associated with the changes in precipitation. Only the pressure increase over the Atlantic relates to the large precipitation decrease in this area.

It is worthwhile to compare these results with those of the NCAR megalopolis experiment (Llewellyn and Washington, 1977). The latter showed a 12°C warming over the energy consumption area. The only other big change reported was a 6°C cooling over Greenland. This is a quite different response compared to MX01 where there was a change of opposite sign over Greenland and no big change at all over M1. The changes in MX01, however, are a hemispheric response to inputs of heat in six areas as compared with one megalopolis in the NCAR experiment.

The hemispheric mean of the total temperature changes for MX01 is negative in the lowest layer, but positive in the higher layers.

3.6.3. Conclusions

It is found that when the heat input is spread over six areas the hemispheric response is comparable to that when the heat input is concentrated at only two energy parks. There is still a sufficient number of areas over which the signal-to-noise ratio is greater than 5.0 to suggest there is a significant model response to the megalopolis heat input. A further result is the strong regional response of some of the megalopolis areas.

As in the earlier model experiments there are large coherent areas of change in the sea-level pressure and 500 mb height fields and distribution of temperature in the lowest atmospheric layer, not only over the area of heat input but elsewhere in the hemisphere.

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4. SOLAR ENERGY

4.1. Introduction

If it is assumed that solar energy conversion systems make a significant contribution to the energy supply in the future, then it can be considered that the systems which have the potential to supply about 30 TW are solar thermal electric conversion (STEC), photovoltaic (PV), ocean thermal electric conversion (OTEC) and solar satellite power (SSP) systems. The impact on climate of SSP systems has not been evaluated in any detail. Other solar energy conversion systems can be used locally or regionally for energy supply (e.g. wind and wave-power systems) but are not expected to contribute largely to the global energy requirement and therefore cannot be expected to have a global climate impact.

The possible climate impact of large-scale deployment of solar energy systems has received little attention. A workshop was, however, held at IIASA (Williams et al., 1977), which made a preliminary evaluation of the available systems, their physical characteristics, potential perturbations to climatic boundary conditions and the climatic implications. Much of the material in this section is based on discussions at that workshop. In addition, results of a joint study between IIASA and SRI International on the effects of STEC plants on mesoscale climate are presented.

4.2. Climate and Solar Energy Conversion

4.2.1. Solar Thermal Electric Conversion Systems (STEC)

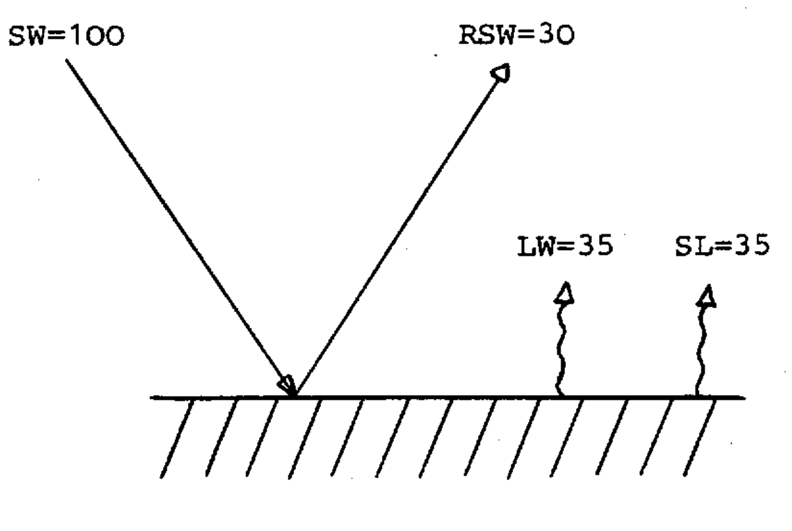
In order to generate electricity from solar energy, several possible systems could be used, but one in particular--the central receiver configuration or solar power tower has received most attention to date. A central receiver is located within an array of heliostats which focus the incident radiation onto the receiver at the top of the tower. The receiver produces either superheated steam or very hot air or other gases for operating a turbine. Hildebrandt and Vant-Hull (1977) state that typically 20,000 heliostats each 40 m^2 in area would be arrayed over an area of 3.5 km^2 surrounding a receiver elevated 260 m above the ground to provide 100 MW(e). The heliostats must be spaced in such a way as to avoid excessive shading of one another or blocking of the reflected radiation in the daily and yearly operation. This is accomplished for a non-uniform mirror distribution resulting in a ratio of reflector area to land area (ground cover ratio) varying from 0.4 to 0.1 and averaging about 0.25. The steam systems require cooling in the form of wet or dry cooling towers.

The major changes in boundary conditions of the climate system due to installation of a STEC system would be:

- changes in the surface energy balance;
- changes in surface roughness, since heliostats are up to 10 m high;
- changes in surface hydrological characteristics if area is paved.

Surface energy balance. The impact of a STEC system on the surface energy balance would in reality be extremely complex since so many variables are perturbed. For example, the changes in surface thermal characteristics through paving, the changes in energy fluxes from the surface through the roughness changes and other microclimatological changes must be considered. A simplified estimate of the impact of STEC systems on the energy balance can be made, however, by considering the basic components of the energy balance.

A simplified description of the energy balance in the absence of a STEC plant is illustrated in Figure 4.1. Of the direct insolation, 30% is reflected away from the surface, 70% is absorbed and then is re-emitted in the form of long-wave radiation, sensible heat and latent heat. As a rough estimate Figure 4.1 divides the energy flux from the surface equally between the long-wave radiation and sensible plus latent heat.



SW = incoming solar radiation
RSW = reflected solar radiation
LW = longwave radiation
SL = sensible plus latent heat flux

Figure 4.1. Energy balance in absence of STEC plant

In the presence of a STEC plant (Figure 4.2) the energy balance is changed differently according to the season. Assuming a STEC plant with a ground cover ratio of 40%, at which 17% of the sunlight impinging on the heliostats is converted to electricity, then the following estimates on the impact on the energy balance can be made. In winter, the sun is low in the sky, thus the heliostats intercept all of the insolation on the area, i.e., there is no reflection from the ground. The heliostats themselves have an efficiency of, say 85%; that is 15% of the light hitting the heliostats is lost due to aiming errors, haze and optical surface imperfections. In addition 10% of the radiation hitting the heliostats will be absorbed by the heliostats. In winter, therefore the reflection from the STEC area is 14% of the total incoming direct radiation, i.e.:

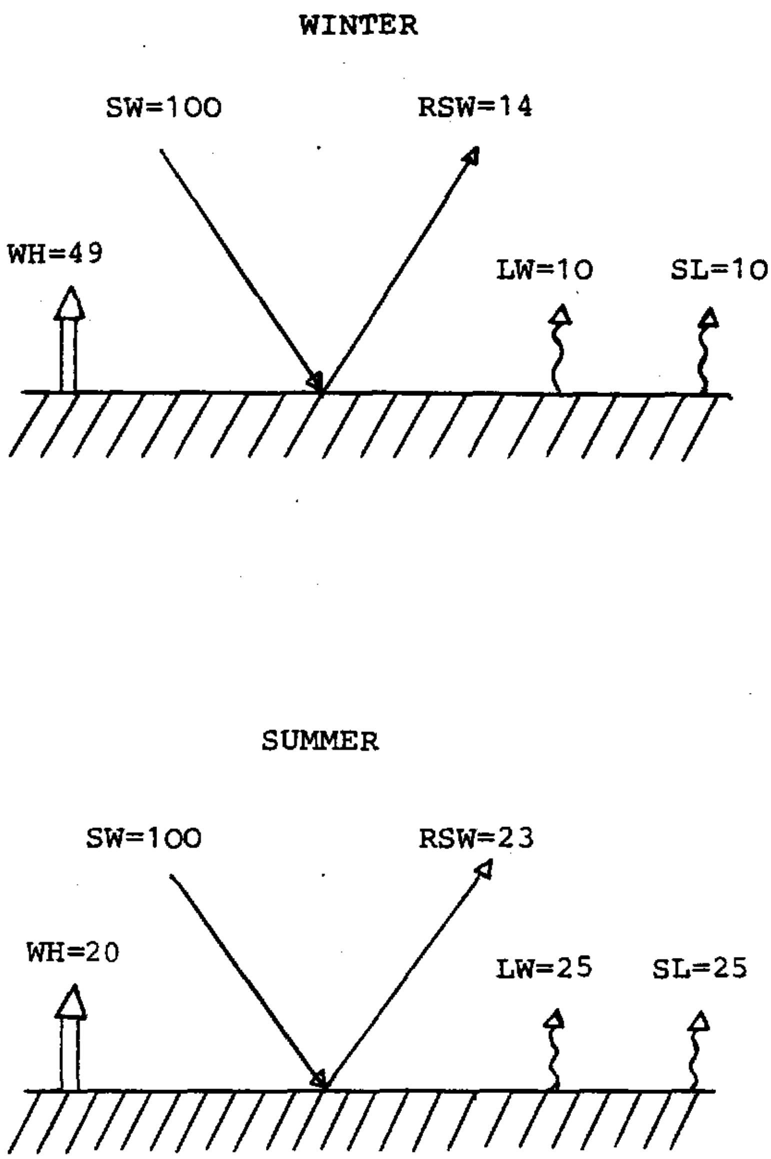
total incoming on mirrors 100%
absorbed by mirrors 10%
optical losses = 15% of the amount reflected = 15% × 90%
= <u>14%</u>

In summer the sun is high in the sky, so that only 40% of the ground is covered by heliostats and thus incoming radiation is also reflected by the ground. Reflection from the ground is then 60% × 30%, assuming that the ground has the same reflectivity as in the absence of the STEC plant. Of the radiation incident on the heliostats, 10% is again absorbed and of the remaining 90%, 15% is lost optically through aiming errors etc. Thus for the summer case the reflection from the STEC area is 23% of the incoming direct radiation, i.e.:

reflection from ground = 30% × 60% = <u>18%</u>
plus
total incoming on mirrors = 40%
absorbed by mirrors = 4%
optical losses = 15% of the amount reflected = 15% × 36%
= ~5%
total reflection (summer) = <u>23%</u>

In the winter season absorption by the soil is 0% since the heliostats intercept all the incoming radiation, while in the summer, of the 60% of incoming radiation which reaches the ground, 14% is reflected (see above) and, thus, 42% is absorbed. As indicated above, the mirrors themselves absorb 10% of the incident radiation.

Of the radiation which reaches the receiver there are losses which have been estimated as 6% of the incident radiation on the heliostats, i.e. 6% of the total incident radiation in winter and 2% (= 40% × 6%) of the total incident radiation in summer. In addition to the receiver losses, there are so-called "piping" losses, which have been estimated as 4% of the incident radiation on the heliostats, i.e. 4% of the total incident radiation in winter and 2% (= 40% × 4%) of the total incident radiation in summer.



SW = incoming solar radiation
RSW = reflected solar radiation
LW = longwave radiation
SL = sensible plus latent heat flux
WH = waste heat

Figure 4.2. Energy balance with STEC plant

Over the STEC area as a whole, therefore, the energy leaving the surface (ground plus plant) is, expressed as a percentage of the total incident radiation on the whole area,

	winter	summer
from the soil (equals that absorbed)	0%	42%
from mirrors (" " ")	10%	4%
from receiver	6%	2%
from piping	4%	2%
Sum	20%	50%

Assuming, as done for the case without a STEC plant, that this energy flux from the surface is divided equally between long wave radiation and sensible plus latent heating then the above sum can be divided:

	winter	summer
long wave radiation	10%	25%
sensible plus latent heating	10%	25%

17% of the radiation incident upon the heliostats is converted to electricity, that is, in winter 17% of the total incident radiation on the STEC plant and in summer 7% (40% × 17%) of the total incident radiation. The remainder of total incident radiation is emitted as waste heat at cooling towers. The amount of waste heat, as a percentage of the total incident radiation is:

	winter	summer
reflected from area	14%	23%
soil, mirror, receiver, piping losses	20%	50%
electricity generated	17%	7%
subtotal	51%	80%
remainder = waste heat at cooling towers	49%	20%

These numbers are shown diagrammatically in Figure 4.2 and a comparison with Figure 4.1 shows that in the presence of the STEC plant the total of the energy flux from the surface into the atmosphere (~70% of the incident solar radiation on the area) does not differ from that in the absence of the STEC plant. However, the distribution is changed. The long wave radiation from the surface is reduced from the 35% in the case of no STEC plant to 10% (winter) or 25% (summer) in the presence of the STEC plant. Similarly, the sum of sensible and latent heat flux from the surface is reduced to 10%-25%. The significantly lower heat release from the surface is compensated by a release of waste heat from cooling towers upon energy conversion. In this respect some impacts of STEC systems upon climate can be evaluated in the same way as the potential impact of waste heat from fossil fuel or nuclear power plants.

As with the discussion of the impact of waste heat release (see Section 3) the impact of surface energy balance changes will depend on the scale (horizontal dimensions) and the magnitude of the perturbation. That is, when the perturbations are not of a large scale they can be expected only to influence local climatological conditions. If, however, the perturbations are large enough to influence the atmospheric circulation, then the impact can be on a global rather than a local scale. Sawyer (1965) suggested that anomalous heat sources and sinks more than 1000 km across and of magnitude 20 Wm^{-2} or more could influence the atmospheric circulation.

The results of a project to investigate the regional meteorological effects of a large STEC installation are described at the end of this section.

Global climate patterns. The potential impact of STEC plants on global climate patterns has received little attention. In particular, the implications of large-scale changes of surface energy balance, roughness and hydrological characteristics are not well understood. A few relevant studies are available, however, and these indicate at least the kinds of impacts that could be expected. Of most interest is a series of experiments made with models of the atmospheric circulation, which have investigated the impact of large-scale changes in albedo. The impetus for these experiments came when scientists were attempting to explain the origins of the Sahel drought. Charney (1975) proposed a bio-geophysical feedback mechanism to explain the drought. He argued that the reduction of vegetation, with consequent increase in albedo in the Sahel region would cause sinking atmospheric motion and additional drying and would therefore perpetuate the arid conditions. To test this hypothesis Charney et al. (1975) used the GCM developed at the Goddard Institute for Space Studies to compare the atmospheric circulations simulated when the albedo in the Sahel area was 0.14 and 0.35. A decrease in precipitation and convective cloud cover were reported as a response to the increased albedo. Similar experiments made by Ellsaesser et al. (1976) with a zonally averaged model further supported Charney's hypothesis.

Charney et al. (1977) have reported on a further series of experiments with the GCM, which better took into account the interaction between surface hydrological processes, albedo changes and the atmospheric circulation. Results of the experiments showed that in an area where appreciable evaporation from the surface occurs, an increase of albedo reduces the absorption of solar radiation by the ground and consequently the transfer of sensible and latent heat into the atmosphere. The resulting reduction in convective cloud cover then tends to compensate for the increase of albedo by allowing more solar radiation to reach the ground, but it reduces the downard flux of longwave radiation even more so that the net absorption of radiation by the ground is decreased. Without evaporation, the increase of albedo causes a decrease of radiative flux into the ground and thus a decrease of convective cloud and precipitation. Two further results of the work of Charney et al. (1977) are of significance to the discussion of the climate impacts of STEC systems. Firstly, the various experiments showed that changes in evaporation rate are as important as albedo changes. In any case changes in surface energy balance conditions can apparently influence the local cloudiness and precipitation patterns through changes in the vertical circulation in the overlying atmosphere. Secondly, in a discussion of the least dimension of an area for which albedo and ground moisture changes can be expected to influence convective rainfall, Charney et al. suggest that a plausible rule of thumb is that observable effects can be expected when the characteristic time for a change in the surface flux of moist static energy to penetrate to cloud base is smaller than the time required for new properties to be advected into the region. This suggests a minimum dimension of 40-80 km.

A local atmospheric circulation model developed by Berkofsky (1976) also shows that the vertical circulation and thus cloudiness and precipitation respond to surface albedo changes in desert areas. In particular this model showed that a lowering of the surface albedo in a desert region could lead to increased vertical velocity and possibly to increased rainfall.

Further experiments have been made with albedo changes with the NCAR GCM (Chervin, personal communication). In the first experiment the albedo was increased to 45% over the Sahara and the High Plains area of the U.S.A. The precipitation was reduced over the area of albedo change and increased to the north and south of that area. Signal-to-noise ratios suggested that the precipitation changes are significant over the albedo change area and elsewhere. There was an increase in downward motion over the albedo change areas, suggesting that east-west circulations had changed. In a second experiment, the albedo was changed to 30% over a smaller area than in the first experiment (in particular, over only one row of grid points over the Sahara). The effects were qualitatively similar over the High Plains area but not so clear over the Sahara area. An important result of these two experiments is that apparently the role of the *shape and orientation of the albedo change area is important* in determining the impact. For example, a solid block of changed grid points is more effective than a single row of changed points. For the evaluation of the impact of solar energy conversion systems, therefore, the location and orientation of the changes in climatic boundary conditions could be of significance.

One preliminary experiment to evaluate the impact on climate of STEC systems has been made by Potter and MacCracken (1977). The model used is a zonally-averaged model; that is, it considers a two-dimensional (latitude-height) climate system. A scenario for albedo modification due to intensive solar energy production, derived by Grether et al. (1977) was used for the input to the model. This scenario assumed a world population of 10 billion with a per capita energy requirement of 10 kW. It was further assumed that to generate 100 MW(e) a reflector area of 3 km^2 would be required (this is an overestimate to take into account the effects of access roads, population increases etc. in the collector region). The total land area required for generating 100 MW(e) was assumed to be 9 km^2. It was suggested that a rough estimate of the albedo change due to STEC facilities could be obtained by assuming that an area equal to the total reflector area has become completely black. Thus the new albedo is approximately 2/3 of the natural albedo in a region of intensive solar energy conversion. Figure 4.3 shows the land area assumed by Grether et al. (1977) to be devoted to STEC facilities.

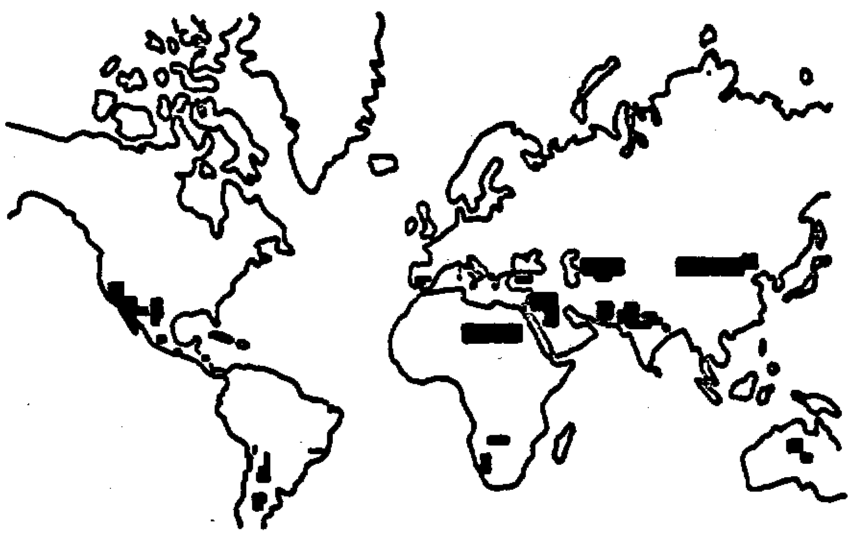


Figure 4.3. Scenario for land area devoted to solar energy conversion. Source: Grether et al. (1977)

Using this scenario, Potter and MacCracken (op. cit.) modified the zonally averaged albedo in the model within the zone 50°N to 40°S correspondingly. No other surface boundary conditions were altered (e.g. runoff, evaporation and surface roughness) even though these could also be influenced by large-scale deployment of STEC systems. Figure 4.4 shows the latitude-height change in atmospheric temperature between the case with STEC related albedo changes and the control case of the model.

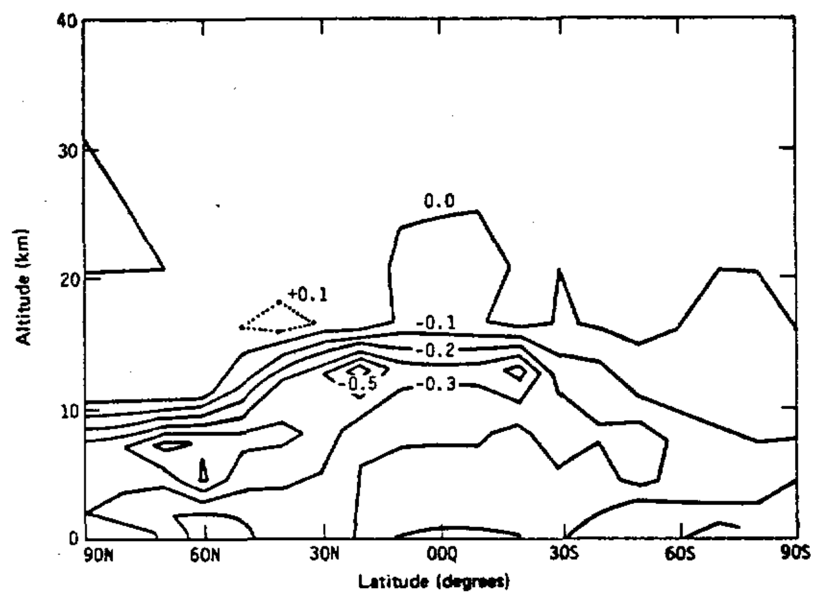


Figure 4.4. Latitude-height distribution of difference in temperature between model case considering large case solar energy conversion and control case (°C) Source: Potter and MacCracken (1977).

As might be expected, the troposphere warmed because of the increased absorption of solar radiation. The maximum warming occurred over the latitudes of largest coverage of solar facilities in the given scenario. Figure 4.5 illustrates the latitudinal distribution of precipitation change for the land area in each zone. A maximum increase in precipitation occurred in the Northern Hemisphere subtropics. In general, Potter and MacCracken (op. cit.) summarized the results of the experiments by characterizing the model response in the following feedback sequence: decreased surface albedo → warmer surface → increased evaporation and increased convection → increased precipitation in the subtropics and increased water vapour in high latitudes → increased surface temperatures at high latitudes → decreased equator-to-pole temperature gradient → decreased Hadley cell intensity → possible northward shift of the ITCZ (Intertropical convergence zone).

The results of the experiment made with the zonally averaged model by Potter and MacCracken should be considered as preliminary for two basic reasons. Firstly, the scenario investigated has several limitations not only because of the large amount of solar energy conversion that it assumes, but also because of the simple assumption made regarding the effective change in

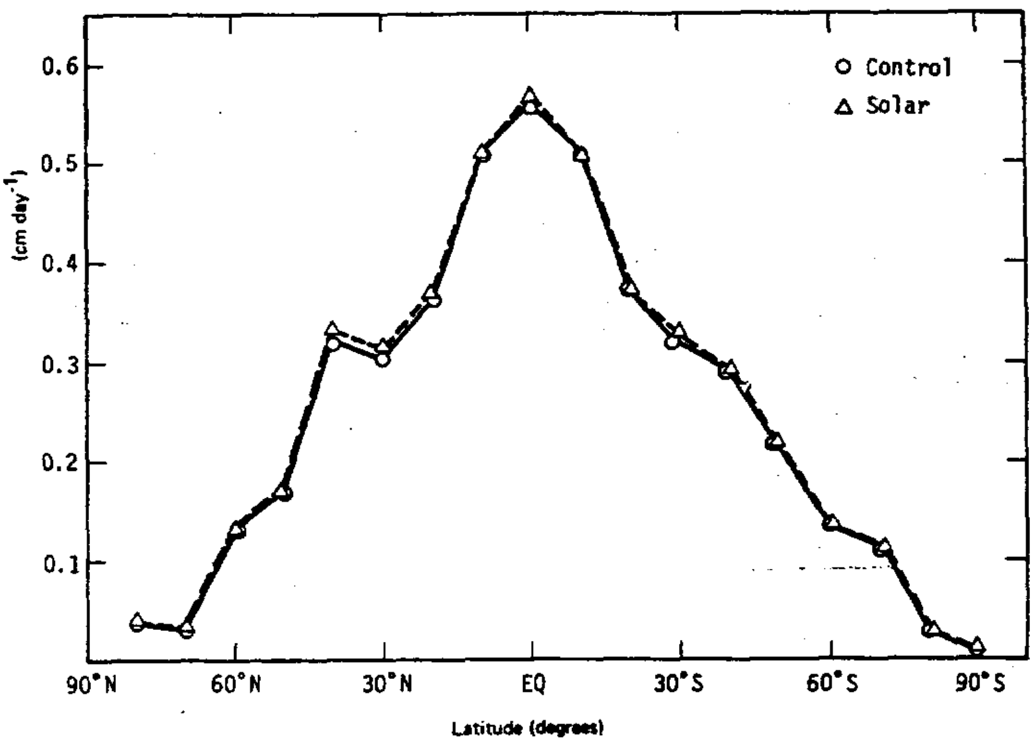


Figure 4.5. Daily average precipitation averaged over four simulated months for the control case and the case considering large-scale solar energy conversion (cm day^{-1}).
Source: Potter and MacCracken (1977).

boundary conditions. As described earlier in this section the large-scale deployment of STEC facilities is likely to change the local energy balance rather than the albedo, in particular because of the release of waste heat. Secondly, the effects of a zonally averaged albedo change were investigated within a zonally averaged model and it is difficult to extrapolate the results in order to evaluate the impacts of regional energy balance changes on the general atmospheric circulation. Nevertheless, the results do show that impacts are possible on the scale of the scenario illustrated in Figure 4.3.

Surface roughness. Very little is known about the potential impact of changes in surface roughness over large areas. In atmospheric GCMs a drag coefficient, which takes into account surface roughness, is used in the computations of horizontal stress components and the vertical fluxes of sensible heat and water vapor in the surface boundary. A limited number of experiments have been made with GCMs to investigate the impact of changes in the drag coefficient. The results of these experiments were briefly reviewed by Williams (1977) and suggest that the changes can have an impact on climate patterns but no scenarios relevant to the large-scale deployment of STEC facilities have been studied.

Surface hydrological characteristics. The potential impact of large-scale changes in surface hydrological characteristics deserves considerable attention. Results of model studies have recently confirmed the importance of large anomalies in surface wetness in influencing the atmospheric circulation. Namias (1960) has discussed the influence of abnormal heat sources and sinks on atmospheric behavior and in particular discussed the reasons for persistence of drought in the Great Plains area of the United States. The occurrence of an upper level anticyclone with dry subsiding air is characteristic for drought in the Great Plains area. Between spring and summer there is a tendency for upper level anticyclones to develop over the Southern Plains but there are many years when the anticyclone fails to become established. Studies of observed data show that if the upper level anticyclone is going to emerge strongly and persistently over the Plains in summer the spring contour pattern usually reveals a positive anomaly in the area. Namias (op. cit.) therefore investigated reasons for this correlation between the seasons and suggested that soil conditions play an important role. Thus, when the Southern Plains have been dominated in spring by a very dry regime, which is also usually very warm, and the soil is dessicated, it appears that the opportunity for persistent lodgement for the upper level anticyclone in the early summer would be favored because the area may assume characteristics like those of deserts above which upper level anticyclones are found. On the other hand, Namias suggested, after a wet spring some of the heat normally used to raise the temperature of the ground surface might be used to evaporate the excess water in and on the soil, and thus not be able for sensible heating of the air perhaps necessary to sustain the upper level anticyclone. Observed data support this hypothesis.

Walker and Rowntree (1977) examined the sensitivity of a model of the tropical atmospheric circulation to changes in moisture content. The model considered a zonally symmetric representation of West Africa. In one experiment there was a desert in the same latitudes as the Sahara; in another experiment the desert was replaced by wet land. Results suggested that once the land was moist it maintained itself in this state for at least several weeks, whereas initial aridity north of 14^0N was sustained, suggesting that ground dryness itself can cause deserts to persist and vice versa. Barry and Williams (1975) noted that the absolute values of precipitation in a July control case of one version of the NCAR GCM were almost consistently too large, primarily because of the assumption of a Bowen ratio (ratio of sensible to latent heat flux at the surface) equal to unity. An experiment with the Bowen ratio equal to ten, which corresponds to greatly reduced evaporation, gave much more realistic (i.e., compared with observed data) values of released latent heat at 1500 m (and presumably therefore precipitation) over arid regions of the world.

It can be concluded that large-scale changes of albedo, surface roughness and surface moisture characteristics can influence the atmospheric circulation and, in particular, several feedback mechanisms can be elaborated. Although the impacts of large-scale deployment of solar energy conversion facilities have not been investigated in detail, model and observational studies suggest that impacts are possible.

4.2.2. Photovoltaic Conversion Systems (PV)

A second alternative to produce electricity from solar energy is the direct conversion of solar energy using solar cells, referred to as photovoltaic (PV) conversion. Solar cells are highly absorbing when coated with an antireflection layer; the absorptivity can reach 95%. The conversion efficiency, however, of PV elements ranges from about 5% for CdS thin film cells to about 20% for GaAs/GaAlAs cells. Silicon cells have exhibited efficiencies as high as 18%. For the large-scale conversion of solar energy, one can envisage the paving of large regions with PV converters, embedding them in the ground with a coverage of perhaps 95%. If a maximum conversion efficiency of 20% is assumed then a one-square-meter array of silicon solar cells would generate 200 W when the axis of the array is directed at the sun. It has also been suggested that at an efficiency of 10% a collector area of 10 km^2 could be used to generate a peak power of 1000 MW.

The impact on climate of large-scale deployment of PV conversion systems has not been evaluated. If we assume a zero-order description of such a system, which absorbed 95% of the incident radiation and converted 20% of that energy to electricity, then of 100 units of incoming radiation only 5 units would be reflected, 14 units would be carried away as electricity and the remaining 76 units would enter the atmosphere immediately overlying the solar cells as longwave radiation, sensible heat and latent heat. On such a simple level, therefore, the PV cell array would act as a local heat source. This ignores questions regarding requirements for cooling of the arrays in order to maintain efficiency, for example. Nevertheless, it would appear that to a first approximation the climate impact would be similar to the impact of a large-scale reduction of the albedo and this has been discussed in the previous section. The possibility that the addition of heat to the atmosphere could cause increases in convection and cloudiness and rainfall should be considered. The second impact of large-scale PV conversion would be through the paving of large areas, leading to changes in surface hydrological characteristics and this topic has also been discussed for STEC systems.

4.2.3. Ocean thermal energy conversion systems (OTEC)

Ocean thermal plants would use the vertical thermal gradients (20°C) of the tropical oceans to produce shaft horsepower in low temperature difference turbines, which could then be used to produce electricity, synthetic fuels, or liquid air. Unit sizes under consideration are as large as 480 MW. An important point is that the conversion efficiency of such systems is very low (~5% at best) and the temperature difference involved is very small implying the need for large flows of water.

Zener (1973) calculated that by siting OTEC plants all through the oceans between 20°N and 20°S a total of 60 TW(e) could be generated and estimated that this would result in a persistent 1°C decrease in the ocean surface temperature over this zone. Harrenstien and McCluney (1976) calculate that OTEC plants would lower the surface temperature of the Gulf Stream by 0.5°C if there were enough plants to generate the current U.S. electrical demand of $\sim 2 \times 10^5$ MW(e).

A second possibility for the extraction of energy from the oceans is that of using the kinetic energy of strong ocean currents. Von Arx, Stewart and Apel (Stewart, 1974) estimate the effect on the Gulf Stream near the coast of Florida of extracting electrical power by using turbine arrays. They suggest that a reasonable turbine array could yield about 1000 MW. However, as Baker (1977) has pointed out, the total kinetic energy of the current in this location is 25,000 MW and the turbine array would therefore be extracting at least 4% of the kinetic energy. The effect of such an extraction on Gulf Stream dynamics is not known, but could be important because of the potential sensitivity of the meandering path of such western ocean boundary currents to local changes and the possible importance of that path to air-sea exchange in subpolar regions.

In addition to the impacts on the ocean temperature distribution and kinetic energy of ocean currents, the climate impact of OTEC systems could arise through secondary effects from the transer of colder deep ocean water to the surface layers. Firstly, the colder deep ocean water is enriched in CO_2 and von Hippel and Williams (1975) suggest that the release of this water at the surface will mean that an ocean thermal plant would release about one-third as much CO_2 to the atmosphere as does a fossil fuel power plant of equivalent energy production. Secondly, the deeper ocean water has an enhanced nutrient supply and it is therefore possible that the release of this water at the surface will lead to phytoplankton blooms and thus possibly to widespread ocean surface albedo changes.

The largest effect on climate likely to arise form large-scale deployment of OTEC systems would be caused by OTEC-induced sea surface temperature anomalies (SSTAs). The other major effect is likely due to the interference with ocean currents. The poleward transport of energy by ocean currents plays an important role in the climate; Vonder Haar and Oort (1973) estimate that in the region of maximum net northward energy transport (30^0N to 35^0N) the oceans transport 47% of the required energy. At 20^0N the peak ocean transport accounts for 74% of the required energy transport at that latitude. Interference with the northward transport of energy by the oceans could have large-scale climatic effects.

4.2.4. Wind and wave energy conversion systems

The practical maximum use of wave energy conversion is likely to be less than 1 TW, so it is unlikely that any climatic impacts from the deployment of such systems could be perceived. The practical maximum use of wind energy conversion systems, it is suggested, is on the order of 1-10 TW.

Wind energy conversion (WEC) is accomplished using wind turbines. The individual units for a central power station would be quite large, a horizontal axis machine might have a blade diameter of 100 m and an output rating of 2 MW(e) for winds of 7 m/sec. The maximum extractable power is considerably smaller than the total available power. The power that may actually be recovered from a wind energy machine is a function of a number of variables including the windspeed itself. The theoretical maximum efficiency for a given windspeed is about 60% but in practice efficiencies of 47% and 35% have been found for horizontal and vertical axis wind machines respectively.

The main effect on climate of WEC systems would be on a local scale. Hewson (1975) in assessing the impact of large-scale use of wind power, states that it is improbable that any appreciable impact on climate could be detected. He suggests that the possible effects may be thought of as growing a number of groves of tall trees. In a wind the branches of the trees extract energy from the wind (as shown by their swing) as do the rotating blades of a turbine. There might be a slight slowing of the winds for a short distance downwind from an array of windmills, but the winds would rapidly accelerate because of downward transport of momentum from the stronger winds aloft.

4.2.5. Hydropower systems

The practical maximum use of hydropower systems is 5 TW compared with a present supply of less than 0.2 TW. Further development of hydropower is resource limited in most industrialized nations, with the greatest remaining resources in Africa and Latin America. From the maximum practical use of hydropower, no global scale climatic changes can be expected. On a local scale, changes in evaporation, cloud cover and precipitation could occur due to the damming of large amounts of water. Another possible source of hydropower has been discussed recently by Partl (1977), who suggests that in the southern parts of Greenland, large quantities of water melting every summer offer favorable conditions for a large-scale hydropower development. From 12 to 15 potential sites a total installed capacity of 60-120 GW is calculated. Partl (op. cit.) judges that no climatological impacts of global importance are likely from this scheme. 100-200 km^3 of ice mass would be tapped annually in excess of the present conditions because of increased melting. However, it is judged that this is negligible in comparison with the total volume of the Greenland ice cap of 2.600,000 km^3 and the limits of natural variations of accumulation and ablation. Local impacts are likely because of the supply of warmer water from reservoirs to the surrounding ocean. If this scheme were realized then clearly a climatological impact assessment would be necessary.

4.2.6. Biomass conversion

High quality fuels such as ethanol, produced from biomass, could be of great importance in much of the developing world and in some regions of the industrialized world. However, although total photosynthetic production exceeds present primary energy consumption by a factor of 10 or more, competing demands for land for food, fibre and lumber, will probably limit this option to a few TW(th). The maximum theoretical efficiency for photosynthetic energy conversion is about 6.5% while actual efficiencies in the most productive species (sugar cane, certain algae) are about 2%, with the net throughput efficiency from solar energy to high quality liquid and gaseous fuels of about 1%.

It is probably unrealistic to contemplate extremely large-scale deployment of biomass conversion systems, mostly because of the land requirements and further agricultural problems. It has been calculated that a 400 MW steam electric plant might be supported by a plantation of 370 mi^2, compared with a self contained coal fired facility operating on an area of about 1.6 mi^2 (Bhumralkar, 1977).

The potential climatic effects can be divided between those due to the production/collection of biomass and those due to the conversion of biomass into electrical or chemical energy. Among the former, albedo, roughness and surface hydrological characteristic changes are possible due to widespread biomass cultivation. Among the latter, changes in atmospheric concentrations of gases and particulates, and additions of waste heat are possible.

4.2.7. Solar satellite power systems (SSPS)

These systems would consist of geosynchronous satellites converting solar radiation to microwaves which would be beamed to the earth's surface and converted there to electricity. The resource requirements, development costs and economics of mature plants mean that it is questionable whether these systems will contribute to the global energy supply. Ridpath (1978) points out that studies indicate that over 100 SSPs could provide 30% of the U.S. electricity needs by the year 2025. The satellites would be heavy (estimated: 18,000 tons each) and launched by space shuttles capable of launching 500 tons into orbit at a time. The present shuttle will lift 29 tons or so. Thus, the environmental impact of a steady stream of super-rocket launchers (perhaps one a day for years on end) must be evaluated. In addition the impacts of the microwaves and of their collecting system would also have to be evaluated if large-scale deployment of SSPS were to be considered.

4.2.8. Conclusions

The physical characteristics of the various solar technologies are now sufficiently well known to permit preliminary studies of possible environmental impacts. In many cases the necessary analysis and/or physical measurements have not been carried out. Hence some of the physical consequences of the conversion systems must be inferred in a semiquantitative or semiqualitative manner through recourse to analogies.

The climatic implications of the physical effects of the solar systems are hard to quantify. Estimates must be made on the basis of results from climate models or observations of analogous perturbations in the climatic system. An example is the speculation on the possible climatic impacts of OTEC plants using the results of analysis and observation on the effects of large-scale SSTAs. So, identification of possible climatic impacts has proceeded from a highly quantitative engineering description of the technologies to a semiquantitative description of the physical effects of such systems, to a qualitative description of climatic implications.

Two areas have to be investigated further: the direct physical effects of solar facilities, and the subsequent climatic implications of these effects.

With regard to the physical effects of the facilities, considerable work, including analysis and computer modeling, as well as measurements on scale models and actual facilities, is required to quantify these effects. The further investigation of the climatic implications of such effects will involve both computer modeling and investigation of analogies in the climatic system. Because of uncertainties in the technical and economic status of all of the solar technologies, it is not obvious which (if any) of these will be used initially on a substantial commercial scale. Therefore we recommend investigating the climatic implications of each of the major solar technology options, at a level consistent with the utility of the available tools, especially computer modeling.

4.3. Regional Meteorological Effects of STEC Systems--Joint Project with Stanford Research Institute International (SRI) to Investigate the Regional Meteorological Effects of a STEC Power Plant in Southern Spain

4.3.1. Introduction

As a result of the discussions at the workshop on climate and solar energy conversion described above, a joint project was set up between the IIASA Climate and Energy Subtask and the Stanford Research Institute International (Menlo Park, California) to make a preliminary evaluation of the impact of the large-scale installation of a STEC plant on regional meteorological conditions.

4.3.2. The numerical model

The numerical model used in this joint project was developed by Bhumralkar and a brief description can be found in Bhumralkar and Alich (1976). The main characteristics of the model are described in Table 4.1; it is two-dimensional and suitable for analysis of weather disturbances with dimensions of several hundred kilometers initiated by perturbations only a few kilometers in size. A version of the same model without the ground surface temperature computation was used by Bhumralkar and Alich (1976) to assess the meteorological effects of the ejection of large amounts of waste heat from a power park.

Table 4.1. Main characteristics of the numerical model used to investigate the effects of a STEC plant on meteorological conditions

Characteristics	Model Treatment
Geometry	Rectilinear (two-dimensional).
Domain	Variable grid mesh length. For this study, the vertical dimension was taken as 8 km, the horizontal dimension as 400 km. The grid spacing in both dimensions is unequal.
Horizontal wind	Initial ambient wind is specified.
Boundary layer	Ground surface temperature computation (Bhumralkar, 1975).
Hydrodynamic equations	Primitive, hydrostatic.
Variables considered in this study	Vertical velocity, relative humidity, potential temperature, precipitation/supersaturated areas.

It was decided to investigate the effects of a STEC facility in Southern Spain on the meteorological conditions in both January and July. In order to examine the effects of large-scale installations, an area of about 1000 km^2 for the STEC plant has been assumed. Such a plant could generate roughly 30 GW(e) and might be considered more as a "solar power park". Figure 4.6 shows the location of the STEC plant which has been studied, together with a schematic representation of the grid used within the model. It is seen that, through the assumption of an area of about 1000 km^2, the horizontal dimension of the plant is 32 km. However, a total horizontal dimension of 400 km is considered in order that meteorological conditions upstream and downstream of the STEC plant could be accounted for.

The STEC plant was considered to have a SW-NE orientation, since this is the direction of the prevailing wind. The map in Figure 4.6 also shows the locations of meteorological stations, from which meteorological data have been derived for the initial conditions of the model integrations (e.g., initial wind direction and speed, temperature, humidity). The data for these stations were plotted and interpolated to the model grid points.

The land surface was divided up in the moded integrations to include the effects of the STEC installation, and the components of the surface energy balance for grid points which were not affected by the STEC plant. There are basically four types of surface to be considered in the model calculations. The ocean surface, with a reflectivity of 6% and land area with a reflectivity of 15% are unaffected by the STEC plant. In addition, there is land area which contains the structures of the STEC plant (cooling towers, storage facilities, etc.) which is assumed to have a reflectivity of 30% since man-made surfaces are generally considered to have a higher reflectivity than natural ones.

For the ocean area, for example, of the 100 units of incoming solar radiation, 6 units are reflected. The remaining 94 units are absorbed by the surface and 60 units are emitted as long-wave (infrared) radiation while 34 units enter the atmosphere as sensible and latent heat (by conduction, convection and evaporation). The division between LW and SH just described, was made on the assumption that the ratio of LW/SH equals 1.8.

For the grid points in the land area containing STEC structures the only difference in the energy balance components arises because of the different reflectivity of the surface. For the mirror-covered area (25% of the area of the STEC plant), the energy balance components are quite different. Of the incoming direct solar radiation which reaches the mirror surface, 90% is reflected and 10% is absorbed. The latter 10% is subsequently re-emitted as long-wave radiation and sensible or latent heat. 15% of the 90% that is reflected (i.e., 13% of

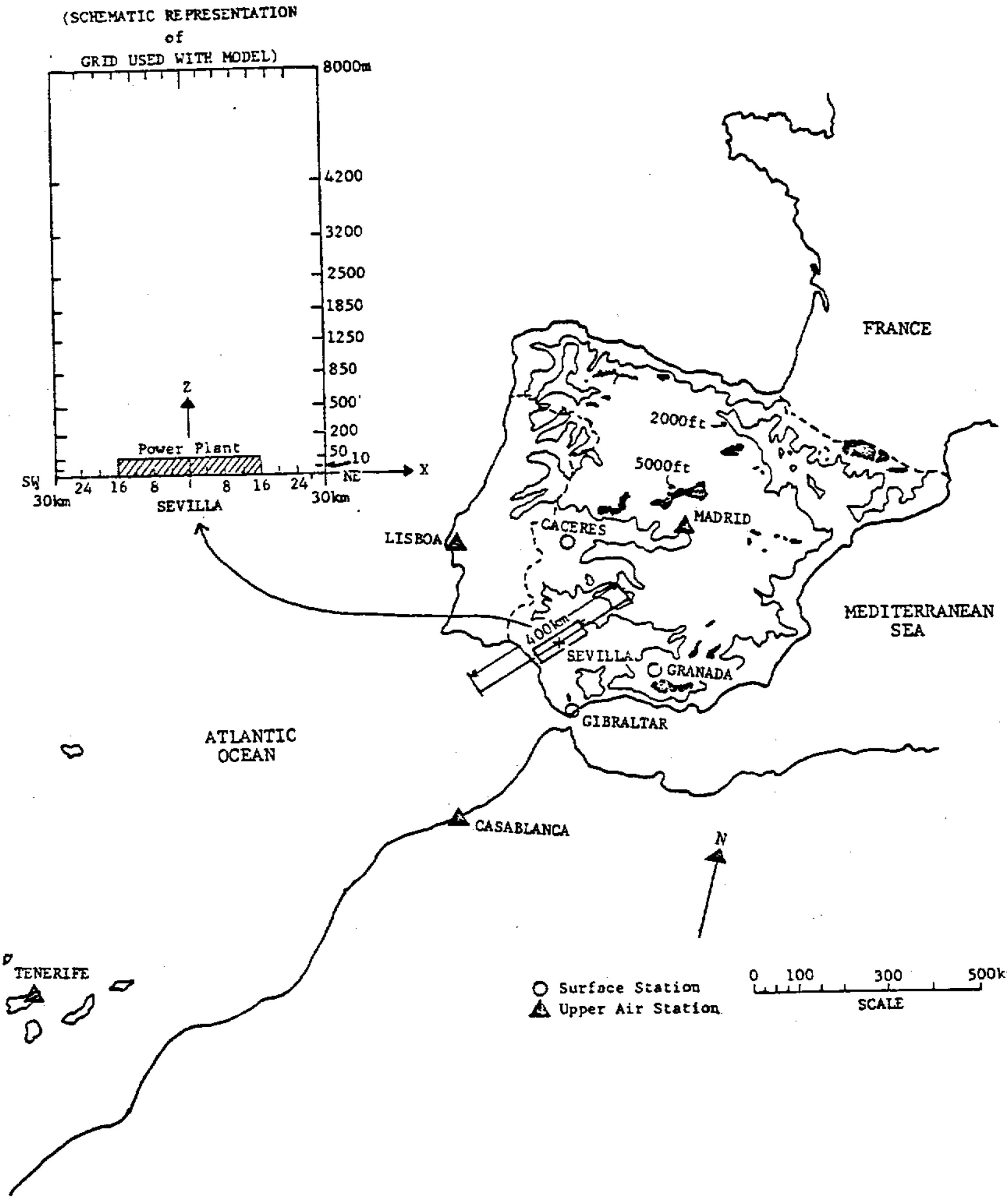


Figure 4.6. Location of STEC plant, together with a schematic presentation of the grid used within the model

the incoming radiation) goes to the atmosphere, while the remaining 77% of the incoming radiation is reflected to the central receiver. The receiver losses, due to non-ideal absorption, amount to 6% of the radiation incident upon the heliostats. Piping and storage losses amount to 4% of the radiation incident upon the heliostats. After these losses, 66% of the radiation incident upon the heliostats is available for electricity generation, and assuming an efficiency of 0.30, 22% goes to the electricity grid while 44% is released as waste heat.

These perturbations to the energy balance were used as input to the numerical model to simulate the effects of a 1000 km^2 STEC plant. It was assumed that the heliostats would all be grouped together, covering 25% of the STEC area. This is a "worst case" assumption, since in reality they would be distributed over the whole area. The waste heat was inserted at the level of the model atmosphere 200 m above the surface.

The results of four runs of the model will be described below. The first two cases were started with initial conditions derived for a July day. The second two cases were started with initial conditions for a January day. Each pair of integrations consists of a control case, with unperturbed surface energy balance, and a STEC case, with surface energy balance changes due to the STEC plant as described above.

4.3.3. Results of model experiments

Impact of STEC plant in Southern Spain on July meteorological conditions. As mentioned above, the initial conditions for the summer cases were interpolated from the meteorological stations indicated in Figure 4.6 for a particular July day. The model was integrated forward in time for a simulated period of 9 hours. Figure 4.7 shows the development of the surface potential temperature for the summer control case during the first two hours of the simulation. After an initial drop between $t = 0$ and $t = 0.5$ hours, the temperature at all of the grid points increases with time. In contrast, Figure 4.8 shows the development of the surface potential temperature during the first two simulated hours of the summer case with the STEC plant. The location of the grid points which are in the STEC plant area are indicated. It is clear that the STEC plant is causing a perturbation to the surface potential temperature in comparison with the control case. Over the mirror-covered area the potential temperature decreases as a function of time, because the ground surface is absorbing less solar radiation than it would in the absence of the heliostats. The surface potential temperature in the land area covered with STEC plant structures is increasing with time. Thus, comparing the surface potential temperature at $t = 2$ hours in the summer control and STEC plant cases, it is seen that at the grid points where

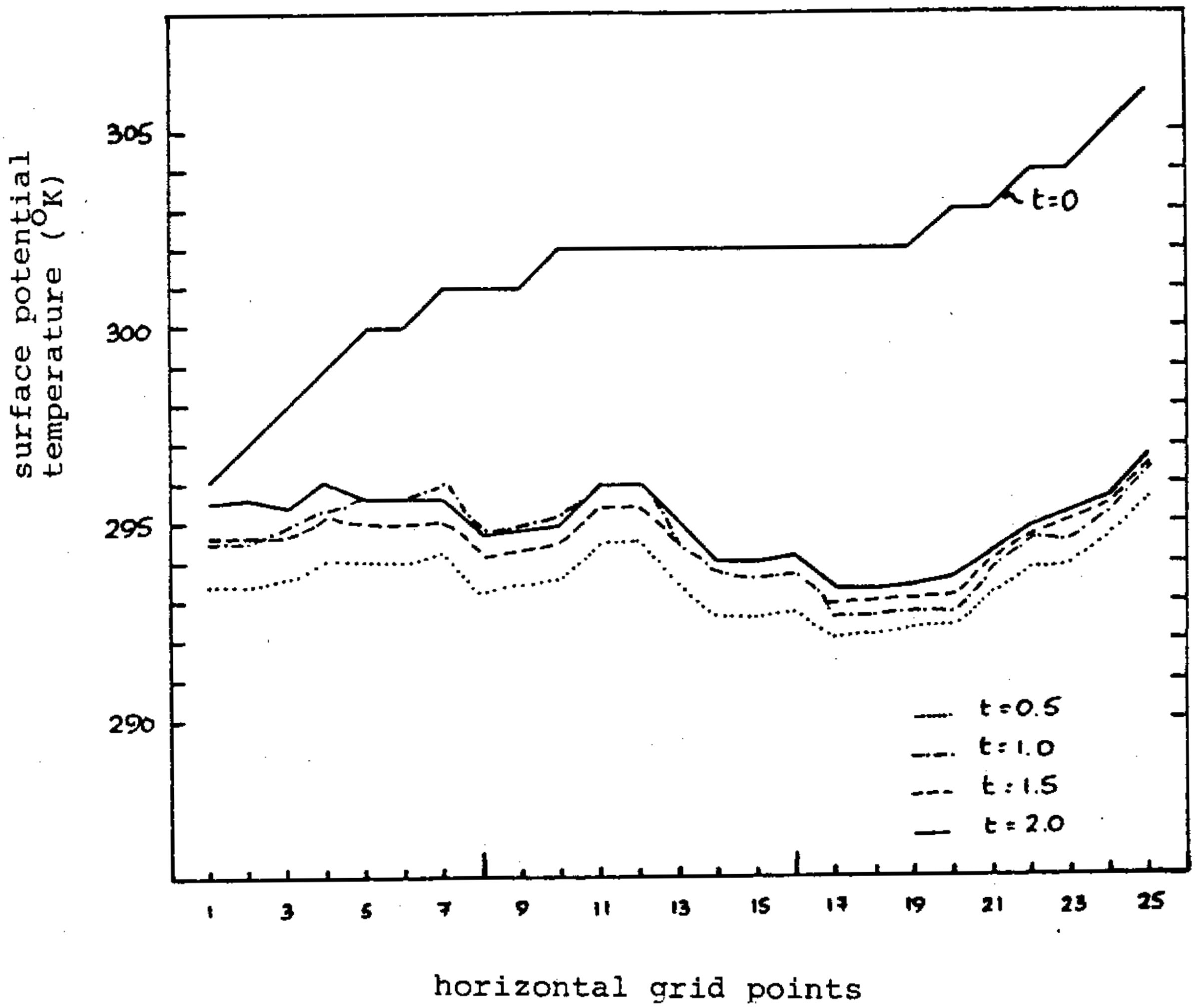


Figure 4.7. Development of surface potential temperature for first two hours of simulation in summer control case.

the surface energy balance was not perturbed the temperatures are similar in the two cases. At the grid points with the STEC plant, the largest temperature increase occurs on the upstream side of the mirrored area.

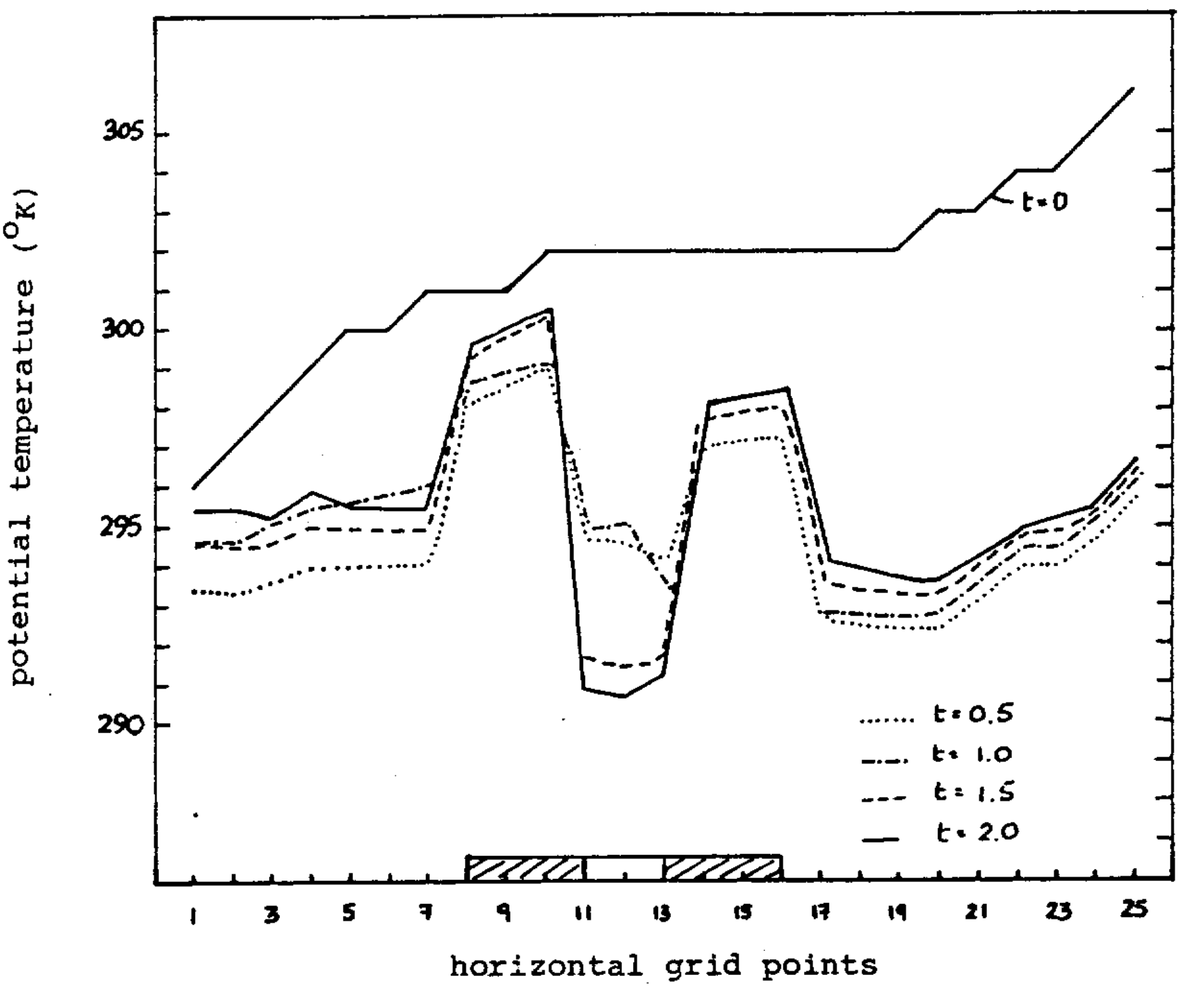


Figure 4.8. As in Fig 4.7 but for summer STEC plant case

Figure 4.9 shows the horizontal-vertical distribution of vertical velocity w in the atmosphere for the initial conditions and for t = 6 hours in the summer control case and the summer STEC plant case. For the initial conditions the vertical velocities are weak or non-existent with one small area of sinking air over the land area. After six hours of simulated time in the control case, the vertical velocities have a larger magnitude, with very weak sinking motion in the lower atmosphere over the land area. After six hours of simulated time in the case with the STEC plant, it is seen that a region of strong upward vertical velocity has developed over the land area affected by STEC structures upstream of the mirror-covered area. This is the area over which it was noted that a considerable increase in surface potential temperature has occurred by t = 2 hours.

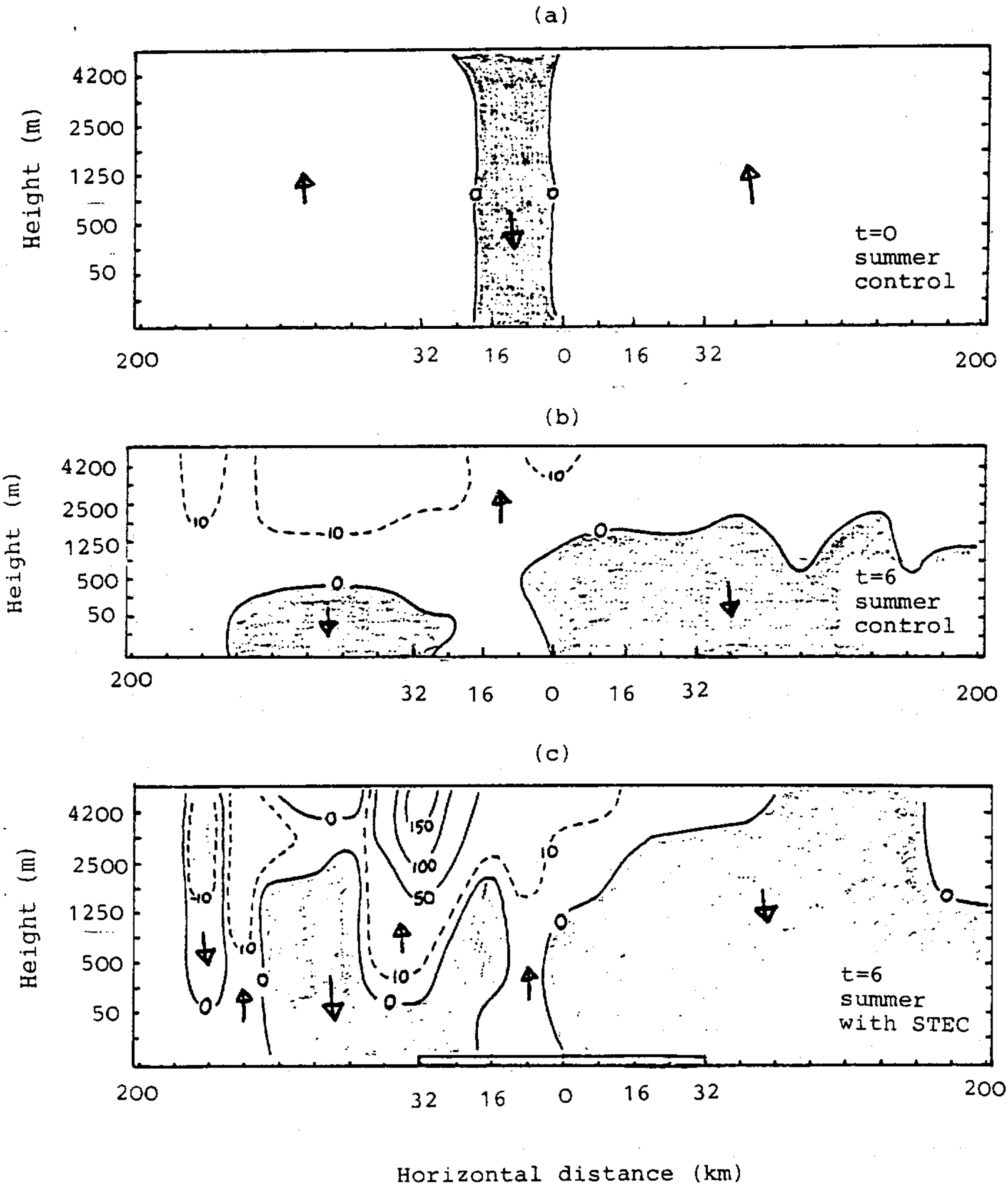


Figure 4.9. Horizontal-vertical distribution of vertical velocity in the atmosphere for (a) initial conditions (b) after six hours simulated time in summer control case (c) after 6 hours of simulated time in summer STEC case.

Figure 6.10 shows the horizontal-vertical distribution of relative humidity for the initial conditions and after 6 hours of simulated time in the summer control case and case with the STEC plant. In the initial conditions the relative humidities are around 70-90% in the lower third of the atmosphere and less than 50% in the top half of the atmosphere. After 6 hours of simulated time in the summer control case there is a reduction of the relative humidity in the lower third of the atmosphere to around 70-75%, while there is an increase in the relative humidity higher up, where the values are about 80-90%. At no point in the control case has the relative humidity reached 100%. In the case with the STEC plant, the surface energy balance changes which were introduced, together with the waste heat added from cooling towers, has led to a region where the relative humidity is greater than 100%. This area can be considered to be cloud and further investigation showed that over the area of greatest surface potential temperature increase, where the vertical velocity became strongly upward and the air became supersaturated, there was precipitation. In the control case no precipitation occurred after six hours of simulated time.

After 8 1/2 hours of simulated time the summer control case reached a steady-state condition. After 8 hours in this control case some cloud formation was noted over the land area, but this appeared to be a normal meteorological situation, which can be referred to as a sea breeze situation. The air begins to rise over the land and clouds form when the upward motion and humidity conditions permit cloud formation. The sea breeze consists basically of air rising over the land, sinking over the ocean, with compensating landward breeze at the surface and oceanward aloft. The sea breeze thus acts to move the clouds away from where they form in a normal situation toward the ocean. This was observed in the summer control case without the STEC plant.

In the summer case with the STEC plant the vertical motion, which was noted after six hours of simulated time, subsequently weakened and the system began to die out.

It can thus be concluded that for the July case which investigated the inclusion of the surface energy balance effects of a 1000 km^2 STEC plant in Southern Spain, these changes lead to earlier and more persistent cloud formation than in the normal sea breeze situation in which the clouds form later in time and are quickly moved oceanward rather than remaining over one area.

Impact of STEC plant in Southern Spain on January meteorological conditions. Using the same physical characteristics for the STEC plant as described in Section 4.3 and used in the July case, but with different initial conditions, the impact on January meteorological conditions was investigated.

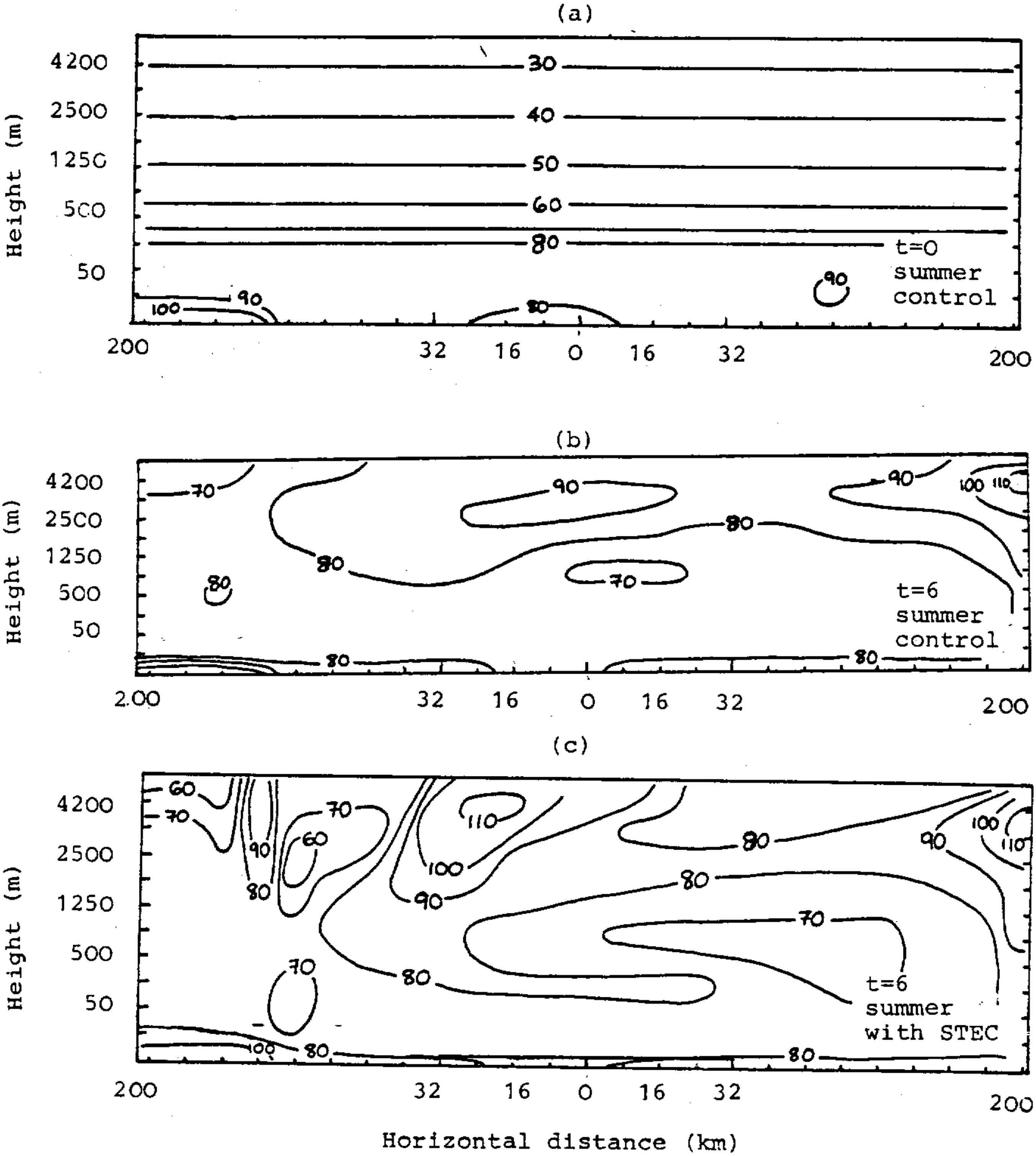


Figure 4.10. As in Fig. 4.9 but for relative humidity

The control case and the case with the STEC plant were integrated out for 4 hours of simulated time. It was found that in the January case, the prevailing wind was strong enough to prevent cloud cover over the land developing although in the case with the STEC plant a small increase in humidity was noticeable.

4.3.4. Discussion

This preliminary effort, using a validated model of regional meteorological conditions, has shown the potential impact of large-scale deployment of STEC facilities on the January and July conditions in Southern Spain. The results suggest that with the STEC plant, the cloud development is earlier and more persistent during the summer. In winter the prevailing wind is strong and thus the area around the power plant is ventilated and no regional meteorological effects were found.

The results are however preliminary. There is a need to carry out further sensitivity tests--further January and July simulations the same as those described above. Also, different initial conditions should be investigated--different sized STEC plants, dry cooling instead of wet cooling. The impact of large-scale deployment of STEC plants in other climatic regions would also be valuable.

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5. THE IMPACT ON CLIMATE OF PARTICLES AND GASES

5.1. Introduction

In addition to releasing waste heat and/or carbon dioxide into the climate system, energy conversion processes can emit other gases and particulate matter which are able to influence the climate. Combustion of fossil fuels releases soot and ash directly into the atmosphere and particles are also formed by chemical reactions within the atmosphere from the gaseous products of combustion--sulphates, organic nitrates, sulphuric and nitric acid and hydrocarbons. Other gases which are released into the atmosphere as a result of man's activities include: chlorofluorocarbons (CF_2Cl_2 and $CFCl_3$), CH_4, NH_3, NHO_3, SO_2, C_2H_2 and CH_2Cl_2.

5.2. Sources of Particles and Their Impact on the Earth-Atmosphere Heat Balance

It has been established from theory and observation (see, for example, Mitchell, 1975) that particles with a diameter of order 0.1-5 μm are of special concern in the heat balance of the earth-atmosphere system, since they are relatively abundant in the atmosphere and are highly effective in scattering, absorbing and attenuating solar radiation. Particles smaller than 0.1 μm have a negligible mass and larger particles do not have a sufficiently long residence time in the atmosphere to have more than a very localized effect on climate.

Table 5.1, adapted from Robinson (1977), summarizes two estimates of the annual production of particles by natural and anthropogenic means. The ranges given in the table illustrate the considerable uncertainties in the estimates. It is clear that global particulate release due to man's activity is smaller than the total natural release but not an insignificant fraction. A further estimate of the source strength of atmospheric particles is given by Mitchell (1975), who estimates that the total source strength of particles smaller than 5 μm diameter is 1.6×10^9 tons yr^{-1}. Of this about 20% ($\sim 3 \times 10^8$ tons yr^{-1}) is from direct inputs from man's activities and a further 10% is estimated to derive from natural sources that arise indirectly from man's activities, such as grass and forest fires set by man, slash and burn agricultural practices, wind blown dust associated with man's disturbance of the natural ground cover etc. About 90% of the particles in the atmosphere at the present are confined to the troposphere. The remaining fraction is contained in the stratosphere and consists primarily of volcanic dust. The stratospheric loading may vary by as much as two orders of magnitude from year to year since it depends on the timing and magnitude of significant volcanic injections.

Particles in the size range 0.1-5 μm diameter have a relatively small impact on terrestrial long-wave radiation (larger sized particles are more likely to interfere with long-wave

Table 5.1. Global amounts of particulate release to atmosphere (Tg/year) (Adapted from Robinson, 1977)

Source	Natural	Anthropogenic
A. Primary particles		
fly ash		36
iron & steel industry		9
nonfossil fuels (wood, mill wastes)		8
petroleum combustion		2 (10-90)
incineration		4
agricultural emission		10
cement manufacture		7
miscellaneous		16
sea salt	1000	
soil dust	200 (428-1100)	(?)
volcanic	4	
forest fires	3 (3-150)	(?)
Subtotal	1207	92
B. Secondary particles		
sulphate from H_2S	204 (130-200)	
sulphate from SO_2		147 (130-200)
nitrate from NO_x	432 (60-430)	30 (30-35)
ammonium from NH_3	269 (80-270)	
organic aerosol (terpens, hydrocarbons, etc.)	200 (75-200)	27 (15-90)
Subtotal	1105	204
TOTAL	2312 (773-2200)	296 (185-415)

radiation, but as pointed out above, large concentrations of these particles are considered to occur only locally in dust-storms or near urban-industrial centers). In the past it was often assumed that the interaction of particles with solar radiation is due almost entirely to the scattering effect of the particle. However, it has become clear that some kinds of particles have absorpiton efficiencies which are large enough to impact the atmospheric temperature.

If a non-absorbing particle scatters solar radiation, some of the scattered radiation will be directed upward and this radiation will be lost to space resulting in an increase in the net albedo of the earth-atmosphere system and thus a net cooling. When a particle absorbs some of the solar radiation, the particle and the air around it become heated, while the total energy *available* to heat the earth's surface is decreased. The question of whether the particles cause a net heating or cooling of the earth-atmosphere system requires consideration not only of the absorption and scattering characteristics of the particles but also the albedo and water content of the underlying surface (see, for example, Mitchell, 1975; Kellogg, 1978). These two properties are of major importance in determining the extent to which the *available* solar energy which is denied to the surface by the absorption and scattering of the particles would *actually have been used* for heating in the absence of the particles and where in the atmosphere the heating would have occurred in the absence of the particles. Figure 5.1, from Kellogg (1977) computed by Chýlek and Coakley (1974) shows the relationship between the ratio of the particle absorption to its backscatter (a/b) and the albedo of the underlying surface. For conditions occurring in the domain above the curve there would be a decrease in the net earth-atmosphere albedo and consequently a warming of the earth-atmosphere system. As shown in the figure, when particles of a given a/b are over a dark surface, such as the ocean, they are more likely to increase the net albedo than when they are over a more reflecting surface such as a snowfield, a low cloud cover or over land generally. Weare et al. (1974) have shown how the impact of added particles depends on the location of the particles within the atmosphere with respect to average cloud amount, the cloud reflectivity and the underlying surface reflectivity.

The ratio of absorption to backscatter for different kinds of particles is not an easy property to measure directly or infer from theory. For example, the scattering efficiency of particles depends on factors such as the complex index of refraction (real and imaginary parts), the particle size spectrum and the particle shape. There are thus very large uncertainties regarding the impact of anthropogenic particles. Kellogg (1978) states that recent evidence points out that most of the anthropogenic particles exist over land, near where they are formed, and that they are sufficiently absorbing to reduce the net earth-atmosphere albedo and thereby warm the system (Kellogg et al., 1975; Eiden and Eschelbach, 1973; NSF, 1976; Weiss et al., 1977; Brosset, 1976).

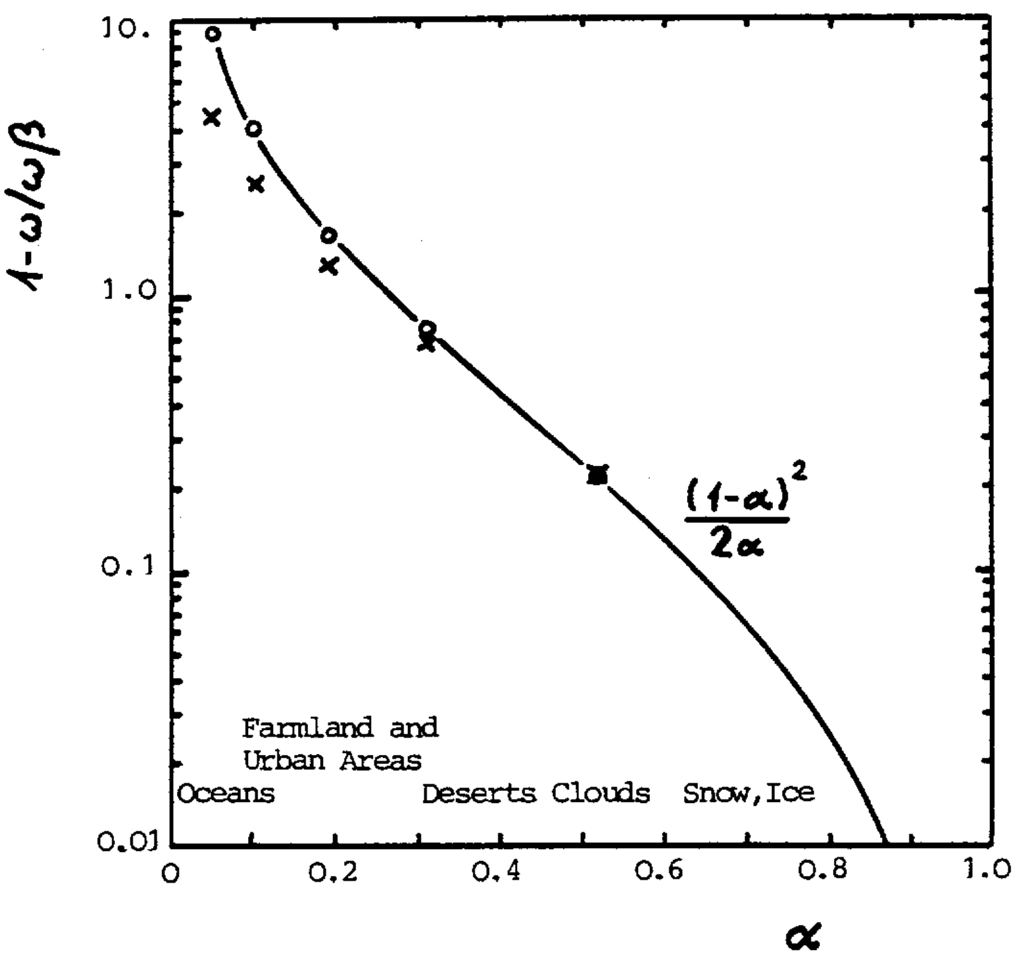

Figure 5.1. Critical ratio of solar radiation absorption to average upward-scattering cross sections as a function of surface albedo. The curve with the circles represents results of the radiation model of Chýlek and Coakley (1974), which takes account of solar radiation only. For conditions represented in the domain above this curve there will be a decrease in the net earth-atmosphere albedo as a result of the aerosols, and consequently a warming. The "x" symbols represent a typical case, calculated by Coakley (private communication), in which both solar and infrared effects are combined, showing that the infrared effects tend to enhance the warming influence of aerosols.

Mitchell (1975) points out a further interaction between the atmosphere and particles which emphasizes the uncertainty in determining whether a warming or a cooling of the earth-atmopshere system would occur. To the extent that atmospheric particles attenuate solar radiation (through absorption or backscatter) the particles are likely to reduce the rate of evaporation of water from the surface and thus lead to a decrease of global average cloudiness and precipitation. The decrease in cloudiness could be enough to allow more solar radiation to the surface and offset the initial surface cooling. However, it is unlikely that the cloudiness would *exactly* offset the initial thermal reaction to particles, or do so in the same geographical areas. Since the particle loading is and will be non-uniform over the globe, geographical inequalities in the radiative effects of particles could induce large-scale changes in the atmospheric circulation and regional temperature changes which differ from the global average change. There is an obvious need to study the interactions between particles, radiation, the temperature distribution of the earth-atmosphere system and ultimately the entire climate system with the aid of models and the required improved observations of the distribution and properties of man-made particles.

It should be mentioned at this point that there is a difference in the impact of man-made particles which mainly stay in the troposphere and volcanic particles which are injected into the stratosphere (Mitchell, 1975). A net cooling of the earth's surface and the lower atmosphere is to be expected and has been observed following an increase in stratospheric particle loading. After the 1963 eruption of Mount Agung in Bali, northern hemisphere temperatures fell by about $0.5^{0}C \pm 0.14^{0}C$, significant at the 1% level (Angell and Korshover, 1975). Krakatoa in 1883 produced a world-wide cooling, together with spectacular sunsets, as its dust spread around the world and scattered sunlight.

Reck (1974, 1975) has investigated the response of the Manabe and Wetherald (1967) radiative-convective model to particle loading. Results of one set of experiments suggested that a doubling of the particle loading in the lower layer of the troposphere in polar areas would lead to a surface temperature increase.

Another interaction between particles and the radiation balance has been suggested by studies such as those of Twomey (1972) and Liou (1976), who find that theoretical calculations involving the scattering and absorption by plain water droplets would suggest that clouds should be more reflective than they are actually observed to be. The difference is thought to be due to the presence of particles and the decrease in cloud reflectivity is thought to occur whether the particles are included within the cloud droplets or floating between them. The observed reduction of cloud reflectivity is 10-20%, so that any increase in absorbing particles could cause probably significant additional absorption of radiation by clouds and this represents a further source of atmospheric heating due to particles added to the lower atmosphere.

5.3. The Effects of Particles on Condensation and Precipitation

In addition to interacting with the radiation field, it has been noted that particles, in particular those produced by combustion of fossil fuels, incineration of garbage and running of automobiles, act as condensation or freezing nuclei. That is, the particles can initiate the formation of cloud droplets or hasten the freezing of cloud droplets at temperatures below 0^0C. The most common kind of particle produced by combustion of coal and oil, sulphates, are very efficient condensation nuclei.

Detailed observations of the quantitative aspects of these phenomena are still lacking. However, there is some evidence that the amount of rainfall over cities has increased (see review by Landsberg, 1975; Huff and Changnon, 1973) although not all of the increase can be attributed to the increase in cloud condensation nuclei since the heating could also increase precipitation.

A review by Schaefer (1975) of measurements of particle concentrations near urban areas and their observed effects indicates that particulate pollution is modifying the cloud patterns over large areas of the globe and influencing precipitation patterns and types. As Kellogg (1977) points out, it is difficult to assess quantitatively these effects even on a regional scale and at the present time it is only possible to recognize this potential impact as a very real one.

5.4. The Impacts of Other Gaseous Emissions

5.4.1. Sulphur dioxide and sulphates

The input of sulphur due to fossil fuel combustion represents a considerable perturbation upon the global natural sulphur cycle. It has been observed that sulphate particles produced from sulphur dioxide have become a dominant factor in regional air pollution (e.g. Weiss et al., 1977). Bolin and Charlson (1976) computed the impact on the scattering of solar radiation by sulphate particles and suggest that the change in scattering of solar radiation in the polluted areas of the eastern United States and Western Europe today could correspond to a temperature change of several degrees.

5.4.2. Atmospheric trace gases

In Chapter 2 the role of carbon dioxide, one of the atmospheric trace gases, in warming the surface of the earth through the so-called "greenhouse effect" was discussed. This effect occurs because the gas absorbs long-wave radiation within the wavelength band 7-14 μm which is the band in which most of the thermal radiation from the earth's surface is transmitted. Wang et al. (1976) have pointed out that there is in fact a large number of trace gases which have strong infrared absorption bands in the same region: examples are N_2O, CH_4, NH_3, HNO_3, C_2H_4, SO_2, CCl_2F_2, CCl_3F, CH_3Cl and CCl_4. Through the production and use of chemical fertilizers and the combustion of fossil fuels, the concentrations of certain of these gases in the atmosphere is being changed. Other gases (for example, the chlorofluorocarbons CCl_2F_2 and CCl_3F) have a purely anthropogenic origin. At the present time it is not possible to forecast the changes in concentrations of such trace gases but it is of interest to note the order of magnitude of the temperature changes to be expected from potential changes.

Wang et al. (1976) have used a radiative-convective atmospheric model to compute the global average surface temperature increase due to the greenhouse effect associated with increases in the trace constituents. Results of the computations are given in Table 5.2.

The most important of these constituents seem to be N_2O, CH_4 and NH_3 which when their concentration is doubled in the model give temperature increases of 0.7 K, 0.3 K and 0.1 K respectively.

5.4.3. Chlorofluorocarbons

These gases, used in spray cans and as refrigerants, have been a subject of concern in recent years because they are extremely stable, non-toxic and persist in the troposphere for a very long time. As shown in Table 5.2, the infrared absorption properties of these gases are such that a substantial increase in their atmospheric concentration would lead to a surface temperature increase. This effect was pointed out by Ramanathan (1975). If the chlorofluorocarbons were produced at the 1973 production rates then a temperature increase of 0.5°C by 2000 AD could be expected. If the production rate continued to increase by 10%/year as it was doing until recently then a temperature increase of 1°C by 2000 AD could occur. A second impact of these particular gases arises because the molecules which diffuse up into the stratosphere are broken down by ultraviolet radiation and the resulting products could interfere with the ozone layer at that altitude (see for example Crutzen, 1974; NAS, 1976).

While changes in atmospheric concentration of chlorofluorocarbons and consequent changes in surface temperature and/or the ozone layer are not directly attributable to energy conversion processes, the subject is introduced here as an example

Table 5.2. Changes in global average surface temperature due to specified changes in atmospheric trace constituents. Results from radiative-convective model of Wang et al. (1976)

Trace gas	Assumed present concentration (ppmv)	Factor modifying concentration	ΔT^1 (^0K) CTT[2]	ΔT^1 (^0K) CTA[3]
N_2O	0.28	2	0.68	0.44
CH_4	1.6	2	0.28	0.20
NH_3	6×10^{-3}	2	0.12	0.09
HNO_3	*	2	0.08	0.06
C_2H_4	2×10^{-4}	2	0.01	0.01
SO_2	2×10^{-3}	2	0.03	0.02
CCl_2F_2	1×10^{-4}	20	0.54	0.36
CCl_3F	1×10^{-4}	20		
CH_3Cl	5×10^{-4}	2	0.02	0.01
CCl_4	1×10^{-4}	2		
H_2O	*	2	1.03	0.65
CO_2	330	1.25	0.79	0.53
O_3	*	0.75	- 0.47	- 0.34

1) Change in global average surface temperature

2) Computed with the assumption of constant cloud-top temperature

3) Computed with the assumption of constant cloud-top height

*) See comments by Wang et al. (1976)

of what Schneider (1977) has termed an "energy externality"--that is, not energy-producing but nevertheless energy-dependent activities.

5.5. Concluding Remarks

During the last one hundred years there has been an increase in the rate at which particles have been produced by human activities (see for example SMIC, 1971; Mitchell, 1975) and many non-urban stations (but not all) have recorded some long-term upward trends in total particle content of the atmosphere.

In the light of the observed increase in particle loading of the atmosphere, the impact of particles on climate has been increasingly discussed. Several complicating factors have confused this discussion. Firstly, in addition to particles produced by industrial activities, there are also natural and indirect additions of particles to the atmosphere. The indirect addition arises from such occurrences as wind erosion of land disturbed by man's activities. Of the natural sources of particles a distinction between those particles which are added to the lower atmosphere, e.g. from sea spray or wind-blown dust, and those added to the upper atmosphere, i.e. volcanic dust, must be made. Large uncertainties exist in the estimates of the magnitude of the natural and anthropogenic particle sources and on their interannual variability so that the magnitude of the industrially-produced aerosols in comparison with the natural sources is not well-known.

In general the impact of the particles on climate has been considered in terms of the interaction between the particles and the radiation field and the condensation/precipitation process. Much confusion has been generated on the first of these topics with both a warming role and a cooling role for particles being concluded. This is largely because the interaction of the particles with the radiation field depends on so many factors. Firstly it depends on the characteristics of the particles (which determine how much radiation the particles scatter and how much they absorb), but it also depends on where the particles are in terms of their vertical and horizontal distribution and in terms of the underlying earth's surface conditions and/or cloud characteristics. Confusion has also arisen because it has not always been defined whether a warming/cooling of the earth's surface or of the entire earth-atmosphere system is being referred to. It is clear from the discussion in the first part of this section that a layer of particles could cause a cooling at the earth's surface while at the same time cause a net decrease of the earth-atmosphere albedo. Concensus of opinion presently seems to be that industrially produced particles cause a warming of the earth-atmosphere system but a detailed evaluation of the regional and global climatic impacts is not possible at the present time.

All of the discussion of the impacts of particles on climate emphasizes the need to consider many interactions within the climate system. It is seen for example that a layer of particles, by interacting with the radiation field could change atmospheric stability and thus possibly convection, cloud cover and precipitation.

Likewise the impact of particles on condensation/precipitation processes involves many interactions. The fact that all of these non-linear interactions must be accounted for together with the non-uniform distribution of industrially produced particles and the occurrence of natural and indirect sources of particles point to the need for detailed study of the problem with a range of climate models and the need for improved observations.

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6. RESILIENCE AND DYNAMICAL SYSTEMS [1]

6.1. IIASA's Early Interest in Resilience and Dynamical Systems

From the earliest days of IIASA the concept of resilience has been discussed at the Institute. C.S. Holling, an ecologist with particular interest in the theory of predator-prey systems, defined resilience as the "ability of systems to absorb changes in the values of state variables, driving variables and parameters and still persist" (Holling, 1973). It was soon realized that the proper mathematical way to express the ideas associated with the concept of resilience was the global theory of (non-linear) dynamical systems given by differential equations. The geometric point of view underlying this theory--concepts like state space, fixed point, limit cycle or closed orbits and basins are used--makes it easier to understand the global structure of a given dynamical system; the emphasis is shifted from the study of single trajectories--evolutions from specified initial data--to the totality of all trajectories and their long-time behavior. Many qualitative ideas about the behavior of systems can be rigorously expressed in the mathematical language of dynamical systems.

This interest in dynamical systems was further enhanced by the suggestion (due to T.C. Koopmans) that so-called combinatorial algorithms originally developed for problems in mathematical economics would be suitable for the calculation of fixed points (= equilibria) in general dynamical systems, even when the fixed points are unstable. As the determination of all the fixed points of a system is the first step in investigating its structure this property of combinatorial fixed-point algorithms is very important. The algorithms proceed by triangulating state space (covering it with a net of simplices) and then, starting from any corner, tracing a path of simplices necessarily ending in a fixed point; some of them can be restarted to find further fixed points. Thus, it was decided to organize a workshop on "Analysis and Computation of Equilibria and Regions of Stability" (Grümm, 1975) which took place in July 1975; this workshop brought together the mathematicians--the method producers--and ecologists, economists, researchers in chemical kinetics and climatologists[2]--the method users.

6.2. Dynamical Systems Theory in Climatology

Among the applications of dynamical systems theory to climatology discussed at the workshop, the work of Lorenz (1963, 1968, 1972) was prominent. He showed the possibility of vacillation--erratic oscillation between two regions of state space--for highly simplified circulation models. He especially emphasized the extreme sensitivity of results, mainly time-averages of non-linear models, to variation of parameters.

[1] This section was contributed by H.R. Grümm, IIASA.

[2] J. Charney (MIT) and K. Fraedrich (FU Berlin).

It was the concensus of the climatologists at the workshop that the general theory of non-linear dynamical systems would be very useful to theoretical climatology. The ultimate goal to be achieved was intended to be a shortcut to the determination of time-averages in meteorological models--from the simplified ones of Lorenz to, perhaps, full-size GCMs--through understanding of their attractors.

By the term "attractors" we understand those regions in state space which are the future limits of time evolutions. It is expected that, in general, attractors of non-linear dynamical systems will be "strange", i.e. resulting in erratic, "turbulent" motions of the system close to them. By necessity, information about the systems is lost continuously as it evolves in time: close to a strange attractor any small deviation from a trajectory grows exponentially until it is completely uncorrelated with the original trajectory; still both trajectories are moving on the same attractor, thus time-averages (= "climates") can be calculated from both. This observation should have consequences for the theoretical possibility of long-time weather prediction.

An extremely interesting fact is the following: On a large class of attractors there exists a measure enabling one to calculate the long-time averages of all functions on state space (like state variables themselves, mean square deviations, etc.). Thus a direct approximative calculation of this measure for a circulation model would yield all time-averages without having to do simulation runs. However, these measures will be very complicated in general; at the current state-of-the-art, we are far from any general method for calculating them. Numerical experiments have been made at IIASA in the case of the Lorenz attractor (and similar models) in order to throw light on the structure of its time-averaging measure. Details can be found in Grümm (1979).

6.3. General Research in Resilience and Dynamical Systems Theory

Expanding on the idea of Holling, a mathematical treatment of resilience was given by Grümm (1976). The emphasis was laid in this paper on adapting the language of dynamical systems as a field of pure mathematics to actual applications in ecology, climatology, etc. For instance, a replacement for structural stability[3] notions was suggested under the name of "resilience of the second kind"; this looser concept allows one to speak of the Lorenz attractor (see below) as resilient although it is neither structurally stable nor Ω-stable. The structure of a systems is described via the phase portrait giving the division of the state space into *basins*, each basin corresponds to a possible long-time mode of behavior of the system. This mode

[3]For the definitions of all mathematical concepts used, see Grümm (1979).

is given by the *attractor* of a basin. This description is akin to distinction of transitivity vs. intransitivity in the work of E. Lorenz. A full analysis of a system in this "topological sense" has been made to this date only for relatively simple systems like the Lorenz attractor since it would entail a complete topological description of the attractors occurring as well as the exact location of the basin boundaries.

To facilitate the application of the techniques, a tutorial paper on dynamical systems theory has been written (Grümm, 1979), based on lectures given at the Institutes of Meteorology of MIT and the Free University of Berlin.

6.4. Limit Cycles and Time Averages

H.R. Grümm of IIASA has collaborated with researchers at the Institute of Meteorology of MIT (J. Charney, E. Rives and D. Strauss). The starting point for the studies was the fact that the more complicated attractors in models like the ones of Lorenz arose through a sequence of Hopf bifurcations (transitions from a stable fixed point to a stable closed orbit or limit cycle in the simplest case). To understand the structure of those attractors and to obtain approximations to time-averages, the determination of *unstable* closed orbits arising in the bifurcation process is essential. A program using Poincare-cross-section methods and the combinatorial fixed point algorithms mentioned above was set up at MIT and run for some simplified (six- to fourteen-dimensional) circulation models. A number of unstable closed orbits has been found. (Similar progress has been made in equation systems describing chemical evolution via DNA-protein-interactions.)

6.5. Simple Climate Models and Catastrophe Theory

K. Fraedrich of the FU Berlin in collaboration with H.R. Grümm has constructed simple climatological models with one state variable (globally averaged temperature) involving albedo and CO_2-content varying with temperature. The bifurcation of these models under parameter variations were studied using catastrophe theory.

The time-derivative of the average temperature is given by polynomials with coefficients determined by the model parameters. Equilibria are given when these polynomials are zero, the stable ones can be interpreted as stable global climates of the earth ("glaciated", "ice-free", etc.). The surfaces in parameter space along with stable equilibria appear or disappear from the "catastrophe surface" of the model. The catastrophe surfaces occurring are known in the vernacular of catastrophe theory as "butterfly" and "wigwam". Using two-dimensional cross-sections, which can be found for example in Woodcock and Poston (1974), it is possible to determine the parameter values at which the climate "flips over".

Extensions of this approach to a three-dimensional model (using as state variables: average temperature of glaciated respectively non-glaciated areas as well as average latitude of the boundary between them) is under way.

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7. CONCLUDING REMARKS

The impact of energy systems on climate has received increasing attention recently as awareness of man's potential to alter the earth's climate has developed, as our knowledge of the complexity and sensitivity of the climate has increased, and as observations of the changes being made on a local scale--such as the formation of urban heat islands and high levels of air pollution--have been reported.

Energy systems can have an impact on climate on a local, regional or global scale. Currently, no observed global climatic changes can be attributed to energy conversion but possible future changes on this scale, perhaps of an undesirable and irreversible nature are of concern. Since the study on energy and climate described in this report has been carried out within the context of the IIASA Energy Systems Program, the impacts of energy systems on regional and global climate have been emphasized, rather than impacts on microclimate or local climate.

The scenarios for energy supply and demand in the year 2030 derived within the Energy Systems Program suggest that the order of magnitude of demand at that time will be 24-40 TW, compared with about 8 TW today. It is further suggested that there are three energy supply sources which could be developed on a large scale to satisfy this demand and these are solar and nuclear energy and coal. Thus this systems study on energy and climate has concentrated on the impact on climate of these three energy supply sources. Realistically, one can expect a combination of these sources to supply the total energy requirement, but in general their impacts on climate have been considered independently.

The impact of increasing atmospheric CO_2 concentrations is perceived as the greatest risk at the present time. A secular rise in the atmospheric CO_2 concentration is already observed and it is accepted that this increase is due to the increasing combustion of fossil fuels, which releases CO_2 into the atmosphere; however, it is also argued that tropical deforestation has contributed to the increase. That the oceans act as a sink for atmospheric CO_2 is clear, but the role of the biosphere, i.e., whether it acts as a source or a sink (or both) for CO_2, must still be resolved. Uncertainty concerning the biogeochemical carbon cycle thus means that it is not possible at the present time to reliably predict the future atmospheric CO_2 concentration as a function of the input to the atmosphere of fossil fuel and biospheric CO_2 and the oceanic and biospheric sinks.

Due to the physical properties of the gas, all other factors being equal, an increase in the atmospheric CO_2 concentration would lead to an increase in the globally averaged surface temperature. However, although there is a virtual consensus at the present time regarding the increase in global average surface temperature for a doubling of CO_2 concentration, there is little certainty regarding the regional changes in temperature and rainfall, for example, which would accompany the global average change. The IIASA Workshop on Carbon Dioxide, Climate and Society concluded that because such uncertainties in our knowledge of the climate system and of the carbon cycle are so large it is not possible to reliably predict the consequences of increasing use of fossil fuels and a prudent energy policy would maintain flexibility at the present time, while a period of 5-10 years is devoted to intensive research. Policies which actively encourage or discourage the use of fossil fuels are not justified at the present.

A series of simulations has been made with a model of the general atmospheric circulation, to investigate the impact of the addition of large amounts of waste heat at point sources. The results of the experiments suggest that emissions of waste heat would have to be extremely large (of order 100 TW) to perturb the global average climatic state. This is not to say that such perturbations due to energy systems would not influence climate on a local or regional scale. However, within the Energy Systems Program, it has been suggested that waste heat can be handled intelligently or non-intelligently as far as the engineering systems are concerned and thus the climatic impact could be reduced or amplified.

It is also clear that changes in the characteristics of the earth's surface, such as albedo, roughness or wetness, would have to be on a large scale to influence global climate, though again, local and regional climate changes are possible.

There are three approaches to investigating the potential impact of energy systems on climate. The first is to use models of the climate system (numerical or analogue) and perform sensitivity experiments to examine the response of the climate model to imposed perturbations. The second approach is to analyse observed data for analogue situations to the suggested perturbation, to produce a scenario for a possible response of the climate system: for example, a warm era in the earth's climate history could be taken as an analogue for the climate when the atmospheric CO_2 concentration has doubled and the global surface temperature is higher. The third approach is what has been called "letting the atmosphere itself perform the experiment"--merely waiting to see what the impacts of additions of waste heat, changing concentrations of atmospheric constituents and changing characteristics of the earth's surface will be.

In order to avoid, if possible, undesirable and irreversible climatic changes, the first two approaches are called for. Likewise, if energy policies are to be devised which take into account the climate constraints of energy supply sources, then these constraints must be quantified. It becomes clear that not enough information is available at the present to make this quantification. In the case of solar energy systems, the basic information on how the systems would perturb the climatic boundary conditions are often not yet available. An evaluation of the impact of increasing atmospheric particle concentrations is not easy at the present time because of the many non-linear interactions which must be accounted for and because the physical-chemical properties of the particles are not sufficiently documented. Climate models have already proved to be useful tools in the study of the processes of the climate system and the mechanisms of climate change or variation. However, much-improved versions of climate models are required before they can be used for "impact studies". In particular, as has been noted often elsewhere, climate models which consider the other components of the system, especially the oceans and ice and snow, will be needed to produce acceptable predictions of the impacts of such perturbations as waste heat and carbon dioxide. Therefore it is clear that major uncertainties still exist regarding the many feedbacks within the climate system and thus it appears that even basic theoretical research is required in order that prudent energy policies, in which energy-climate interactions are considered, can be devised and used.

To end, however, on a more positive note, the successes of this systems study of energy and climate should be emphasized. A great deal of time and money was spent in running and analyzing the results of 9 simulations with a large numerical model of the atmopsheric circulation. In addition to indicating that the model response was non-linear, that the impact of waste heat varied according to the location, amount and manner of heat input, the series of experiments served to give more information on the response of the model in general, since some of the results contrasted with what might have been expected on the basis of the results of earlier experiments investigating related phenomena. The experiments also provided the opportunity to adopt a methodology for evaluating the statistical significance of the results of model sensitivity experiments and to draw the distinction between physical and statistical significance.

The Workshop on Climate and Solar Energy Conversion represents a first comprehensive attempt to describe the characteristics of the major solar energy conversion systems and how they might affect climate, together with an analysis of the tools available for and problems inherent in the study of the impacts of solar energy conversion systems on climate. In addition the workshop stimulated a model study of the effects of a solar thermal electric conversion plant on regional meteorological conditions.

The IIASA Workshop on Carbon Dioxide, Climate and Society was a successful attempt to survey the present state of knowledge on the carbon cycle and the impacts of an increasing atmospheric CO_2 concentration on climate and the environment and to assess the implications of the knowledge for energy policy decision making.

APPENDIX: LIST OF PUBLICATIONS

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