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CLIMATE AND ENERGY: A COMPARATIVE ASSESSMENT OF THE SATELLITE POWER SYSTEM (SPS) AND ALTERNATIVE ENERGY TECHNOLOGIES

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DEFINITIONS OF UNIT SYMBOLS

Btu:	British thermal unit
°C:	degrees centigrade
cm:	centimeter
GW:	gigawatt (i.e., 10^9 watts)
GWe:	gigawatt (electric)
GW-yr:	gigawatt-year
J:	joule
K:	Kelvin (unit of temperature)
kg:	kilogram
km:	kilometer
kW:	kilowatt
kWe:	kilowatt (electric)
kWt:	kilowatt (thermal)
m:	meter
min:	minute
mm:	millimeter
m/s:	meter per second
mW:	milliwatt
MW:	megawatt
MWe:	megawatt (electric)
MWt:	megawatt (thermal)
MW-yr:	megawatt-year
μm:	micrometer
ppm:	part per million (by weight)
ppmv:	part per million (by volume)
t:	metric ton (1,000 kg)
W:	watt

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (Cont'd)

EXECUTIVE SUMMARY

The potential climatic impacts of five electrical energy techologies -- coal combustion, light water nuclear reactors, the satellite power system (SPS), terrestrial photovoltaics (TPV), and fusion were assessed. The objectives of this assessment were to identify major issues surrounding the effect of technology deployment on climate and to assess the degree to which these five technologies might contribute to significant climatic changes.

In the course of this work, the state of the art of climate study was reviewed and is described in this report. Particular focus is placed on the impacts of waste heat rejection, emissions of atmospheric aerosols, and emissions of carbon dioxide (CO_2). Impacts are identified as being global, regional, or local in scale, and the tremendous uncertainties of attempting to predict the future climate are discussed.

The potential impacts of the energy technologies on the climate were evaluated by comparing the emissions of heat or pollutants from each technology to the amount of such emissions currently considered necessary to produce significant climatic perturbations. Only operating emissions were considered, except for the SPS, which would involve emissions from heavy-lift launch vehicles (HLLV). Also considered were impacts resulting from individual facilities, clusters of facilities on a regional scale, and widespread utilization of technologies on a national or global scale. The major results of this comparative assessment appear in Sec. 3 (Table 3.4, p. 48) and are discussed in the following paragraphs.

Waste Heat

On a global scale, waste heat will not produce any detectable climatic change until world energy use increases by at least two orders of magnitude; thus, global waste heat will not be an issue for any of the technologies considered. On a regional scale, waste heat from energy facilities may produce some noticeable impacts on temperature, cloudiness, and precipitation patterns, particularly if facilities are sited close together, as in power parks. Due to its large size (100 km^2),* an SPS rectenna may produce small temperature increases comparable to those occurring in a typical suburban area. The most noticeable waste heat impacts will occur on a local level,

*See p. iv, "Definitions of Unit Symbols."

within a few kilometers from large heat releases. Heat and moisture released from cooling towers have been shown to increase the occurrence of fog, clouds, and precipitation. The extent of these impacts depends on the amount of heat released, how much heat is released in the sensible and latent forms, the height of release, and the ambient meteorological conditions. A comparison of the heat released per unit of energy produced by each technology appears in Table 1. Although the figures in this table do not represent the comparative magnitudes of impacts, it is apparent that coal and nuclear technologies are the most likely to produce noticeable impacts, particularly because of unit capacity.

Atmospheric Particles

The climatic effect of changes in atmospheric particulate loading has not been clearly established. Emissions of primary particles as well as of gases such as sulfur oxides (SO_x) and nitrogen oxides (NO_x), which are converted to particles in the atmosphere (secondary particles) are responsible for the increases in the anthropogenic input to particulate levels. An increased particulate loading in the atmosphere affects the climate by changing the radiative properties of the atmosphere. However, whether an increase or decrease in global temperature will occur depends on the optical properties of the particles emitted as well as on their vertical distribution. Particulate emissions can also affect regional climate by contributing to the number of condensation and freezing nuclei in the atmosphere, thus influencing clouding and precipitation processes. In addition, an abundance of particles can block solar radiation.

Table 1. Energy Released per Unit of Useful Energy Produced by Different Technologies[a,b]

Facility	MWt-yr/MWe-yr
Coal	1.9
Nuclear	2.0
Solar	
Terrestrial Photovoltaic	1.5
SPS	0.25

[a]Includes only energy released due to production of energy, not the use of it.

[b]Ref. 83

Of the energy systems considered, only coal technologies will produce primary and secondary atmospheric particles. HLLV launches associated with the SPS may produce small amounts of secondary particles, and these emissions may contribute slightly to regional climatic modification. The contribution of coal-combustion particles to any global warming or cooling should be small. Table 2 shows that the primary particulate emissions from coal-fired utilities constitute a very small fraction of total particulate emissions in the U.S. However the contribution of coal combustion to secondary particulate loadings by emission of SO_x and NO_x may be more important than the emission of primary particles, but the increasing use of emission control devices should limit these impacts.

CO_2 Impacts

Gaseous CO_2 is transparent to incoming solar radiation, but is a strong absorber of terrestrial radiation. Hence, an increase in atmospheric CO_2 can produce an increase of absorbed terrestrial radiation in the troposphere, which is the portion of the atmosphere that is below the stratosphere and extends 10 to 15 kilometers from the earth's surface. The net effect has been shown to be tropospheric warming and a slight stratospheric cooling.

Table 2. Annual Primary Particulate Emissions from U.S. Coal-Fired Utilities Compared with Annual Particulate Emissionsfrom All Sources

Year	Coal Use (GWe)[a]	Emissions from Coal Use (10^6 t)	Emissions from All Sources (10^6 t)
1976	191.9	82[b]	3,606
1985	317.6	45[c]	5,132
1990	351.6	50[c]	6,244

[a]Source: The National Energy Plan, Executive Office of the President, Energy Policy and Planning, April 29, 1977.

[b]Assumes average ash content of 15%, removal efficiency of 70%.

[c]Assumes average ash content of 15%, removal efficiency of 90%.

Measurements have indicated a steady increase of CO_2 content since the late 1800s, most of which is due to increased use of fossil fuels. If trends in fossil fuel use persist, the atmospheric CO_2 content will be double the preindustrial levels of about 300 ppm by the mid 21st century. Recent atmospheric models predict a global temperature increase of 2-3°C for a doubling of atmospheric CO_2, and increases near the poles of the earth may be considerably larger.

Of the technologies considered, only coal combustion will result in substantial emissions of CO_2. Space vehicle launches for SPS construction will emit some CO_2, but these emissions should be two orders of magnitude smaller than the coal emissions per unit of energy produced. Coal combustion can contribute substantially to global CO_2 levels. Table 3 compares the current and predicted CO_2 emissions from U.S. coal combustion alone to current and projected global CO_2 emissions. This comparison indicates that coal-fired energy generation may have a major impact on climate.

Other Contributions to Climate Change

In addition to the waste heat, particle, and CO_2 influences, other parameters can affect climate. Natural climatic fluctuations may either augment or mask an anthropogenic effect. The current cooling trend of the earth is probably due to natural fluctuations and may obscure CO_2 warming

Table 3. Projected Annual Emissions of CO_2 from U.S. Utility Coal Combustion Compared with Projected Annual World Emissions of CO_2

Year	Coal Use[a] (GWe)	Emissions (10^6 t)		
		Conventional[b]	Equivalent Combined-Cycle[c]	Projected Worldwide
1976	191.9	4,200	3,200	18,400
1985	317.6	7,000	5,300	26,190
1990	351.6	7,700	5,800	31,860

[a]The National Energy Plan, Executive Office of the President, Energy Policy and Planning, April 29, 1977.

[b]Assumes thermal efficiency of 34%.

[c]Assumes thermal efficiency of 45%.

[d]Assumes 4% annual increase.

effects for a few decades. The increasing levels of chlorofluoromethanes (FC) and nitrous oxide (N_2O) in the stratosphere may deplete the ozone layer, which could result in either surface warming or cooling depending on the vertical distribution of ozone (O_3). A number of industrial gases such as nitrous oxide (N_2O), methane (CH_4), ammonia (NH_3), and sulfur dioxide (SO_2) can act as greenhouse gases by absorbing terrestrial radiation in the troposphere. The magnitude of their effect is uncertain, although some investigators believe that the collective effect of these gases may be comparable in magnitude to the effect of CO_2.

Conclusions

The CO_2 warming effect has the greatest potential for altering global climate over the next few centuries, and this greenhouse effect may be augmented somewhat by other industrial gases. The impact on climate of particulate emissions should be minimal, particularly if they are controlled to meet health standards. Compared to the CO_2 effect, warming due to waste heat should not be an issue of global proportions. Local and regional "hotspots" of heat release may produce some local or regional modifications in climate.* As indicated in Table 3.4 (p. 48), coal appears to be the technology most likely to have an impact on global climate because of large CO_2 emissions. SPS launchings may affect global climate somewhat by altering the stratosphere, but significant changes are currently not predicted. All of the technologies appear capable of causing some local or regional climatic perturbations from heat release; however, such impacts will be principally site specific.

The impacts of energy on climate, particularly from CO_2 emissions, could be substantial in the next century or two. Unfortunately, knowledge of climate change and response to anthropogenic (man-induced) influences is still limited. Much important information regarding sources (e.g., combustion of fossil fuels, decomposition of biomass) and sinks (e.g., oceans, vegetation) of CO_2, atmospheric feedback mechanisms, and natural climatic fluctuations must be gathered. Thus, although the possibility of energy-related climatic effects should be considered in the formulation of long-term energy policy, global climatic change *per se* cannot at this time be used as a decision criterion.

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*Weinberg, W.M., and R.P. Hammond, *Limits to the Use of Energy*, In: Is There an Optimum Level of Population?, S.F. Singer, ed., McGraw-Hill, New York, pp. 42-56 (1971).

ABSTRACT

The potential effects of five energy technologies on global, regional, and local climate were assessed. The energy technologies examined were coal combustion, light water nuclear reactors, satellite power systems, terrestrial photovoltaics, and fusion. The assessment focused on waste heat rejection, production of particulate aerosols, and emissions of carbon dioxide. The current state of climate modeling and long-range climate prediction introduces considerable uncertainty into the assessment, but it may be concluded that waste heat will not produce detectable changes in global climate until world energy use increases 100-fold, although minor effects on local weather may occur now; that primary particulate emissions from coal combustion constitute a small percentage of total atmospheric particulates; that carbon dioxide from coal combustion in the U.S. alone accounts for about 30% of the current increase in global atmospheric CO_2, which may, by about 2050, increase world temperature 2-3°C, with pronounced effects on world climate; that rocket exhaust from numerous launches during construction of an SPS may affect the upper atmosphere, with uncertain consequences; and that much research in climatology is needed before potential effects can be quantitatively predicted with any confidence. Although climatic impact is an appropriate concern in formulating long-term energy policy, the level of uncertainty about it suggests that it is not currently useful as a decision criterion.

1 INTRODUCTION

It is becoming increasingly evident that human activities have the potential for significantly perturbing the global as well as the local environment. Of particular importance is the extent to which human activities are inadvertently modifying the earth's climate. The worldwide population explosion has created increasing demands for the production of food, and as population pressures increase, the competition for finite food supplies could severely threaten world peace and stability. Relatively small global climatic changes can substantially alter patterns of agricultural production as well as affect the total amount of biological production. Therefore, it is apparent that the potential of human activities for changing the earth's climate is a global issue of enormous proportions.

Man has the ability to change the earth's environment in several different ways. The increase in size and distribution of human populations

has changed the characteristics of its surface. Excessive destruction of forests and grasslands in conjunction with the urbanization of large land areas has resulted in changes in the surface radiation balance, as well as changes in the fluxes of moisture to and from the surface. Of greater impact on a global scale, have been the direct anthropogenic releases of heat and various pollutants into the atmosphere. These releases have affected the transmissivity of the atmosphere and have changed the radiation balance of the earth-atmosphere system. Although the magnitude of these man-induced changes in the atmosphere has been thus far too small for them to be reliably measured and identified as global climatic changes, it is possible that this situation can change within the next 50 to 100 years.

The major human activity that releases pollutants into the atmosphere is the satisfaction of energy demands. Use of fossil fuels as the principal source of energy has been the major anthropogenic contribution to the steady increase of atmospheric carbon dioxide (CO_2) levels. Additionally, fossil fuel utilization has contributed to the increasing global levels of atmospheric aerosols. Both CO_2 and aerosols play important roles in the radiation balance of the earth-atmosphere system and thus can substantially affect global climate.

Many atmospheric models predict that the increasing use of fossil fuels could result in a measurable global climate change by the year 2000 due to increased atmospheric CO_2 levels. It has been suggested that, to avoid substantial changes in climate beyond 2000, the use of fossil fuels must be curtailed and other sources of energy must be sought. However, uncertainties still exist about the nature of climate change and the magnitude of man's role in it. These uncertainties effectively prevent the direct consideration of impacts on climate in energy policy decisions at the present. What is certain, however, is that man's contribution to climatic change is a global problem. Thus, any effort to reduce man's inadvertent modification of climate must occur on a global scale and involve the energy policies of all nations.

This report has several objectives. The first is to describe the possible anthropogenic contributions to global climate change, particularly from energy production. The current state of knowledge concerning energy and climatic change is reviewed, with particular attention to assessing the unknowns and uncertainties surrounding climatic change and the likelihood

that these unknowns can be clarified in the near future. An attempt is made to rank climatic issues in the order of their potential magnitude of impact.

Climate issues on a global, regional, and local scale are addressed. The role of various energy technologies in contributing to climatic impacts on these three scales is examined from a standpoint of large-scale application of these technologies as well as from that of individual energy facilities. Some of the options for future energy supply and their implications are discussed. Finally, recommendations are made for future work to be performed concerning the SPS assessment, as well as for research needed to develop a better understanding of future climate.

2 ANTHROPOGENIC IMPACTS ON CLIMATE

2.1 WASTE HEAT

Almost every human activity results in the dissipation of heat. The release of heat to the atmosphere directly affects its temperature and thus the local climate. Rejection of heat to the lower atmosphere can also result in a change of atmospheric stability, which directly affects precipitation and cloud formation. As population growth continues, man's energy needs will increase, as will the amount of heat released to the environment. This increased anthropogenic heat rejection may play a role in shaping the future climate of the earth.

It is appropriate to look at the climatic effects of waste heat on three different geographic scales. The release of a large amount of heat at one or a few major sources could produce local perturbations (withing a few kilometers of the source) in climate. Extremely large heat releases from several closely grouped sources or moderate heat release over a larger region, such as from a metropolitan area, can affect the climate on a regional scale (out to about 50 km). The impact of all of the heat released by man can be examined in terms of its possible contribution to changes in global climate. The severity of waste heat impacts varies considerably, depending on the geographic scale of interest.

2.1.1 Sources of Waste Heat

Although man's release of heat to the environment is generally referred to as waste heat, it is important to note that all anthropogenic heat dissipated to the atmosphere will contribute to potential climatic change. An example is a coal-fired electrical generating plant with a conversion efficiency of about 34%. Of the energy input to the plant, approximately two-thirds will be released on the premises as waste heat and one-third will be converted into useful energy. However, almost all of this useful energy, in the form of electricity, will eventually be dissipated to the atmosphere in the form of waste heat from homes, industries, and other locations. Therefore, it is the total energy input to the system that is important in assessing the impact on the global climate. Waste heat should be considered as all heat released to the atmosphere that would not be there as a result of natural sources such as the solar radiation balance or volcanic activity.

Although most of man's activities release heat to the environment, the vast preponderance of the heat released comes from the production or consumption of energy. The human body gives off waste heat at the rate of approximately 100 W (thermal), but this is two orders of magnitude smaller than the per capita energy use of the United States (10,000 W). About 20% of U.S. energy use goes to the production of electricity; other major energy uses include transportation (20%), space heating (15%), and industrial use of heat (20%).[1] The per capita energy consumption for the entire world is currently one-sixth of that in the United States, and the distribution of energy uses in the U.S. is also substantially different from that in less-developed nations.

World energy use has increased substantially over the past century. Figure 2.1 displays an estimate of the growth of the world's consumption of energy between 1925 and 1971. Between 1925 and 1968, world energy consumption increased at a rate of about 3.5% per year. However, the growth rate itself increased from 2% per year between 1925 and 1938 to 5.5% per year after 1960.[2] This increase is a function of both an increasing world population and an increasing per capita energy demand, although the rise in per capita consumption is probably the dominant of the two factors.[3] In the United States alone, increased population has accounted for only about 20% of the increased electric power consumption. The other 80% of the increase is a result of increases in per capita demand.[4] The growth rate of per capita energy use in the United States is estimated at 2-3% per year.[5]

As less-developed countries become more modernized, substantial increases in energy use can be expected. Furthermore, as supplies of natural resources become depleted, it is likely that energy-intensive substitutes will have to be developed, which will further increase worldwide per capita energy use. Weinberg and Hammond[1] project future energy needs in an industrial society to be as much as 20 kWt* per capita, which is double the current U.S. consumption.

It is obvious that energy use and the resulting heat rejection to the environment will continue to increase. How large these increases will be and what the ultimate heat rejection of the earth might be are the important issues. Table 2.1 contains some estimates of 1970-71 energy use and projections for the future.[1,6-10] There is some disagreement on exactly what the present world energy use is, but most estimates predict increases by a factor of five over current levels by the year 2000.

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*See p. iv, "Definitions of Unit Symbols."

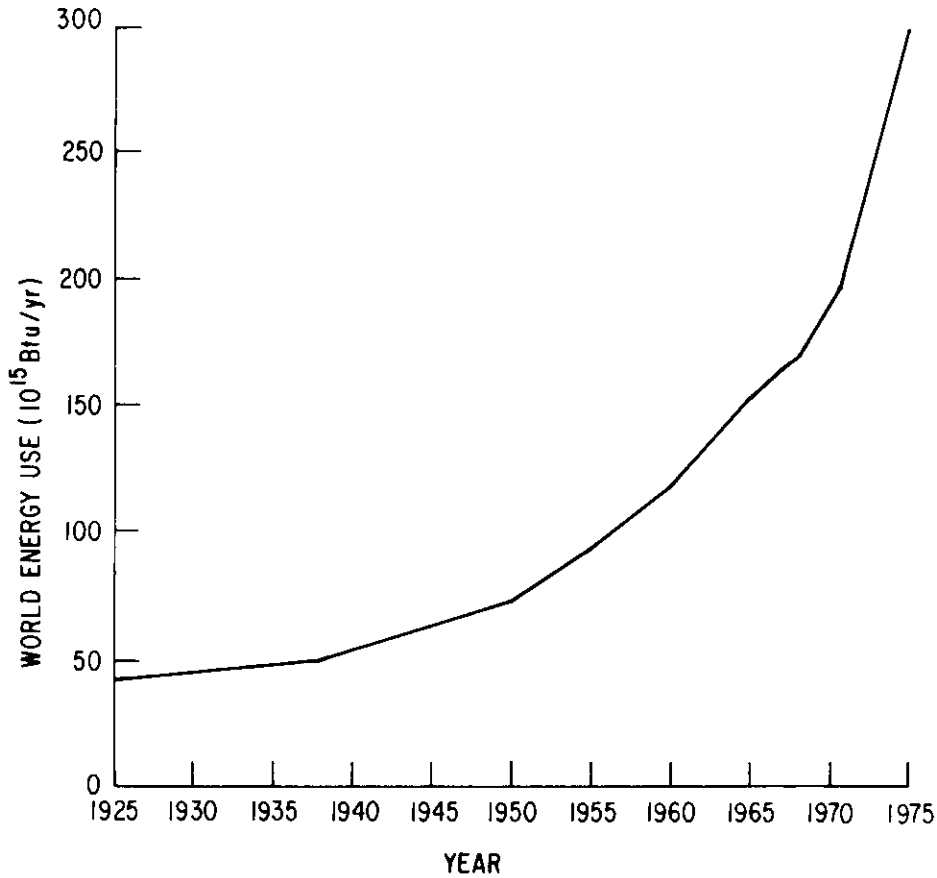

Fig. 2.1. World Energy Use Between 1925 and 1976[10,88]

Table 2.1. Current and Projected Global Anthropogenic Energy Release

Source	Current Energy Use (GW)	Future World Energy use (GW)
Weinberg and Hammond (Ref. 1)	4.9×10^3	4.0×10^5 (ultimate use)
Hubbert (Ref. 6)[a]	4.6×10^3	
SCEP (Ref. 7)	5.5×10^3	3.2×10^4 (in 2000)
Gough and Eastlund (Ref. 8)	5.7×10^3	3.4×10^3 (in 2000)
SMIC (Ref. 9)	8.0×10^3[b]	4.0×10^4 (in 2000)
Perry and Landsberg (Ref. 10)	6.7×10^3[c]	3.9×10^4 (in 2025)

[a]Based on world production of oil and coal; hydro, nuclear, and natural gas sources are not included.

[b]Probably represents an upper estimate.

[c]Based on coal equivalent; represents 1971 consumption.

2.1.2 Global Impacts

Although it is apparent that anthropogenic heat rejection to the environment on a global scale will increase severalfold by the year 2000, the important issue is whether this increase may have significant climatic implications. If noticeable climatic impacts do not occur by the year 2000, it is quite possible that they will occur beyond 2000 when heat rejection may be two orders of magnitude greater than it is at present. Thus, it is important to establish the magnitude of waste heat rejection at which climatic impacts may become an issue and the point in time at which this magnitude might be achieved.

Perkins[11] attempted to put global heat rejection into perspective by comparing global energy use with the solar input to the earth-atmosphere system. Solar input is estimated at 17.3×10^{16} W, of which about 35% is reflected back to space, leaving a net solar input of 11.2×10^{16} W.[6] In comparison to this number, the energy figures in Table 2.1 are quite small. A crude estimate of the atmospheric response to these heat inputs can be made by considering that thermal radiation from a black body is proportional to the fourth power of the absolute temperature:

$$Q_1/Q_2 = (T_1/T_2)^4$$

If the black-body radiation temperature of the earth-atmosphere system is taken as 255 K, then the impact of a heat rejection of 3.35×10^{13} W by the year 2000 can be calculated to produce a global warming of 0.019 K. This is far below the magnitude of natural climatic fluctuations and would not be a noticeable impact. Weinberg and Hammond's[1] ultimate heat rejection estimate of 4×10^{14} W would produce an estimated warming of 0.22 K. Although this is not a substantial global warming, it approaches the magnitude necessary to produce a noticeable change in global climate. Rotty[12] also estimated that noticeable climatic change from thermal pollution can occur with a heat rejection of approximately 3.35×10^5 GW (10^{19} Btu/yr).

Other estimates of the global impact of heat rejection have been made, and several are summarized in Table 2.2. Kellogg[13] compared the heat released by human activities to the amount of solar energy absorbed at the earth's surface. Although man currently releases only 0.01% of the solar

Table 2.2. Projections of Future Global Energy Release and Resulting Surface Temperature Response

Source	Heat Rejection (GW)	Year	Increase in Surface Temperature (°C)
Kellogg (Ref. 15)	6.7×10^{10} (100 times greater than present)	2100	1 to 4
Weinberg and Hammond (Ref. 1)	4×10^5	Time of ultimate, steady-state population	0.2
Perry and Landsberg (Ref. 10)	4.5×10^4	2075	0.2[a]
Perry and Landsberg (Ref. 10)	7×10^6	Time of ultimate, steady-state population	3.8[a]

[a]Using black-body equilibrium temperature relationship.

energy absorbed at the surface, Kellogg predicted a 100-fold increase in heat release by the year 2100. He also suggested, on the basis of a consensus of climate models, that a 1% increase in available heat at the earth's surface translates to a 1° to 4°C increase in surface temperature. This can certainly be classified as a significant climatic perturbation.

General atmospheric circulation models have been used to simulate atmospheric response to man-made heat release. Washington[14] assumed a geographical distribution of energy use on the basis of current population density, and assumed a per capita energy use of 15 kW by an ultimate population of 20×10^9 people. Based on a simulation of positive thermal pollution and a control run, Washington's results (for a time-averaged January simulation) showed temperature changes of up to 10°C in the northern hemisphere and 1-2°C in the tropics. However, further experiments with the model showed that the atmospheric effects of thermal pollution could not be separated from the natural fluctuations of the model over the averaging period used.

A number of simulations have been carried out to investigate the impacts of extremely large energy releases over relatively small areas, to assess, for example, the impacts of intense regional development or of an extremely large energy park. The results of Llewellyn and Washington[16] and Williams et al.[17] show large increases in temperature close to the heat

release and substantial variations in global circulation patterns for extremely large heat releases. However, the simulations represented extreme cases, and the ability of models to give statistically significant results for more realistic experiments is currently limited.

It is possible that the magnitude of heat release impacts is dependent on the season. During the winter, when more stable atmospheric conditions prevail, the impacts of waste heat occur mainly in the boundary layer and have a larger impact on surface temperature. In the summer, an increased vertical mixing of the excess heat and a smaller perturbation of surface temperature is likely.

Thermal pollution cannot be examined in isolation when one is considering global climate changes.[8] Certainly, other climate-forcing parameters play important roles. Carbon dioxide and atmospheric aerosols will be discussed later in this report, and natural climatic fluctuations must also be taken into account.

In addition, it is not possible to calculate reliably an atmospheric temperature increase due to added heat without considering the total response of the atmosphere and potential feedback mechanisms. For example, if the surface temperature increases because of heat added to the atmosphere, evaporation will increase, and this could lead to increased global cloudiness. The clouds could provide negative feedback by reflecting more incoming solar radiation into space. On the other hand, a warming of the earth's surface could result in a decrease of surface albedo due to melting of snow and ice cover. This would lead to increased surface absorption of solar radiation and enhance the warming trend.

It is not clear from current knowledge whether anthropogenic heat rejection at any time in the future will significantly alter global climate. It can be said with reasonable confidence that significant global impacts from waste heat are unlikely in the next 50 to 100 years. Beyond that time frame, if energy use continues to grow, global impacts of a noticeable, if not substantial, magnitude are possible.

2.1.3 Regional Impacts

Although it is apparent that man's worldwide energy release is not particularly large in comparison to the incoming solar flux, this is not

always the case for smaller geographic scales, as Figure 2.2 illustrates. The figure is a plot of energy density versus area for different locations. Net surface radiation is shown on the graph for comparison. Some highly developed urban areas of 100-1000 km^2 are currently releasing more energy to the environment than the net surface radiation.

In the future, energy releases of such magnitudes may not be limited to urban areas. Some consideration has been given to the future construction of large energy centers or parks in which 20,000 to 50,000 MW of electrical energy will be produced on one 100-km^2 site. This would result in substantial savings in construction costs, maintenance, safeguards, and transmission lines compared to dispersed individual facilities. However, the waste heat rejection from such a power park would be 4 to 10 times the global average net radiation at the surface.

It is apparent that man is capable of, and in fact is currently, releasing as much or more energy to the environment in certain regions than

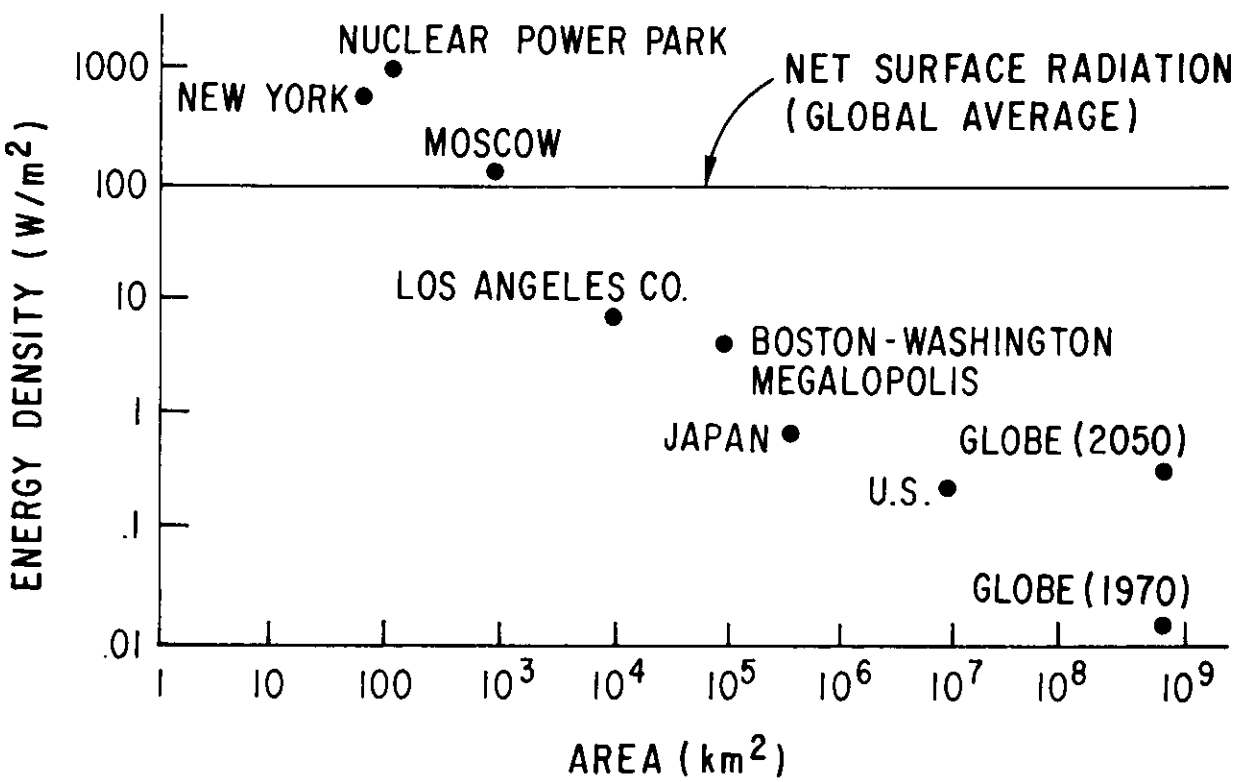

Fig. 2.2. Anthropogenic Energy Densities Compared to Net Surface Radiation over Various Areas

the earth is receiving from the sun. As population and energy demand increase, the number and sizes of these areas will likely increase substantially. The question of concern is whether or not these perturbations of the heat balance of the lower atmosphere will produce significant climatic perturbations.

Considerable work has been done to evaluate and describe the impact of large urban areas on weather and climate. Man-made heat islands have been studied by Landsberg and Maisel,[18] Ludwig,[19] Clarke,[20] and others. The urban heat island exists during both the day and the night but is much stronger at night. In large urban areas, temperatures can be as much as 5°C to 10°C warmer than nearby rural areas. Studies have indicated that the mean annual minimum temperature of a city may be as much as 2°C higher than surrounding rural areas.[21,22] However, this temperature increase is not due solely to the waste heat released from the cities. Urbanization results in the replacement of natural vegetated surfaces with brick, asphalt, and concrete, which store heat much more effectively than vegetation and release more stored heat to the environment at night.

In addition to the effects of waste heat on temperature, it has been observed that urban areas can affect precipitation patterns. There are several causal factors that increase precipitation around an urban center; these include combustion vapor added to the atmosphere, greater surface roughness to enhance mechanical turbulence, the presence of greater concentrations of condensation and ice nuclei in the urban atmosphere, and higher temperatures to increase thermal convection. Table 2.3 summarizes the urban effects on summer rainfall in nine metropolitan areas. In addition to increasing precipitation, cities quite possibly influence the occurrence of severe weather in their vicinities. Table 2.4 displays the increase in hail-days at several cities, where increases in thunderstorm occurrences of up to 50% at a given point have also been observed.[23]

Although these precipitation increases appear to be real, the exact causes have not been quantified. It is likely that waste heat has a role, although not a major one, in climatic change. The contribution of energy production to creation of urban heat islands and their precipitation impacts is somewhat less certain.

Table 2.3. Summary of Urban Effects on Summer Precipitation at Nine Locations[a]

City	Observed Effect	Maximum Change mm	Maximum Change %	Approximate Location
St. Louis	Increase	41	15	16-19 km downwind
Chicago	Increase	51	17	48-56 km downwind
Cleveland	Increase	64	27	32-40 km downwind
Indianapolis	Indeterminate	--	--	--
Washington	Increase	28	9	48-64 km downwind
Houston	Increase	18	9	Near city center
New Orleans	Increase	46	10	NE side of city
Tulsa	None	--	--	--
Detroit	Increase	20	25	City center

[a]Source: Ref. 23.

Table 2.4. Hail-Day Increases for Eight Cities[a]

City	Maximum Increase (%)	Location
St. Louis	150	Area 18-32 km downwind
Chicago	246	Point 40 km downwind
Cleveland	90	Area 18-32 km downwind
Indianapolis	0	--
Washington	100	Area of city and 18 km downwind
Houston	430	Point 16 km downwind of urban area
New Orleans	160	Point (city)
Tulsa	0	--

[a]Source: Ref. 23.

The effects of waste heat rejection from large nuclear power centers or parks will become more important for energy production in the future. Because of the increasing difficulties in finding suitable sites for power

plants and the problems of handling radioactive waste materials, consideration has been given in the United States to locating more and more generating capacity on a given site.

These envisioned power parks would consist of 20,000 to 50,000 MWe of generating capacity on a land area of 20-100 km^2. A number of studies have been conducted to assess the possible impacts of the dissipation of waste heat from large electric power centers.[24-27] The impacts most often studied include heat-island formation, initiation of convective clouds, increased humidity and precipitation, fog formation, and vorticity concentration.

The potential for climate and weather modification in the vicinity of power parks can be visualized by examining the energy density of the waste heat being rejected from them. Table 2.5 compares the energy production of natural atmospheric events to that from three groups of existing power plants and three hypothetical energy-park configurations. The table shows that the heat released from an energy park will greatly exceed the solar flux at the ground and may even approach the latent heat release of a thunderstorm that covers approximately the same geographical area. It should be noted that if evaporative cooling towers were used in the energy park, only about 20% of the waste heat would be rejected as sensible heat and the rest as latent heat. Nevertheless, the heat release from an energy park is of the same magnitude as the energy of many natural phenomena.

At the least, power parks will produce sizable heat islands or thermal mountains that can increase cloudiness and precipitation by triggering or enhancing convective activity. The increase in convective precipitation produced by such a power park depends on the local climate. Increases would probably be most significant in the southern and southwestern United States.[24,27]

The production and enhancement of ground fog is also considered an important impact of power parks and is expected to be most common for parks located in the Northwest and in the Appalachian Mountain regions.[27] A potentially serious consequence of energy parks could be the release of large amounts of waste heat, which could concentrate atmospheric vorticity and increase the possibility of severe weather. Vorticity concentrations from power-park energy releases would be most probable in areas where, and during seasons when, convective vortices are most likely to occur naturally.

Table 2.5. Energy Production Rates of Natural Atmospheric Processes and Anthropogenic Sources

Process	Area (km^2)	Energy Production (kW/m^2)	Fraction of Solar Flux at Ground
Natural Sources			
Solar energy flux: at top of atmosphere	5.1×10^8	0.35	--
Solar energy flux: at ground	--	0.16	1
Cyclone: latent heat release[a]	1.0×10^6	0.20	1.3
Great Lakes snow squall: latent heat release[b]	1.0×10^4	1.0	6
Thunderstorm: latent heat release[c]	100	5.0	30
Tornado: Kinetic energy[d]	1.0×10^4	10.0	60
Waste Heat from Power Plants			
Dresden, LaSalle, Braidwood (area sufficient to include all three)	634	0.02	0.12
Summit, Salem, Hope Creek	155	0.07	0.46
Peach Bottom, Fulton, Summit, Salem Hope Creek, Bainbridge, Conowingo	1,294	0.02	0.14
Waste Heat from a Hypothetical Electric Power Center (36,000 MWe)			
Bhumralkar and Alich (Ref. 28)	6.4	11.2	67.4
Ramsdell et al. (Ref. 27)	100	0.72	4.5
Koenig and Bhumralkar (Ref. 24)	36	2.0	12.5

[a]Assumes half life of 3 days, rainfall rate = 1 cm/day.

[b]Assumes snowfall rate of 4 cm/hr.

[c]Assumes half life of 30 min, rainfall rate = 1 cm/30 min.

[d]Assumes half life of 10 min.

2.1.4 Local Impacts

Noticeable atmospheric modifications are currently occurring within a few kilometers of large, industrial emitters of heat and moisture. In particular, large electric generating facilities, which reject large amounts of heat to the environment by means of cooling towers, cooling ponds, or other means, have been shown to alter the local climate. The geographical extent

and severity of these local climatic impacts appear to be largely a function of site-specific criteria such as local meteorology, the magnitude of heat release, and the means of heat rejection.

A considerable amount of work has been done to characterize the atmospheric impacts of cooling towers. Most cooling towers are, and most likely will continue to be, "wet" towers, in which heat exchange occurs by evaporation from countless water droplets generated by splashing warm water over successive barriers. There are two major types of cooling towers in use today: mechanical-draft and natural-draft. In mechanical-draft towers, large fans force the vertical air flow, whereas in natural-draft towers, the great size of the tower causes vertical air flow to develop without a fan because of density gradients.

Of the two types of cooling towers, the natural-draft tower appears to cause less serious local impacts. In the United Kingdom, it is felt that the impact of these towers on local climate has been negligible throughout 50 years of operational experience.[29] Although visible plumes of water droplets frequently occur near natural-draft cooling towers, ground fog due to downwash occurs infrequently.[30-32] In fact, in many cases, downwind measurements of ground-level relative humidity have shown no measurable increase.[29]

The output of heat and moisture from natural-draft cooling towers is believed to enhance development of cumulus clouds, particularly when the atmosphere is unstable or conditionally unstable. In several cases, anomalous precipitation events have been observed within a few kilometers of large heat and moisture releases from natural-draft towers.[33-35] However, measurements from local weather stations taken over several years have not shown that statistically significant increases in precipitation occur near large cooling towers.[36,37]

Drops of cooling water can be carried out of the top of the tower as water splashes over the heat exchange surfaces. These drops can contain inpurities such as salts and fungicides and can damage local vegetation. This phenomenon, called "drift deposition," may be an important environmental impact but should not significantly change the local climate.

Mechanical-draft cooling towers are much more likely to produce fog because they are not so tall as natural-draft towers. Fog is common within a few kilometers of these towers at wind speeds of 3-5 m/s or greater, due to

downwash effects. Increases in relative humidity and decreases in sunshine duration have also been measured within a few kilometers of mechanical-draft towers.[38] Currently, the sun shading produced by cooling tower plumes is of great concern in Europe. Over a period of several years, changes in solar radiation can cause changes in natural vegetational cover.[30]

Fog frequently occurs over and near cooling ponds, especially during meteorological conditions that normally produce fog, such as cool, calm mornings.[39] In the winter, such fog can produce light icing on vertical objects; however, both the fog and icing are limited to within a few hundred meters of the cooling pond.

In general, it appears that although the atmospheric impacts of waste heat rejection at an individual site are often noticeable, these impacts will be confined to an area close to the site. Thus, site selection and the selection of the appropriate cooling technology will be important in minimizing the adverse impacts of these local atmospheric perturbations.

2.2 ATMOSPHERIC PARTICLES

Suspended particles, chiefly in the size range of 0.01-10 μm, are abundant in the atmosphere. The properties of these particles affect weather and climate in two ways. First, particles act as condensation and freezing nuclei for the formation of cloud droplets and ice crystals in the atmosphere. Thus, particles play an important role in cloud and precipitation processes. Second, because of their optical properties, particles interact with both solar and terrestrial radiation. Atmospheric aerosols (i.e., the suspension of particles in the atmosphere) can scatter and absorb incoming solar radiation and absorb and re-emit terrestrial infrared radiation. The proportion of the anthropogenic contribution to the total amount of atmospheric particles has increased over the past century. The particles produced by man may be currently influencing weather and climate and may play an important role in future weather and climatic change.

2.2.1 Sources and Sinks of Atmospheric Particles

Sources

Atmospheric particles are generated by both natural and anthropogenic sources. They can be injected into the atmosphere as primary particles or be

formed in the atmosphere by chemical reaction of anthropogenic or natural gaseous emissions.

The major natural emissions of primary particles occur as a result of wind-raised dust and wind-raised sea salt. However, the contribution of particles through gas-to-particle conversion of natural emissions of H_2S, NO_x, NH_3, and organic compounds may be as great as that from dust and salt. Anthropogenic primary emissions occur from industrial and utility combustion, cement and metals manufacturing, agricultural operations, and several other sources. However, the most important anthropogenic contribution derives from the conversion to sulfates and nitrates of SO_2 and NO_x emissions.

Estimates of the source contributions to atmospheric particles are contained in Table 2.6, which reveals that the anthropogenic contribution to global particle emissions is only about 10% of the total. Mitchell[40] estimates a somewhat higher percentage of anthropogenic input (28%). The major energy inputs to this contribution occur as a result of fly ash from

Table 2.6. Estimates of Source Contributions to Atmospheric Particulate Matter

Source	Contribution (10^9 kg)	
	Natural	Anthropogenic
Primary particle production		
Fly ash from coal	--	36
Iron and steel industries	--	9
Nonfossil fuels	--	8
Petroleum combustion	--	2
Incineration	--	4
Agricultural emission	--	10
Cement manufacturing	--	7
Miscellaneous	--	16
Sea salt	1000	--
Soil dust	200	--
Volcanic particles	4	--
Forest fires	3	--
Gas-to-particle conversion		
Sulfate from H_2S	204	--
Sulfate from SO_2	--	147
Nitrate from NO_x	432	30
Ammonium from NH_3	269	--
Organic aerosols (terpines hydrocarbons, etc.)	200	27
Total	2312	296

coal combustion and emission of NO_x and SO_2 from fossil fuel combustion. The uncertainties in these estimates are fairly substantial; probably, the estimate of natural emissions in Table 2.6 is high. However, the natural component is definitely the dominant one.

Worldwide particulate loading produced by human activity has increased significantly in this century.[40] Increasing population and energy consumption in the future portend increased atmospheric levels of particulates. However, in recent decades many nations have taken steps to control pollutant emissions to protect public health: for example, air quality measurements in the United States indicate that in the past decade urban SO_2 and total suspended particulate levels have decreased.[41] Therefore, it is conceivable that in some locations the anthropogenic contribution to global particle loading could remain fairly constant or even decrease in the future despite increasing population and energy use. However, the potential exists for several-fold increases in world anthropogenic particle emissions in the next 50 to 100 years.[10,40]

Sinks

Despite the extremely large input of particles into the atmosphere, they are removed quite efficiently, which prevents a large, cumulative buildup of particles in the global atmosphere. The mean residence time of a particle in the troposphere is of the order of a few days to a few weeks.

There are two major mechanisms by which atmospheric particles are removed. The first is the gravitational fallout of particles, which are eventually deposited on a surface (dry deposition). The second is referred to as wet deposition, which occurs when water vapor condenses on a particle, forming a cloud droplet, which eventually falls as precipitation (rainout). Wet deposition also occurs when a particle is captured by falling rain or snow and is carried to the ground (washout).

The residence time of any given particle in the atmosphere is dependent on the characteristics of the particle and its location in the atmosphere. Particles capable of acting as cloud condensation nuclei or freezing nuclei are much more likely to be removed by cloud and precipitation processes. Particles emitted in or injected into the stratosphere, such as those from aircraft or volcanoes, may remain in the atmosphere for considerable periods

because they are physically separated from the immediate influence of precipitation processes.

2.2.2 Potential Climatic Response

Mesoscale Response

The role of particles in cloud and precipitation processes may be significant to weather and climate over a mesoscale (50 km) area where pollutant emissions have created an abundance of condensation and freezing nuclei. Numerous studies have shown an increase in precipitation in the vicinity of large urban areas such as St. Louis[42] and Chicago[43] where there is an abundance of particles. The cause of precipitation anomalies around cities has not been established. Particles may play an important or a negligible role in comparison to waste heat and mechanical turbulence caused by cities. At this time, it is impossible to link an excess of particles with any local or mesoscale precipitation increase. Certainly this would apply as well to any energy facility or energy park.

Particles can substantially alter radiation processes over a mesoscale area. Measurements have indicated that many cities have experienced an attenuation of 10 to 30% in surface solar radiation,[21] and a large portion of this attenuation is caused by particles in the atmospheric boundary layer. The attenuation is made up of a scattering component and an absorption component. Calculations have shown that aerosol absorption can cause warming at the surface of up to a few degrees centigrade in a polluted atmosphere.[44,45]

Global Response

Currently, the effect of changes in atmospheric particle concentration cannot be clearly identified. The impact of volcanic activity on tropospheric and stratospheric temperatures appears to exist in the measured records but cannot be interpreted as a causal relation.

The backscatter and absorption components of the total attenuation by particles have competing effects on atmospheric temperature. The backscattered radiation is unavailable for heating of the earth's surface and atmosphere and is lost to space. On the other hand, the solar radiation absorbed by particles is not available to heat the surface but does heat the atmosphere.

The determination of whether or not increased particle concentrations will cause a warming or cooling effect depends on several considerations. Two important factors are the earth's surface albedo and surface water content, which determine how much of the radiation lost to the surface due to absorption and backscatter would have been used for heating if particles were not present. The vertical location of particles is also important. Particles in the stratosphere will result in surface cooling due to attenuation of solar radiation and the fact that heating due to absorption will occur in the stratosphere and have minimal effect on the surface. Possibly the most important factor is the efficiency of atmospheric particles as backscatterers as opposed to their efficiency as absorbers. Unfortunately, this cannot be reliably measured or inferred.

The direction of the effect of increased particle loadings on the global climate is uncertain. An increase in the albedo of the earth-atmosphere system would probably lead to surface cooling. However, depending on particle distribution and characteristics, and underlying ground reflectivity, a net global warming may be favored. In fact, Bryson[46] suggests that the atmospheric warming effect of CO_2 has been more than offset by the cooling effect of increased particle loading of the atmosphere over the past few decades. The calculations of Rasool and Schneider[47] would tend to support this view. However, more recent evidence suggests that the ratio of absorption to back-scatter in atmospheric aerosols is likely to be high and thus they may create a warming rather than a cooling effect.[48] Another viewpoint is that the effect of increased particle loading will be very small[49] on either the increase or the decrease of temperature. The emphasis of researchers today on the CO_2 issue rather than the particle issue would tend to support the latter opinion.

2.3 CARBON DIOXIDE

The steadily increasing level of carbon dioxide in the atmosphere is a potential cause of near-term global climate change that is currently being given the most attention by investigators. Most of these investigators expect the so-called "greenhouse effect" of CO_2 will result in much warmer global temperatures. Depending on the magnitude of the atmospheric response to increased CO_2, this warming could have serious implications for future climate and society.

2.3.1 Increase of Atmospheric CO_2

Over 97% of the energy demand of the industrial world is being met through the combustion of conventional fossil fuels.[50] The major by-product of this fossil fuel combustion is carbon dioxide, which is injected directly into the atmosphere. Although the production of cement and the flaring of natural gas are sources of CO_2 emission into the atmosphere, fossil fuel combustion releases the largest amount of CO_2.

Carbon dioxide is the only combustion product for which a global increase has been documented.[5] In particular, the increase in atmospheric CO_2 levels in the last few decades has been significant and has corresponded to a similar increase in fossil fuel use.

The base concentration of CO_2 in the atmosphere in the pre-industrial, late 19th century is generally accepted to have been around 290 ppm. Currently (in 1978), global CO_2 concentrations are approximately 335 ppm, which represents close to a 15% increase over the past 100 years.[51] This averages out to an increase of about 0.4 ppm/yr; however, the most recent trends indicate that the increase has accelerated beyond 1.0 ppm/yr.[40] Figure 2.3 shows global carbon dioxide production from 1880 to 1975.

Since 1958, the concentration of CO_2 in the atmosphere has been measured at two remote stations: Mauna Loa Observatory in Hawaii and the South Pole.[52] A plot of the data from Mauna Loa (Figure 2.4) shows the steady rise of CO_2 levels as well as seasonal variations. The seasonal cycle is due to the uptake of CO_2 during photosynthesis and its eventual release to the atmosphere when organic matter rots or otherwise oxidizes.

2.3.2 Global Carbon Budget

The CO_2 present in the earth-atmosphere system is located in the atmosphere, the oceans, and in the living and decaying biomass. There is continuous exchange between the reservoirs, as well as an input of CO_2 from the combustion of fossil fuels. Figure 2.5 summarizes the reservoirs for CO_2 and the exchanges between them. The important issue from the standpoint of climate change is to determine the reason for the observed rise in the global concentration of CO_2.

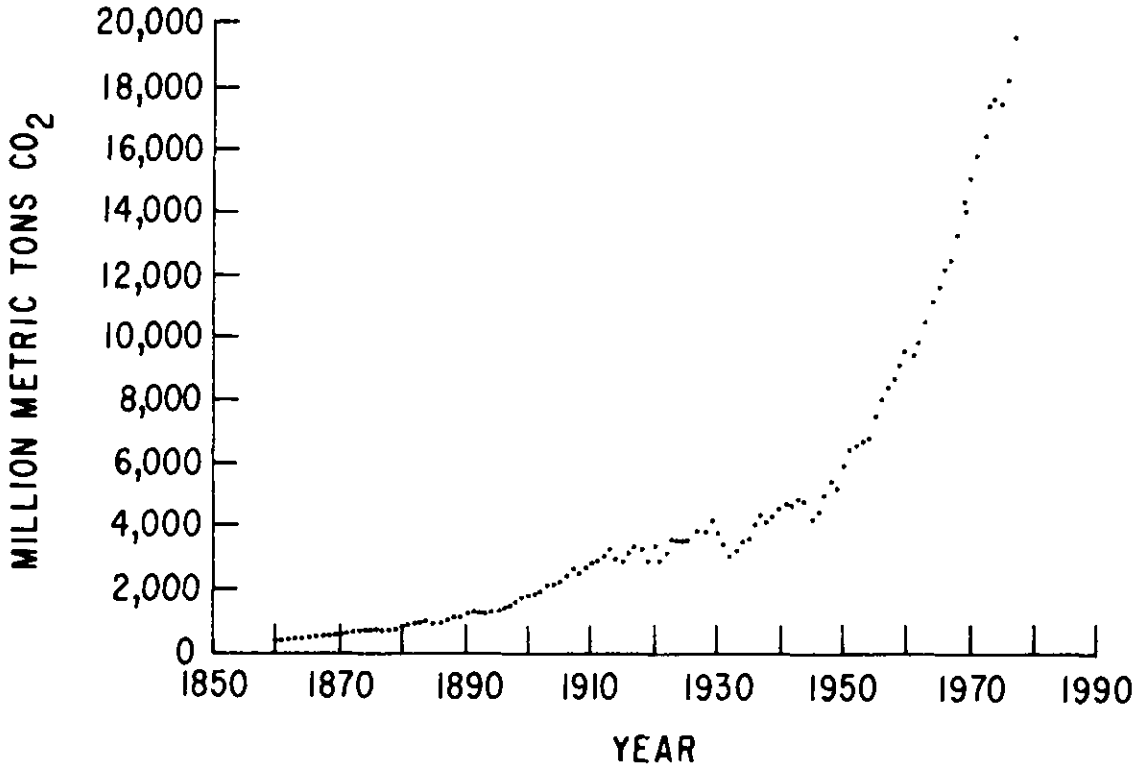

Fig. 2.3. Annual Production of CO_2 from Fossil Fuels and Cement (Source: Ref. 34)

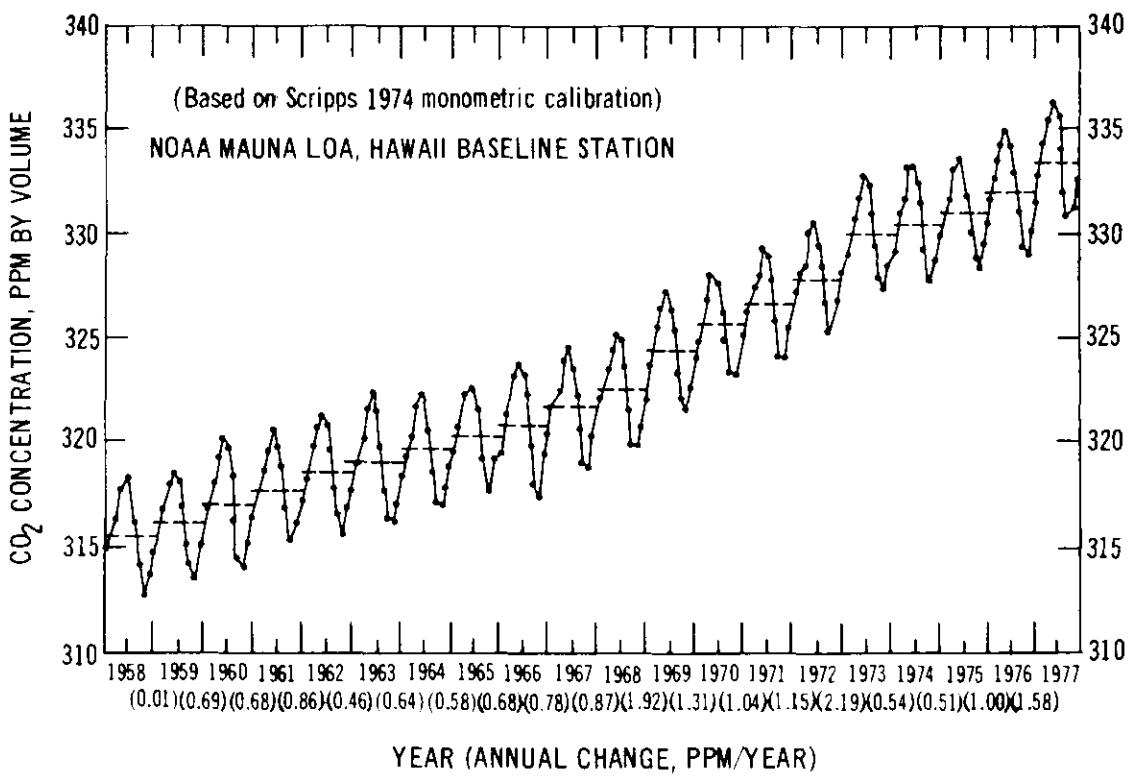

Fig. 2.4. Atmospheric CO_2 Concentrations

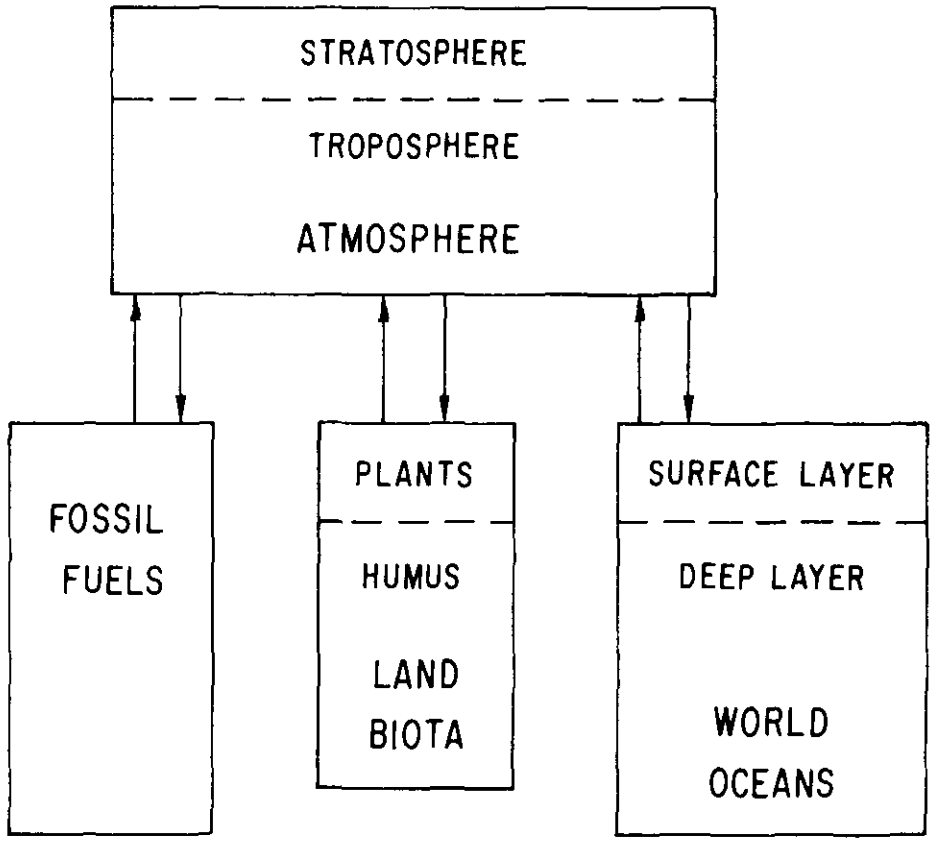

Fig. 2.5. Major Reservoirs and Exchanges in the CO_2 Cycle

The importance of man's contribution to the global carbon cycle cannot be underestimated. It has been estimated that the burning of fossil fuels now releases almost 2.0×10^{13} kg of carbon dioxide per year. This is of the same order of magnitude as the carbon dioxide annually consumed in photosynthesis (11×10^{13} kg), and, more importantly, it is considerably larger than the carbon dioxide annually consumed to produce new fossil carbon (10^{11} kg) Thus, the reservoir of fossil carbon is being depleted more than one hundred times faster than it is being renewed.

Plants remove CO_2 from the biosphere by photosynthesis and release it during respiration. The carbon content of short-lived biomass (1-10 years) is only 10% of that of the atmosphere, but the long-lived biomass (10-100 years) contains twice as much carbon as the atmosphere.[51] In response to increasing atmospheric CO_2 levels, the biosphere should grow faster and increase its storage of carbon. However, the ability of the biosphere to take up this increase in CO_2 is limited. An increase of 10% in the CO_2 content of

the atmosphere corresponds to only a 5% to 8% increase in photosynthesis. This is because plant growth in many parts of the world is not limited by CO_2, but rather by temperature, light, water, and soil nutrients. Furthermore, the major sinks for carbon storage on land occur in forests covering much of Canada, the Soviet Union, and the tropics. Due to increases in population and per capita consumption of natural resources, much of these forests may be exploited for wood products or cleared for agricultural use. It is currently unknown whether the global land biomass has increased during this century, in response to increased CO_2 levels, or has decreased due to deforestation.[53] Some investigators claim that the destruction of the biosphere is a source of atmospheric CO_2 that is of a magnitude comparable to man's fossil fuel input.[54,55]

The carbon content of ocean waters, to a depth of 100 m, is approximately equal to that of the atmosphere.[56] The partial pressure of the CO_2 in equilibrium with the sea water is determined by the alkalinity, the total dissolved inorganic carbon, and the temperature of the sea water. A 10% increase in the partial pressure of CO_2 in equilibrium with sea water leads to a 1% increase in the total inorganic carbon content of the water. If the inorganic carbon content of the water is constant, the partial pressure of CO_2 in equilibrium with the water rises 4% per 1°C rise in water temperature. The average sea-surface temperature of the North Atlantic decreased by 0.6°C over the period 1951-1972,[57] which would indicate an increase in the ability of the oceans to act as a sink for atmospheric CO_2 over this period. However, a warming of the sea-surface, caused by global warming due to CO_2, would presumably reverse this trend.

The ability of the oceans to act as a buffer for atmospheric CO_2 changes is limited. Only the well-mixed surface layer of the ocean can exchange CO_2 with the atmosphere and remain in equilibrium with it in the course of a few years. The deep waters below 1 km contain 60 times as much CO_2 as the atmosphere, but the time needed to exchange this water with surface water is probably 500 to 1000 years or more. Thus, the ocean has a limited ability to take up additional CO_2 in a short time.

Records of observed increases in atmospheric CO_2 and the release of fossil fuel CO_2 to the atmosphere verify that the biosphere and oceans are limited sinks for atmospheric CO_2. Table 2.7 summarizes the atmospheric

Table 2.7. Atmospheric Response to Fossil Fuel CO_2 Input

Year	Observed CO_2 Increase[a] (ppm)	Fossil Fuel Input (ppm)	Airborne Fraction (%)[b]
1955		0.98	
1956		1.03	
1957		1.08	
1958	0.89	1.10	81
1959	0.80	1.15	70
1960	0.55	1.19	46
1961	0.90	1.24	73
1962	0.76	1.30	58
1963	0.50	1.38	36
1964	0.40	1.46	27
1965	0.90	1.52	59
1966	0.76	1.60	48
1967	0.68	1.63	42
1968	0.98	1.73	57
1969	1.51	1.83	83
1970	1.31	1.97	66
1971	0.85	2.04	42
1972	1.47	2.12	69
1973	1.41	2.26	62
1974	0.45	2.26	
1975		2.26	
1959-1973 (Inclusive)	13.78	24.42	56

[a]Average of seasonally adjusted records of Mauna Loa Observatory and the South Pole.

[b]Assumes no biospheric (e.g., deforestation) sources.

response to fossil fuel CO_2 input from the mid 1950s to the mid 1970s. The percentage of fossil fuel CO_2 remaining in the atmosphere varied over this period from 27% to 83% annually, with a mean value of around 56%. Some scientists believe that the percentage of man-made CO_2 input remaining in the atmosphere will increase considerably in the next 50 to 100 years.[56] This will occur as a result of deforestation, which will reduce the biosphere reservoir, and of a small decrease in the ocean's ability to take up atmospheric CO_2.

Investigators feel that one of the major gaps in knowledge in the field of climate change is in the understanding of the carbon cycle.[48] Current models of the carbon cycle may underestimate the amount of CO_2 that

the oceans are able to take up. The impacts of deforestation on CO_2 levels are not well established, and it is not even reliably known if the biosphere is currently increasing or decreasing. These deficiencies will need to be overcome if the impacts of man's input to the carbon cycle are to be evaluated.

2.3.3 Projected Future CO_2 Levels

The future concentration of CO_2 in the atmosphere is a function of two factors: the growth of global fossil fuel utilization and the fraction of fossil fuel CO_2 input that remains in the atmosphere. If energy policies similar to those of the past 25 years prevail in the near future, the world consumption of fossil fuels may continue to increase by 4% per year for at least a few decades. It seems unlikely, in any case, that the growth of global fossil fuel utilization will be substantially slowed before the year 2000.

The fraction of fuel-derived CO_2 remaining airborne has probably been fairly constant during the past, with short-term variations. It is probably reasonable to assume that up to the year 2000 the airborne fraction will remain constant at around 50%. However, significant increases or decreases in the biosphere could change this.

Numerous projections of global atmospheric CO_2 levels have been made up to the year 2000.[50,58,59] The projections generally fall in the range of 375 to 400 ppm as compared to the current concentration of about 330 ppm. Beyond 2000, projections become much more difficult to make. Man's input will depend on energy policies and the emergence of nonfossil energy technologies.

It is important to be able to project CO_2 levels for the 21st century, because by that time the levels are expected to be extremely high and possibly significant with regard to global climate. An important parameter in making such estimates is the total fossil fuel reserves that can produce CO_2. This has been estimated as being between 5 and 15 times the preindustrial amount of CO_2.[60-62] Other important parameters are the rate at which fossil fuel resources are exploited, and as previously mentioned, whether or not the airborne fraction of CO_2 will change appreciably in the future.

Keeling and Bacastow[50] developed a model that predicts future CO_2 levels in the atmosphere, assuming that fossil fuel reserves can produce 8.2 times the preindustrial amount of CO_2. This model takes into account the amount of carbon currently present in each reservoir, exchanges between reservoirs, and a growth factor of biota up to the year 2010 based on increased CO_2 levels. Rather than predict a single fossil fuel combustion pattern, they chose to look at the response to four different patterns. All of the patterns showed an initial rapid rise in CO_2 levels consistent with current trends, a peak level in the period between 2100 and 2300, and then a slow decline over many centuries. The four patterns indicate peak CO_2 concentrations of six to eight times preindustrial levels. Because the residence time of CO_2 in the atmosphere is of the order of centuries, CO_2 levels are predicted to remain at more than five times the preindustrial levels for several centuries after the peak level is reached.

2.3.4 Climatic Response to Increased CO_2 Levels

It seems to be well established that CO_2 levels have increased since the late 1800s and will continue to increase in the future as the use of fossil fuels increases. Thus, the important issue is how the earth's climate will respond to increasing atmospheric concentrations of CO_2.

The major primary climatic impact of increased CO_2 is a cooling of the stratosphere and an increase in surface temperature.[63] Carbon dioxide is virtually transparent to incoming solar radiation but absorbs outgoing terrestrial infrared radiation in several wave bands. This outgoing radiation would normally escape to space and result in a heat loss from the lower atmosphere.

Numerous different atmospheric models have been used to simulate the response of the atmosphere to changing CO_2 levels. Three basic types of models have been used. Initial efforts were made with one-dimensional, radiative-convective models that yield vertical temperature profiles based on assumptions concerning solar input, surface albedo, humidity, cloudiness, and the nature of absorption, scattering, and reflection of radiation in the atmosphere.[64] A second type of model is a two-dimensional energy balance model that is similar to the one-dimensional radiative-convective model but also allows for north-south fluxes of heat.[65] The most sophisticated type of

model used in climate assessment is the three-dimensional general circulation model.[66] This type of model accounts for both horizontal and vertical motions and includes snow cover, rainfall, and the vertical lapse rate of temperatures as dependent variables. Part of the value of this last type of model lies in the fact that it can predict climate change for specific geographic regions of the earth, not merely for the whole globe or for latitude belts.

Table 2.8 compares the predictions of global surface temperature of several different models. Models are generally compared by examining their response to a doubling of atmospheric CO_2 levels, which is particularly appropriate because a doubling of CO_2 over preindustrial levels is possible by the early 21st century. The models listed in Table 2.8 tend to show a global surface temperature increase of 1° to 3°C for a doubling of CO_2 level. The

Table 2.8. Predictions by Different Models of Surface Temperature Response to a Doubling of CO_2

Source	Type of Model	Surface Temp. Increase (°C)	Key Assumptions
Plass (Ref. 67)	1-D Surface energy balance	3.6 2.5	Clear skies Average cloud distribution
Moller (Ref. 68)	1-D Surface energy balance	1.5 1.0	Fixed absolute humidity (a.h.) Fixed relative humidity (r.h.)
Manabe and Weatherald (Ref. 64)	1-D Radiative-convective	2.92 2.36 1.36 1.33	Clear skies, fixed r.h. Avg. cloudiness, fixed r.h. Clear skies, fixed a.h. Avg. cloudiness, fixed a.h.
Manabe (Ref. 69)	1-D Radiative-convective	1.9	Avg. cloudiness, fixed r.h.
Sellers (Ref. 70)	2-D Energy balance	1.3	Fixed r.h., cloudiness, and lapse rate
Manabe and Weatherald (Ref. 66)	3-D General circulation model	2.9	Fixed cloudiness, no heat transfer in ocean, hydrological cycle
Rasool and Schneider (Ref. 47)	1-D Radiative-convective	0.8	Fixed lapse rate, r.h., Stratospheric temp and cloudiness

dependence of temperature on CO_2 levels follows an approximately logarithmic relationship.[71] Thus, a fourfold increase of CO_2 levels would result in a doubling of the temperature increases in Table 2.8. However, these increases are averaged over the entire globe. The models tend to show fairly small temperature increases near the equator and fairly large temperature increases in the polar regions. In addition, the northern hemisphere is expected to warm slightly more than the southern hemisphere because of its greater land area and the larger thermal inertia of the southern oceans. The general circulation model of Manabe and Weatherald[66] predicted temperature increase of up to 10°C at high northern latitudes for a global temperature increase of 3°C.

The climatic impacts of atmospheric warming due to CO_2 would not be limited to surface temperature increases: higher temperatures could very likely produce a substantial increase in global precipitation.[72] However, this does not mean that all regions of the earth would experience increased precipitation. Some areas may even experience decreased precipitation. It has been suggested that the western United States could be one of the latter areas.[13] In addition, global warming may produce a decrease in the temporal variability of precipitation.

Another consequence of global warming due to CO_2 could be the alteration of atmospheric circulation patterns. With more warming at upper latitudes than at lower latitudes, the flux of heat from equator to pole will be decreased. This may serve to change the intensity and/or frequency of weather patterns.

A warmer climate might seem to be beneficial from a standpoint of longer growing seasons, which would allow the production of more food. It has been estimated that an increase of 1°C in average annual temperature at a location is equivalent to about a 10-day increase in the growing season.[72] However, an extremely rapid change in regional climate could prove to be detrimental rather than beneficial, because crops and other vegetation are adapted to existing conditions. Rapid changes in climate may result in reduced biological fitness and productivity before readjustments in human activities or in nature can be made.[60]

A potential impact of global warming that has been frequently discussed is a rise in sea levels resulting from the melting of glacial ice. Complete

melting of this ice could raise ocean levels by more than 50 m. Even a partial melting could have a pronounced effect on seashore areas. However, the mechanisms for this melting process are not well understood, and thus the rate of melting cannot be predicted. It is expected that the melting process due to warmer air would be extremely slow. A more important event would be that warm polar waters would cause a flow of ice from the continental shelves into the open seas, possibly raising the sea level by several meters in 300 years.

2.3.5 Possible Mitigating Measures

Should it be well established that increasing atmospheric CO_2 levels will produce serious environmental threats, there are several options open to counteract the problem. The most obvious is a switch from fossil fuels to alternative energy sources. However, the lead time required for such a switch could be considerable, and new technologies may entail environmental problems of their own.

Another option would be to increase the biospheric sink for CO_2 by planting more trees. Doubling the mass of living trees would store about 3×10^{12} t of carbon, which is between a third and a sixth of what might otherwise accumulate in the atmosphere from fossil fuel combustion.[73] This would have a significant mitigating effect, but would be almost impossible to accomplish within the time frame in which large impacts could occur. Furthermore, trends in forest cover are currently going in the other direction due to population increases and needs for forest resources.

Removal of CO_2 emissions from major sources is a possibility, although a costly one, as yet unproven, and quite likely energy-inefficient. Other potential mitigating techniques include fertilizing the oceans to accelerate oceanic uptake of CO_2.[74] Other forms of human intervention are possible. The addition of aerosols over oceans might act to counterbalance the greenhouse effect. Increasing the surface albedo by some means could reduce the amount of solar energy absorbed in the earth-atmosphere system.

The actual result of some of these mitigation strategies is only speculative. The only option that would appear to be immediately available would be a curtailment in the use of fossil fuels, but given the global nature of the CO_2 issue, any action along these lines could not be taken by the United States alone but would require the cooperation of all nations.

2.4 UNCERTAINTIES CONCERNING CLIMATIC CHANGE

Despite the efforts of researchers to study the various aspects of past and present climate and man's role in producing or enhancing climatic change, there are many uncertainties that prevent confident predictions of climatic change in the near future. Some of the uncertainties result from a lack of information; presumably these can be addressed with increasing research efforts. However, the major uncertainties exist as a result of the extremely complex nature of the earth-atmosphere system and the interrelations between the various parts of the system. These uncertainties may never be resolved well enough to allow reliable forecasts of future climate.

2.4.1 Feedback Mechanisms

Radiative-convective models are useful in determining the immediate effect of a change in the atmospheric concentration of a given pollutant. However, in addition to assessing first-order effects, it is necessary to assess how coupled second-order processes, or "feedback mechanisms," might either enhance or suppress first-order effects on the climate. Effects that accentuate the first-order climatic effect are referred to as positive feedback mechanisms, whereas those that suppress the initial effect are called negative feedback effects.

Some of the major climatic feedback mechanisms are summarized in Table 2.9. The major uncertainty is probably how increased temperatures relate to global cloudiness and how a change in cloudiness will act to either further warm the climate or suppress the initial warming trend. An increase in lower and middle clouds will produce lower surface temperatures,[64] because the amount of absorbed solar energy will be reduced due to reflection from the cloud tops, and because absorption and reradiation to space from the clouds. The decrease of incoming solar energy because of cloud cover may outweigh the decrease in terrestrial infrared radiation, to produce a net cooling. However, this may not be the case for very high, thin cirrus clouds with relatively low albedo.

The response of polar ice to temperature increases is as important as the temperature-cloudiness feedback effect. There is a large difference between the albedo of the surface ocean and the albedo of polar ice. A reduction of ice cover due to melting would decrease the albedo of the earth

Table 2.9. Major Climatic Feedback Mechanisms

Feedback Mechanism	Description	Feedback to Global Temp.
Radiative Temperature	Increased surface temp. causes increased emission of infrared radiation to space.	Negative
Water Vapor-Greenhouse	Increased temp. causes increased evaporation. Higher water vapor concentration causes more absorption of IR radiation.	Positive
Global Cloudiness	Increased cloudiness due to increased temp. and water vapor content decreases absorption of solar radiation.	Unknown, but probably negative. Types, heights of clouds important.
Polar Ice	Melting of polar ice leads to decreasing albedo.	Positive
Sea Surface Temperature	Increase of sea surface temp. leads to decrease in uptake of atmospheric CO_2 by oceans.	Positive

and increase the amount of radiation absorbed. However, the mechanics of the polar ice melting process are largely unknown, and only speculation is possible about the response of polar ice masses to global warming.

The lack of adequate knowledge of feedback mechanisms limits efforts to predict the direction and magnitude of future climatic change. More information needs to be developed on the physical mechanisms of the feedback effects as well as their interrelationships and the magnitude of their influence.

2.4.2 Natural Climatic Fluctuations

Despite the evidence that man's activities may be affecting the net climate in the direction of warming, the fact remains that until the last 10 years or so the earth has actually been cooling. It is unlikely that this cooling can be attributed to man's injection of particles into the atmosphere. Therefore, it is apparent that natural climatic variations have to this point outweighted man's influence on the climate. The reasons for the natural climatic variability probably include variations in solar input, volcanic

activity, glacial surges, and other natural external and internal forcing mechanisms.

It is impossible to predict the future direction of natural climatic variations, although, on the basis of the temperature record, the natural rate of change of mean surface temperature has been predicted to be about -0.15°C for the next decade.[13] Natural trends in the temperature are not likely to exceed ±0.25°C per decade.[75] Assuming a doubling of CO_2 levels by the year 2040 and a resulting temperature perturbation of +1.5° to 3.0°C, the rate of change of temperature due to this impact would be of the order of +0.3° to +0.6°C per decade. It is apparent that man's influence on climate can exceed the natural fluctuations of climate; however, the latter at present are still greater than man-induced fluctuations. The occurrence of natural climatic fluctuations necessitates the development of climate models to predict climatic change, because the record of measured temperature change may not reveal the forcing parameters at work.

2.4.3 Other Forcing Parameters

In addition to the impacts of waste heat, particles, CO_2, and natural climatic fluctuations, numerous other anthropogenic emissions can influence climatic change. Of particular importance may be the pollutants that affect the stratospheric ozone layer. Chloroflorometh anes (FCs) have been recently introduced into the atmosphere through uses such as propellants in spray cans. The migration of FCs and their reactive by-products to the stratosphere can result in a depletion of stratospheric ozone.[50] A similar effect can be produced by nitrous oxide (N_2O) and its by-products. N_2O is produced by biological decay, as well as by conversion processes, and may be increasing in the atmosphere because of the increased use of nitrate fertilizers.[52] An increase in CO_2 could have a significant impact on stratospheric ozone levels due to feedback effects; however, the direction of the temperature change is not altogether certain.[74]

There is no simple, straightforward way of relating perturbations of stratospheric ozone (O_3) to climatic impacts. The vertical distribution of O_3 in the atmosphere is as important as the total amount. Above-average ozone concentrations in the northern hemisphere have been associated with below-average temperatures,[74] but this does not establish a cause-effect relation-

ship. In fact, radiative-conductive models have shown that the reduction of O_3 in the upper troposphere and stratosphere produces a surface cooling effect because of a decrease of the O_3 greenhouse contribution.[76,77]

Numerous other industrial gases can contribute to the greenhouse effect by absorbing terrestrial infrared radiation in the 8-15 μm band. These include FC, nitrous oxide (N_2O), methane (CH_4), ammonia (NH_3), nitric acid (NHO_3), acetylene (C_2H_2), sulfur dioxide (SO_2), methyl chloride (CH_3C_l), and water vapor.[77] Increase of all of these gases will influence surface temperatures in the direction of warming. Table 2.10 summarizes the magnitude of the greenhouse effect arising from changes in concentrations of these species. It is apparent that H_2O, O_3, and CO_2 will have the greatest impact on surface temperature. The impact of other individual species is small. However, the greenhouse effects for such weak absorbers are essentially additive, and the impact of all of these gases together may be significant.

Table 2.10. Greenhouse Effect Arising From Increases in Various Trace Atmospheric Constitutents

Species	Band Center 1 mm	Assumed Present Concentration (ppmv)	Factor Modifying Concentration	Greenhouse Effect (K)	
				Fixed Cloud Top Temp.	Fixed Cloud Top Ht.
N_2O	7.78 17.0 4.5	0.28	2	0.68	0.44
CH_4	7.66	1.6	2	0.28	0.20
NH_3	10.53	6×10^{-3}	2	0.12	0.09
HNO_3	5.9 7.5 11.3 21.8		2	0.08	0.06
C_2H_4	10.5	2×10^{-4}	2	0.01	0.01
SO_2	8.69 7.35	2×10^{-3}	2	0.03	0.02
CCL_2F_2	9.13 8.68 10.93	1×10^{-4}	20	0.54	0.36
CCl_3F	9.22 11.82	1×10^{-4}	20	0.54	0.36
CH_3Cl	13.66 9.85 7.14	5×10^{-4}	2	0.02	0.01
CCl_4	12.99	1×10^{-4}	2	0.02	0.01
H_2O	6.25 10.0 20.0		2[a]	1.03	0.65
O_3	9.6		0.75	-0.47	-0.34

[a]This H_2O change occurs above 11 km with fixed relative humidity below that altitude.

3 ENERGY TECHNOLOGY IMPACTS ON CLIMATE

Many different factors must be considered when determining the potential culpability of the widespread use of various energy technologies in causing climatic change. However, the potential for significant change in climate is a factor that cannot be ignored. This chapter contains a description of the potential contribution of various energy technologies to climatic change on a local and global scale.

3.1 COAL TECHNOLOGIES

3.1.1 Waste Heat Impacts

A conventional coal-fired electric generating plant operates at a thermal efficiency of about 34%.[78] This means that 3 joules of heat input are required for every joule of useful energy output. More efficient methods of coal-fired electrical generation are being developed, and one possible method is the combined-cycle system. A combined-cycle system can achieve a thermal efficiency of as much as 45%.[79] This represents a saving of about 25% of the amount of energy input needed to generate a given amount of useful electrical energy by conventional coal-fired systems.

Potential global waste heat impacts were discussed in Sec. 2.1.2. It appears that coal energy technologies will play a minor role in whatever global impacts could occur as a result of anthropogenic heat release. Table 3.1 compares current and future energy releases from coal-fired utilities in the United States to current and projected global energy releases. The contribution of U.S. coal use to global energy use is extremely small -- 5% or less of the total. Given that the U.S. accounts for a third or more of the world's coal consumption, global consumption of coal as an energy source does not present a problem as far as waste heat is concerned, particularly because no noticeable effects on global climate are expected until the atmospheric thermal loading due to human activities reaches 3.4×10^5 GW (10^{19} Btu/yr). Table 3.1 also indicates that use of more efficient coal technologies will not substantially reduce global energy use.

Impacts of waste heat rejection on a local scale were described in Sec. 2.1.4. These potential impacts include increased fogging, cloud and

Table 3.1. Energy Use in Coal-Fired Utilities in the United States and Global Energy Use[a]

Year	Coal Use[b] (GWe)	Conventional Energy Use[c] (GW)	Equivalent Combined-Cycle Energy Use[d] (GW)	Global Energy Use[e] (GW)
1976	191.9	310	230	6,960
1985	317.6	510	390	9,910
1990	351.6	570	430	12,050

[a]Global energy use is synonymous with global energy release.

[b]The National Energy Plan, Executive Office of the President, Energy Policy and Planning, April 29, 1977.

[c]Assumes all coal use in facilities with thermal efficiency of 34%.

[d]Assumes all coal use in facilities with thermal efficiency of 45%.

[e]Based on Ref. 7 and the assumption of a 4%/yr increase in energy use.

precipitation enhancement, and drift deposition. The probability and extent of these impacts are largely functions of the type of cooling technology and local meteorological conditions. Presumably, local impacts will be minimized on a case-by-case basis through the choice of cooling technology and facility site. Local waste heat impacts should not impede coal use on a global scale.

3.1.2 Impact of Particle Releases

As was indicated previously, the effect on climate of changes in atmospheric particle loading has not been clearly identified. It is thus difficult to assess the contribution of coal combustion to climate change through the emission of particles to the atmosphere. Some perspective on the potential role of coal combustion can be gained by looking at emission estimates.

Table 3.2 compares present and future emissions of primary particles from utility coal use to atmospheric particulate loadings from all sources. The coal emissions are a very small percentage of the total annual particle loading of the atmosphere. However, a larger contribution to anthropogenic particle loading of the atmosphere occurs as a result of gas-to-particle

Table 3.2. Annual Primary Particulate Emissions from U.S. Coal-Fired Utilities Compared to Annual Particulate Emissions from All Sources

Year	Coal Use (GWe)	Coal Use Emissions (10^6 t)	Particulate Emissions from All Sources (Natural and Man-Made) (10^6 t)
1976	191.9	82[a]	3,606
1985	317.6	45[b]	5,132
1990	351.6	50[b]	6,244

[a]Assumes average ash content of 15%, removal efficiency of 70%.

[b]Assumes average ash content of 15%, removal efficiency of 90%.

conversions. Sulfate aerosols formed in the atmosphere from the chemical reaction of anthropogenic SO_2 emissions account for 2-10 times the particle concentration in the atmosphere caused by anthropogenic primary particle emissions. Coal combustion accounts for almost 70% of man's global emissions of SO_2. However, increasing use of SO_2 emission-control devices may to some extent limit the growth of SO_2 emissions in the future. Nitrate aerosols contribute less than do sulfates to total particulate loading of the atmosphere, but emission controls for NO_x are less available and less efficient. Moreover, the combustion of oil and gasoline is also a large source of NO_x.

It is difficult to assess the contribution of coal use to climate change through increased atmospheric particle loading. The impact of coal on global particle concentration may be significant, but it appears to be of less consequence than the impact of coal use on CO_2 levels.

3.1.3 CO_2 Impacts

The combustion of coal releases substantial amounts of carbon dioxide to the atmosphere. It has been estimated that coal combustion, averaged over the earth, releases CO_2 at the rate of approximately 98.6 kg 10^9/J.[61] Thus, a conventional 500-MWe coal-fired power plant[80] will emit about 10^7 t of CO_2 per year. There is at present no effective, efficient method for controlling combustion emissions of CO_2 to the atmosphere. The only practical means of reducing the CO_2 added to the atmosphere by coal combustion is to reduce the amount of coal burned.

Table 3.3 compares the CO_2 emissions from projected U.S. utility coal use to total world production of CO_2, assuming a 4% per year increase in fossil fuel combustion. It appears that coal combustion in the U.S. could contribute significantly to the world increase in CO_2 emissions. In fact, as much as 30% of the projected increase in world CO_2 production over the next 15 years will be attributable to increases in U.S. coal combustion. However, the CO_2 problem is truly a global issue. If no increase in U.S. coal combustion occurred after 1976, the result would only be to reduce the rate of growth of global CO_2 emissions from 4% to 3%. This would serve to postpone by about 15 years the time at which atmospheric CO_2 concentrations reach twice the preindustrial level.

A slower rate of increase of CO_2 levels could be extremely valuable in allowing more time for monitoring the climatic response to CO_2 increases, as well more time for developing and implementing nonfossil-energy options. However, it should be pointed out that the decision for a switch to nonfossil energy technologies must come many years in advance of a significant measureable increase in global temperature because of the lengthy residence time of CO_2 in the atmosphere. A sudden decrease in fossil fuel combustion will not produce an immediate decrease in atmospheric CO_2 levels.

It must be concluded that the future global use of coal as an energy source and the resulting release of large amounts of CO2 to the atmosphere

Table 3.3. Projected Annual Emissions of CO_2 from U.S. Utility Coal Combustion Compared With Projected Annual World Emissions of CO_2

		Emissions (10^6 t)		
Year	Coal Use[a] (GWe)	Conventional	Equivalent Combined Cycle[c]	Projected Worldwide[d]
1976	191.9	4,200	3,200	18,400
1985	317.6	7,000	5,300	26,190
1990	351.6	7,700	5,800	31,860

[a]The National Energy Plan, Executive Office of the President, Energy Policy and Planning, April 29, 1977.

[b]Assumes thermal efficiency of 34%.

[c]Assumes thermal efficiency of 45%.

[d]Assumes 4% annual increase.

could have a significant warming effect on the world's climate. Whether or not this warming would be advantageous or disadvantageous on a global scale is currently unknown. It is generally felt that a decision to curtail fossil fuel combustion to minimize CO_2 impacts on climate would have to be made by the year 2000, and the policy to reduce fossil fuel combustion would have to be global to be effective. Unfortunately, at the present time, the state of the art of climate prediction is not developed enough to provide a solid scientific basis that decision makers could use to implement such a policy.

3.1.4 Other Impacts

In addition to releasing heat, CO_2, primary particles, and precursors of sulfate and nitrate aerosols, coal technologies may affect climate in other ways. The release of water vapor from combustion or from evaporative cooling towers may increase the water vapor content of the atmosphere. Water vapor plays an important role in augmenting the greenhouse effect because it is a strong absorber of several infrared bands. The emission of SO_2 and other gases that are also infrared absorbers may contribute to the greenhouse effect as well.

3.2 NUCLEAR TECHNOLOGIES

3.2.1 Waste Heat Impacts

The major impact that nuclear energy technologies will have on the climate will occur as a result of heat rejection to the atmosphere. A typical thermal efficiency for a light water reactor (LWR) is of the order of 33%, whereas a liquid metal fast breeder reactor (LMFBR) will have a thermal efficiency of around 40%.[78] These efficiencies are similar to those of coal technologies, and thus the waste heat impacts should be similar as well.

Global impacts of the heat rejected by nuclear power plants should not be significant. Local impacts will be a function of cooling technology selection and site selection. Presumably, these local climatic impacts will not constrain the use of nuclear technologies but will require selection of sites or selection of cooling methods to fit local meteorological conditions. Impacts of waste heat rejection may be significant on a regional scale if

numerous nuclear powerplants are sited in large power parks. These impacts could include the formation of heat islands, initiation of convective clouds, increased humidity and precipitation, fog formation, and vorticity concentration. Again, it would seem logical to assume that these potential impacts would not constrain the global level of implementation of nuclear power but rather would constrain dense siting of facilities that would result in extraordinarily large local densities of energy released to the atmosphere.

3.2.2 Other Impacts

No significant amounts of any air pollutant will be released by either a LWR or a LMFBR during normal operations. Small amounts of chromates, zinc, chlorides,and possibly some particulates will be emitted. The effect of these emissions on the radiative balance of the earth-atmosphere system should be minimal. Emissions of water vapor from evaporative cooling systems may contribute to the greenhouse effect.

3.3 SATELLITE POWER SYSTEM

The impacts on climate of a satellite power system (SPS) can be divided into three major areas. First, effluents from the rocket launches during construction of the satellite may have atmospheric impacts. Second, microwave transmission may have impacts on the troposphere. Finally, the operation of a rectifying antenna (rectenna) at the earth's surface may have waste heat impacts.

3.3.1 Rectenna Waste Heat Effects

A microwave beam with a maximum power density of 23 mW/cm^2 will result in an average waste heat release at the rectifying antenna of approximately 75 kW/km^2. A large rectenna may cover a surface area of as much as 100 km^2. The release of this much waste heat may result in noticeable impacts on the weather and climate.

The mechanisms for rectenna waste heat effects are twofold. First, the rectenna structure itself will modify the thermal and radiative properties of the ground on which it is built. Additionally, the operation of the SPS will result in a heat source at the surface due to waste heat rejection, which, from a large rectenna, is expected to be roughly equivalent to the heat

released from typical suburban developments. This waste heat release is less than 10% of the average solar net radiation at the surface; however, it is suspected that changes in surface roughness, due to the rectenna structure, and the rectenna's albedo itself will contribute more significantly to atmospheric perturbations than the waste heat from power conversion.

Although the perturbation of surface heat exchange caused by the rectenna is of the order of 10%, more significant impacts may result due to nonlinear interactions in the atmosphere on both the regional scale (10 to 100 km) and "cloud" scale (<10 km). On these scales, the rectenna may produce small temperature changes (1°C) in conditions of light wind. Changes in the amount of cloudiness can also be expected, whereas anomalies in the distribution of precipitation are less likely, but still possible. The atmospheric impacts will depend on ambient atmospheric conditions and should be mainly site specific.

3.3.2 Microwave Transmission Impacts

Microwave transmission through the troposphere will result in a certain amount of microwave energy absorption. This absorption will occur chiefly within various hydrometeors in the atmosphere, particularly in clouds. This will result in local heating, which can enhance turbulence and possibly alter atmospheric circulation.

However, microwave heating of the troposphere due to absorption by gases or hydrometeors will be extremely small. It is not expected that this heating will have any significant effect on the dynamics and thermodynamics of clouds or other hydrometeors. Conversely, these tropospheric hydrometeors may cause the microwave beam to spread and wander.[81]

3.3.3 Impact of Rocket Effluents

Construction of an SPS will require numerous launches of heavy-lift launch vehicles (HLLVs). These launches will result in the emission of various combustion products into the lower and upper atmosphere.[80] The primary exhaust products will be carbon dioxide and water, but at various altitudes some quantities of sulfur dioxide, hydrogen, and oxygen will be emitted.

The immediate impact of a rocket launch is to form a ground-level cloud from the rocket effluents as ignition occurs. This ground cloud should dissipate fairly rapidly, and the main ground-level impact should be an increase in air pollution concentrations on a local scale, and on a regional scale if launchings are frequent. The emission of waste heat and water vapor at greater heights in the troposphere may lead to the growth and/or enhancement of convective clouds and thunderstorm activity. Effluents from repeated launchings may serve to make this impact regional in scale and may be considered to have potential impact on both climate and weather. A small probability exists that local increases in acid precipitation resulting from rocket effluents could have impacts on surrounding ecosystems.

Some concern has been expressed with regard to an increase in water vapor content in the stratosphere. Calculations have indicated that frequent HLLV launches (500 per year) would produce only insignificant changes in stratospheric water vapor content on a global scale.[81] However, the possibility exists for a "corridor effect" in which perturbations are much more significant in latitudes where the launches occur. Effects of increased atmospheric water vapor are not completely understood, although it is possible it could lead to increased stratospheric cloud formation, which could decrease the amount of solar radiation reaching the surface. Additionally, injection of water vapor into the upper stratosphere may produce some depletion of ozone, but this should not be significant. Some production of nitric oxide (NO) may occur in the rocket exhaust, but this also should be insignificant.[81]

Some impacts of rocket effluents on the upper atmosphere (mesosphere and thermosphere) may occur. Rocket launches may increase the water vapor content of the mesosphere by as much as a few percent. Additionally, the rocket effluents may serve to significantly deplete the total electron content of the ionosphere. Besides the direct effect of this depletion on electromagnetic wave propagation, airglow, and electron temperature profile, there may also be an impact on the troposphere and tropospheric weather. This could occur either through the direct migration of effluents from the upper atmosphere or through triggering and coupling mechanisms that connect changes in the upper atmosphere with effects in the lower atmosphere.[81]

Because carbon dioxide is one of the two major effluents from the HLLV, the issue of how significantly deployment of the SPS will increase

global atmospheric CO_2 levels is important. A single HLLV flight will result in the emission of about 3.67×10^3 t of CO_2.[80] It is estimated that two 5-GWe satellites can be constructed per year, which would entail about 500 HLLV launches.[73] This means that SPS implementation and utilization will result in the emission of 1.835×10^2 t of CO_2 per MWe of system capacity. The conventional combustion of coal for electrical generation will result in an average annual emission of 2.2×10^4 metric tons of CO_2 per MWe of system capacity. Thus, the use of coal will result in CO_2 emissions that are two orders of magnitude larger per unit capacity than those associated with the SPS. It appears that the CO_2 emitted from HLLV launches will not be significant in comparison to other sources of CO_2.

3.4 PHOTOVOLTAIC SYSTEMS

3.4.1 Waste Heat Impacts

The waste heat released by any energy facility is defined as the heat released in excess of the amounts that would be released if the facility were not there. For coal and nuclear technologies, this can be easily defined as all of the heat rejected at the plant and its cooling towers. However, an array of photovoltaic cells is utilizing solar energy that would normally strike the ground, and thus it is important to assess the magnitude of the solar energy absorbed at the collector surface and rejected to the atmosphere above and beyond the amount that would occur at a natural surface.

Some incoming solar radiation is absorbed by the ground, heating it and the surrounding air, and some is reflected back to the atmosphere. The important parameter that determines how much is absorbed is the albedo (or reflectivity) of the surface. Photovoltaic collector cells will have a much lower albedo than the terrestrial surface and hence absorb more solar radiation. The exact amount of waste heat released by photovoltaic collector cells depends on the difference in albedo between the cells and soil surfaces and on the thermal efficiency of the photovoltaic module. For a typical southwestern United States soil cover and a unit thermal efficiency of 13%, the waste heat rejected per unit energy produced has been estimated as 1.5 MWt-yr/MWe-yr.[82] This results in an equivalent waste heat density of about 40 W/m^2, which is several times larger than is expected from a SPS rectenna but of a comparable magnitude to releases from major urban areas.

Although these considerations might suggest that waste heat impacts from photovoltaic systems might be significant, one must look at the potential size of such a facility. A typical application of the technology might supply the electrical energy needs for a town of about 10,000. This would require about 0.25 km^2 of collector area representing a maximum system capacity of about 22 MWe.[83] A somewhat larger system (88 MWe) would require 0.9-1.7 km^2 of collector area.[78] Generic studies have been completed for large-scale applications (100 MW and 1,500 MW); however, the actual utilization of systems of this size will depend largely on the experience with smaller facilities.[84] It is apparent that large-scale photovoltaic facilities will be considerably smaller than a rectenna.

It is thus anticipated that impacts from photovoltaic systems will be minimal and local in nature. Small temperature perturbations over the collector surfaces may occur, particularly during calm weather. Other impacts on local climate will include a change in surface roughness (due to the collector surface), producing a change in the wind structure in the atmospheric boundary layer. Additionally, changes in evapotranspiration at the surface will occur because of the collector. These changes should produce negligible changes in the climate because of the relatively small surface area being disturbed.

3.4.2 Secondary Impacts

Although there are no normal emissions of air pollutants during operation of photovoltaic systems, emissions occur during the manufacture of photovoltaic cells. A modest amount of particulates will be emitted from aluminum and concrete production for the cell arrays.[85] Production of silicon or cadmium photovoltaic cells will entail some emissions of particulates, SO_x, and NO_x. However, on a per-capacity basis,[85] all of these emissions are small in comparison to those from coal-fired electrical generating systems.

3.5 FUSION SYSTEMS

Estimates of fusion power development indicate that precommercial demonstration reactors will not be built until the 21st century and that commercial reactors will not exist until the year 2030, at earliest.[86] It is

not possible to determine at this time what the specifics of a working reactor will be, although most of the research effort to this date has been directed at the Tokamak design of magnetic confinement.[87]

Estimates of the climatic impacts of fusion power generation are thus somewhat conjectural. It is unlikely that any appreciable amount of any pollutant will be emitted under normal operating conditions. Heat releases can probably be assumed to be similar to those from nuclear fission technologies. The size of fusion systems and the method of cooling will determine to a large extent whether local climatic perturbations of temperature, humidity, cloudiness, and precipitation will be significant.

3.6 COMPARISON OF THE CLIMATIC IMPACTS OF THE FIVE TECHNOLOGIES

There are potential risks of climatic impact from coal technologies, nuclear technologies, and the SPS. Table 3.4 contains a qualitative summary of the potential severity of impact of these energy technologies on climate. The intent of this table is not to predict but to identify which energy technologies are most likely to play a role in climate change. An attempt is made to classify whether or not each technology will play an important role, a minor role, or no role at all in each type of impact on climate.

The most serious impact appears to be that of coal combustion on CO_2 levels and the resulting greenhouse effect. Coal combustion will also add to the production of primary and secondary particles, but to a much smaller extent. The impact of particulate loading may also be less severe than that of CO_2-induced warming, although the impact of a global increase in particles has not been well documented.

Coal and nuclear technologies will release water vapor to the troposphere, which may increase the total greenhouse effect, as well as the formation of clouds at lower levels. The injection of water vapor into the stratosphere from HLLV emissions may increase upper-level cloudiness, which could have a definite effect on surface temperatures. Coal combustion may release small amounts of greenhouse gases other than CO_2 and H_2O, but this should not occur to any great extent from SPS, photovoltaics, or nuclear technologies. HLLV emissions may have a significant impact on stratospheric ozone concentrations, particularly in the latitude belts where launches are being made.[81]

Table 3.4. Contribution of Energy Technologies to Potential Climatic Impacts

	CO_2 Release	Primary and Secondary Aerosol Emissions	Primary and Secondary Aerosol Emissions	H_2O Vapor Emissions Into Stratosphere	H_2O Vapor Emissions Into Troposphere	H_2O Vapor Emissions Into Troposphere	Trace Gas Emissions	Waste Heat Release	Waste Heat Release	Waste Heat Release
Scale of Influence	Global	Global	Regional	Global	Global	Reg./Local	Global	Global	Regional	Local
Likely Impact	Warming	Warming or Cooling	Precip. Changes	Strat. Clouds, O_3 Depletion	Warming	Increased Cloud., Humidity	Warming	Warming	Clouds, Precip., Warming	Clouds, Fog, Precip.
Severity of Impact[a]	H	U	M	U	M	M	U	L	M	M
Importance of Energy Technologies[b]										
Coal[c]	3	1-2	1-2	0	1	1	1	1	1	2
Nuclear[c]	0	0	0	0	1	1	0	1	1 (2-3)[e]	2
SPS[d]	1	0	1	1-2	1	0	0	1	2	1[f]
Terr. Photovoltaic[c]	0	0	0	0	0	0	0	1	1	2
Fusion[c]	0	0	0	0	1	1	0	1	1	2

[a]Ranks the likelihood of noticeable climatic impacts according to the following criteria.
H - High - Significant climatic perturbation.
M - Moderate - Noticeable, but not severe impact.
L - Low - Negligible climatic impact.
U - Unknown - Extent of possible impact not known.

[b]Importance of impacts ranked according to the following criteria.
3 - Very Significant - Major contributor to significant climatic issue.
2 - Significant - Major contributor to any climatic issue or minor contributor to significant climatic issue.
1 - Minor - Small, but measurable contribution to any climatic issue.
0 - Negligible - Contribution, if any, is not important.

[c]Considers operating emissions only.

[d]Considers operating emissions and HLLV emissions.

[e](2-3), if large power parks are constructed.

[f]It may be inappropriate to consider any impacts as local because of rectenna size.

Waste heat impacts from all five technology types should be minor on a global scale. However, on a regional level the SPS rectenna will produce effects similar to an urban or suburban heat island. Nuclear power parks could have significant waste heat impacts on a mesoscale, including precipitation and fog enhancement, as well as possible triggering of severe weather. Individual power plants should not produce significant regional impacts, but individual coal and nuclear power plants may produce significant local impacts, particularly if cooling towers are used.

Overall, it appears that coal technologies present the greatest risk of the five for producing global climatic change. This is primarily because of the large amount of CO_2 emitted during coal combustion, and to a lesser extent, the emission of particles and other greenhouse gases. The SPS does not appear to provide any major risks to the climate, although the impact of HLLV emissions on the stratosphere has not been adequately established. Large central-station applications of terrestrial photovoltaics may produce noticeable local waste heat impacts, and the impacts of waste heat release from nuclear power parks could be substantial.

4 UNCERTAINTIES AND CONCLUSIONS

4.1 UNCERTAINTIES AND GAPS IN THE DATA

Despite the amount of research already undertaken in the study of climatic change, numerous uncertainties and gaps in data still persist and make it extremely difficult to project future climate or the response of climate to various anthropogenic inputs. Therefore, it would currently be extremely difficult for decision makers to include climate as a consideration in energy policy.

Some of the gaps in knowledge that need to be filled are as follows:

- The magnitude of the impact of deforestation on global CO_2 levels is not currently known.
- It is not known whether the biosphere is now increasing or decreasing.
- Because of the above two considerations, and because of uncertainties concerning the oceans as a sink for CO_2, a satisfactory model of the carbon cycle has yet to be developed.
- Probably the biggest gap in climate change research is the lack of a believable climate simulation model. Many researchers doubt that one will ever be developed. Part of the problem is the inability to validate such a model.
- Better knowledge is needed of the physical mechanisms of climatic feedback effects. The most important of these are the cloud-temperature feedback and the thermodynamic ocean feedback. Better ways of simulating these feedback mechanisms in climate models also need to be developed.
- More work needs to be done to characterize the optical properties of atmospheric particles. The likely direction of temperature response to an increase in atmospheric particles has yet to be determined.
- A better understanding is needed of how global temperature change will affect regional temperature and precipitation trends and global circulation.
- The dynamics of the melting of polar ice must be better understood so that the impacts of global warming may be ascertained.
- The record of stratospheric and tropospheric temperatures is not extensive and detailed. Trends in such records that exist are somewhat obscured by the effects of volcanism.

- The impact of HLLV emissions on the stratosphere and upper atmosphere needs more investigation, as does the impact of changes in upper atmosphere constituents on the troposphere.

4.2 CONCLUSIONS

There is no question that man is capable of, and indeed has been, modifying the local and regional climate. Our ability to perturb the global chemical content of the atmosphere has been documented for CO_2 and other substances. Global climate models indicate strongly that these perturbations may change the climate of the world, but the exact nature and extent of the change cannot at present be estimated with any certainty, largely because of the great natural variability of climate.

The specific conclusions of this study can be summarized:

- A consensus exists that warming of the lower atmosphere may occur due to increasing concentrations of greenhouse gases, particularly CO_2. A variety of climate models predict a 1° to 3°C warming for a doubling of the CO_2 level, but the magnitude of the consequences are uncertain.
- Noticeable warming should not occur before the end of this century. The current trend of global temperature has been towards cooling, probably due to natural causes.
- The long residence time of CO_2 in the atmosphere could mean that adverse impacts from global warming will persist for several centuries.
- There are substantial uncertainties in the attempts to simulate the response of the atmosphere to climate-forcing perturbations.
- The problem of increased particle loading is currently considered to be of lesser importance than the greenhouse effect. The direction of the particle effect is currently unknown.
- Global waste heat impacts appear to be of negligible importance for the next century or so. If per capita energy use and population continue to increase rapidly, waste heat may become an important global issue after 2100.
- Regional and local waste heat impacts may be significant but will be highly site specific and will depend on cooling technology.
- The rate of climatic change is probably at least as important as the magnitude of climatic change.

- Of the technologies considered, coal technology presents the greatest risk to potential global climate changes because of its large emissions of CO_2.
- Impacts of the other technologies should be limited to local and/or regional effects caused by waste heat rejection, with the possible exception of SPS-related rocket exhaust effects on the stratosphere.
- Given the gaps in knowledge regarding possible energy-related global climate change, it can be concluded that climate is a consideration in energy policy, but in itself cannot currently be a criterion in decision making.

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