CLIMATE AND SOLAR ENERGY CONVERSION

PROCEEDINGS OF A IIASA WORKSHOP
DECEMBER 8-10, 1976

JILL WILLIAMS, GERHARD KRÖMER,
AND JEROME WEINGART, Editors

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PREFACE

The IIASA Energy Program is concerned with global aspects of energy systems in terms of resources, demands, options, strategies, and constraints. One constraint on an energy system is its potential impact on climate. The IIASA Energy and Climate Subtask, which is supported by the United Nations Environment Programme (UNEP), is studying the possible impact on global climate of the three major medium- to long-term energy options: nuclear, fossil fuel, and solar. A workshop was held at IIASA in December 1976 to discuss the potential impact on global climate of large-scale solar energy conversion. The Workshop provided information on characteristics of solar energy conversion systems and on possible ways in which they could alter climatic boundary conditions. The tools available for studying the problem--climate models and case studies--were also discussed. This material forms the basis for a continuing study of the climate constraints of the solar option within the Energy and Climate Subtask, and in cooperation with other groups.

Contents

SUMMARY OF WORKSHOP DISCUSSIONS

PAPERS BY WORKSHOP PARTICIPANTS

APPENDIXES

SUMMARY OF WORKSHOP DISCUSSIONS

BACKGROUND

Introduction

The Workshop brought together a small number of experts from appropriate fields, including engineering, physics, and meteorology, to discuss the climatic aspects of the production of heat, electricity, and fuels from solar energy conversion at the global scale. A number of different professional fields, which normally do not interact extensively, are joined in these Proceedings. Therefore we have prepared a brief overview of the major issues in climate dynamics as they relate to the subject of the Workshop, and a discussion of the various solar energy options and their possible future use. We have emphasized the technological features that are most significant in terms of possible climatic effects.

The first part of the Proceedings has been produced jointly by the editors and several of the participants. The second part contains the contributions of the Workshop participants, modified somewhat by each author during the Workshop and prior to publication of the final version.

The IIASA Climate Project

The IIASA Energy Systems Program is concerned with identifying and understanding the constraints for the large-scale production and consumption of energy, and thus with the evaluation and comparison of various energy options (e.g., coal, fission, fusion, solar, geothermal) in the medium- and long-term future (i.e., 15 to 100 years). This work has been discussed in detail in a number of available IIASA publications and will not be summarized here.

Weinberg and Hammond (1971), Washington (1972), Häfele (1974), and others have indicated that the impacts of the large-scale production and consumption of energy on climate may represent an important constraint on future energy systems. For example, waste heat introduced into the atmosphere in the vicinity of large energy parks may have adverse effects on micro-, meso-, and macro-climate. It has also been recognized that greatly increased use of fossil fuels could lead to dramatic increases in the CO_2 content of the atmosphere, which in turn could lead to significant changes in global climate (Baes et al., 1976). In addition to waste heat and CO_2, other byproducts of the process of energy production, such as particles, gases, and moisture, may have important effects on climate in the future. With energy production and consumption increasing more rapidly than population, it seems important to investigate how these byproducts of energy systems might significantly influence the climate (see, for example, Schneider and Dennett (1975), and Schneider with Mesirow (1976)).

The study of potential impacts of energy systems on weather and climate is an important component of IIASA's research. The ultimate objectives of this research are to investigate the short- and long-term effects of each energy option (and combinations thereof) on weather and climate, to incorporate these effects into the study of the various energy options, and to evaluate and compare their impacts and implications within this framework. The objectives of the energy/climate study include:

- Investigation of the impacts of waste heat on global and regional climate;
- Assessment of the impacts on climate of the large-scale implementation of solar energy systems; and
- Determination of the upper and lower bounds for the effects of certain particulates and gases on global climate.

The initial research in this direction was to investigate the impact of energy parks on climate where large amounts of waste heat (300 TW) are released into the atmosphere. The results of this work have been reported by Häfele (1976), and by Murphy et al. (1976).

Currently the work is continuing on an examination of the effects of concentrated large sources of waste heat, and is expanding to include both the effects of CO_2 on climate and the climatic effects of solar energy conversion (SEC) on the global scale.

Objectives of the Workshop

The objectives of the Workshop were as follows:

- Preliminary identification of the possible impacts of solar energy systems on weather and climate at the micro-, meso-, and macroscales;
- Determination of the effects that should be investigated and to what extent;
- Identification of available tools and their suitability for such investigation;
- Review of previous work which might be relevant to the solar/climate issue;
- Formulation, if possible, of specific proposals for cooperative efforts of IIASA and the institutions represented at the Workshop.

CLIMATE AND MANKIND

General Concerns

Since the beginning of history, climate has played a dominant role in determining where and how people live. Temporal and spatial distributions of climate have determined the patterns of agriculture and the availability of water, and have had a significant role in facilitating much of the biological and cultural diversity that exists. In addition, the fluctuations of the climatic system have produced such physical phenomena as storms, floods, and droughts, which have caused, and continue to cause, substantial human dislocation and suffering.

Long before there was either advanced technology or very many people, the clearing of woodland for agriculture and the overgrazing of grasslands by migratory herds of domesticated animals resulted in substantial changes in the landscape over large areas. In recent centuries, however, our capabilities have grown enormously to the point where mankind has become a global ecological force. However, the combination of rapid population growth, powerful technologies and the energy to exercise them on a global scale may result in substantial changes in the surface of the earth and in the composition of the atmosphere and thus possibly in the climate.

Climate may again become a controlling factor in mankind's development both in the negative sense that our actions may result in substantial and irreversible undesirable changes and in the positive sense that an awareness of the potential for such consequences may modify our behavior so that we can avoid or minimize such changes.

Energy and Climate

The direct conversion and use of energy can be an important force in climatic change. One component of the climatic system that is changing through energy use is the content of CO_2 in the atmosphere as a result of the increased use of fossil fuels initiated by the Industrial Revolution. There is strong evidence to support the argument that these increases in CO_2 content could result in increased temperatures and climatic change. However, the exact relationship between CO_2 and its impact on climate is not fully understood, and requires extensive investigation.

A second way that man may modify climate is through heat released into the atmosphere. At present, these heat releases are invariably concentrated in the dense urban areas, which constitute a very small fraction of the earth's surface. The main effect on the mesoscale is the production of urban heat-islands. In the future, however, large quantities of waste heat may be introduced into the atmosphere through the use of nuclear power "parks".

A number of other possible climatic impacts of energy use have been widely discussed (SMIC, 1971) but not rigorously investigated. For example, any implementation of an energy system that involves large-scale changes in vegetation (such as biomass conversion for producing fuels and electricity) could affect climate. Modification of the natural vegetation affects several significant physical parameters which in turn are linked to the climatic system. These include the surface roughness, albedo, porosity, and conductivity as well as the apportionment of the available net radiation into sensible and latent heating of the atmosphere (SMIC, 1971).

Mitchell (1970) has described the changes in heat budget that occur after conversion from forest to agricultural use, and these differences are certainly significant on a microscale. Deforestation of large tropical areas is potentially more significant; Newell (1971) has suggested that deforestation of the Amazon basin could affect the dynamics of the general atmospheric circulation. This effect has been studied by Potter et al. (1975), using a zonal atmospheric model. Consideration must therefore be given to the possible effects of modifying the earth's surface by large-scale energy systems. This consideration will be significant in the case of large-scale solar energy conversion (SEC).

Likewise, changes in surface water area, by construction of artificial lakes, draining swamps, straightening rivers, flood control, and evaporation of water to produce salt are all likely to influence climate at least on a microscale, and possibly, depending on the extent and persistence of the effect, on the regional and the global scales as well. SCEP (1970) point out, for example, that damming the Congo River would almost certainly affect the climate over a large portion of Central Africa, and that the anticipated water area would be sufficiently large that global climatic changes could not be ruled out. Keller (1970) has estimated that runnoff from the Federal Republic of Germany has decreased 12 percent between 1891 and 1930 and 1931 to 1960, primarily because of increased water uses. Such changes could have an impact on the moisture balance of the earth-atmosphere system.

Other possibilities for climate modification arise from proposals for very large-scale energy production. Marchetti (1976) has suggested the use of the Canton Island for siting a giant nuclear power station (1 TW) whose end product would be hydrogen. Cold ocean water from great depths would be used to dispose of the 2 TW(th) waste heat. The interaction of such schemes and the features of the tropical and, perhaps even the global atmospheric and oceanic circulations, must be considered.

Solar Energy Conversion and Climatic Change

Because of the rapidly growing interest in SEC technologies, and the need to compare large-scale uses of major future energy sources on an environmental basis, it is appropriate to initiate exploration of the climatic implications of the solar option.

There has been a generally prevalent view that environmental impacts of SEC would be minimal even with the very large scenarios considered here. Such attitudes have been expressed regarding potential impacts on weather and climate.

For example, the MITRE Corporation carried out an extensive study of solar energy systems for the National Science Foundation solar energy program in 1973. For ocean thermal energy plants, they indicated that such systems would be "virtually pollution free; no residuals would be produced". For solar thermal electric and photovoltaic plants, the effects that would occur, if any, would be "predominantly associated with the collector arrays", but there was no discussion of what physical or climatic effects could be expected. However, they did indicate that the heat balance of the atmosphere "might be somewhat affected by the transfer of energy from the collector site to the load points of the system". They further point out that for each million BTU of energy produced by solar rather than fossil fueled plants, air pollution would be reduced by three pounds of sulfur oxides, one pound of nitrogen oxides, and one pound of particulates. (They could also have included the reduction in CO_2 injection.)

If solar systems are used on a scale that could really impact world energy needs, the areas involved for SEC plants (land and ocean) would be on the order of 1 to 10 million km^2. The first figure would be for the production of 50 TW (thermal equivalent) at a production rate of 50 W/m^2; the latter is for a more conservative estimate of the production rate per unit land area and for 100 TW (secondary energy) production. This latter extreme scenario was used in the experiments described by Potter and MacCracken in these Proceedings; the scenario itself is described by Grether, Davidson, and Weingart (these Proceedings). The physical characteristics of the region would be permanently altered, and the possibility for climatic change under these conditions cannot be ignored.

Among the effects of SEC on the climatic system are changes in the surface energy balance, altered patterns of local precipitation, changes in local transpiration rates through extensive paving of land surfaces, modification of the surface temperature distribution of the tropical oceans, and alteration of rate coefficients governing CO_2 concentrations in the atmosphere and oceans through the increased mixing rate between surface and deep ocean layers (ocean thermal energy conversion (OTEC) systems). These and other effects require much more extensive investigation if a comparison of energy options including solar is to be made in the area of weather and climate.

Some very preliminary investigations of potential solar-related effects on climate have been made (Meinel and Meinel, 1976; Federal Energy Administration, 1974; von Hippel and Williams, 1975; Williams, 1975).

The Meinels argue that while the use of large SEC facilities (on a scale sufficient to provide the present total US energy demand) will change the surface relectivity and lead to a redistribution of solar energy through its transport to and conversion in urban regions, this effect would be less pronounced than the effects due to existing roads and parking lots. They claim that:

> Further, the plowing of the Midwest each spring and the harvest each fall cause a larger net perturbation of the albedo of the United States than would all the solar collectors in the forseeable future (Meinel and Meinel, 1976).

In addition, they argue that by suitable increases in reflectivity of regions containing solar facilities, effective changes in albedo can be made as small as desired.

Their arguments can be challenged on several grounds. First, Weingart has shown (these Proceedings) that no such general "cancellation" of changes in the albedo is possible, since the natural albedo of a region changes with the season, as does the albedo of the solar facility. Also, the effective albedo of a solar thermal electric conversion (STEC) facility will be a function of the percentages of diffuse and direct beam radiation, and hence will change with the weather. In addition, they ignore other effects, such as changes in hydrology, in the Bowen ratio, and in the surface roughness, and surface temperature distribution, as well as the effects of partitioning a fraction of the incoming solar radiation into (waste) latent and/or sensible heating. Finally, they erroneously compare the effects of a *transient albedo change* (owing to plowing and harvesting) with the effects of a *permanent shift in surface characteristics.* The latter can be extremely important, as indicated by Fraedrich (these Proceedings).

Von Hippel and Williams (1975) have made a preliminary investigation of the possible physical effects of OTEC systems on the climatic system. They have discussed three effects including the lowering of the surface temperature of the Gulf Stream, the modification of tropical ocean ecosystems through artificial (OTEC-induced) upwelling, and an increase in atmospheric CO_2 owing to the increased mixing of the ocean layers. They estimate that the use of OTEC to generate electricity at the rate of present US demand would reduce the surface temperature of the Gulf Stream region by 0.5° K, and indicate that they do not know if this is "too much"; they suggest that such a change might modify the climate of Western Europe. With regard to CO_2, they suggest that the increased upwelling of deep (CO_2 laden) ocean water can lead to increased atmospheric CO_2 burdens, and calculate that the CO_2 released into the atmosphere through generation of 3 kWh(e) by OTEC would be equivalent to that released by the production of 1 kWh(e) by fossil fuel combustion.

Of course, limitations on the state of the art of weather and climate modeling constrain the extent to which the impacts of SEC and other energy conversion systems can be quantitatively investigated. However, the present status of these models is sufficient to examine quantitatively some of the issues such as the effect of large changes in surface albedo over areas of hundreds of thousands of square kilometers. (Ellsaesser et al., 1976; Charney, 1975).

We recognize that a careful examination may indicate that the large-scale use of SEC systems will entail few climatic problems. This is often argued by observing that the areas required for the provision of, say, the total US energy demand by SEC would be on the same order as the land area covered by paved roads (about 80,000 km^2) and that this is considerably less than the total land area that has been dramatically modified by combining roads, urban and suburban settlements, and agriculture. The implication is that if we can live with roads, cities, and agriculture (in climatological terms), then we can live with SEC systems on the largest conceivable scale. What is ignored in such arguments is the effect of differing *spatial patterns* of surface modification. The distribution of roads over the land in the USA is not equivalent, in climatic terms, to the co-location of an equivalent area of solar facilities in the sunny Southwest of the country, for example.

Since work has recently begun on examining the climatic implications of fossil fuel and fission conversion, a similar effort should be undertaken in solar energy to permit detailed comparison. In this sense, if the environmental effects of other energy sources set some limit on the rate or the ultimate scale of their use, and if it turns out that solar systems are more benign, such systems may eventually be used on a large scale for environmental reasons even if their direct cost is higher than the alternatives. (This assumes that the total internalized costs of the solar option would be the same or lower than those associated with other options used beyond a certain scale.)

WEATHER AND CLIMATE MODELS

Scale Definition

Atmospheric dynamics can be considered for a wide variety of time and space scales, and it is necessary to classify atmospheric processes according to scale. Table 1 shows a scale definition and a classification of atmospheric processes, based primarily on the horizontal dimensions of the phenomena as developed by Orlanski (1975). As the latter pointed out, to define an observational or numerical experiment it is essential to determine the scale that is most representative of the particular event.

Models have been developed to apply the different scales of atmospheric dynamics. Global or macroscale models consider large-scale dynamics; microscale models consider the detailed behavior of the immediate surface environment in which man lives. Regional models (Randerson, 1976) consider the beta- and alpha-mesoscale subrange (25-2500 km), while mesoscale models have been developed to study heat-islands.

Table 1. Scale definition and different processes with characteristic time and horizontal scales. (After Orlanski, 1975.)

		1 month	1 day	1 hour	1 minute	1 second	
10,000 km	Standing Waves	Ultra-Long Waves	Tidal Waves			Macro α Scale	
2000 km		Baroclinic Waves				Macro β Scale	
200 km			Fronts and Hurricanes			Meso α Scale	Regional Scale
20 km			Nocturnal Low Level Jet Squall Lines Inertial Waves Cloud Clusters Mountain and Lake Disturbances			Meso β Scale	
2 km				Thunderstorms IGW CAT Urban Effects		Meso γ Scale	
200 m				Tornadoes Deep Convection Short Gravity Waves		Micro α Scale	
20 m					Dust Devils Thermals Wakes	Micro β Scale	
					Plumes Roughness Turbulence	Micro γ Scale	

Models of the Climatic System

The earth-atmosphere system cannot be simulated in any reasonable way in a physical laboratory and for obvious reasons many situations, such as the impact of increased atmospheric CO_2 burdens, cannot or should not be studied by experimenting with the system. In addition, many of the effects of human activities have no precedent either in man-made or natural changes in the climatic system; hence we may have no analogous past situations to guide us. We must therefore seek other methods to assess the potential impact of future human activities on the climate.

The most promising approach to understanding the climatic system and the mechanisms of climatic change is the use of numerical models of climate. Schneider and Dickinson (1974) have given a detailed description of climate modeling, stressing the physical basis of each kind of model and its contribution to an understanding of the climatic system. Reviews of the physical basis of climate and the development and use of climate models are given by GARP (1975) and by the US Committee for GARP (1975). Observations and theoretical studies of the general circulation of the atmosphere have been described recently by Smagorinsky (1974) and by Arakawa (1975).

The processes of the climatic system may be expressed in terms of a set of dynamic and thermodynamic equations for the atmosphere, oceans and ice, together with appropriate equations of state and conservation laws for selected constituents (e.g. water, CO_2, and ozone in the atmosphere). These equations have been used to model climate (see for example GARP (1974)); however, physical and numerical approximations must be made because of a lack of information on both the observed climate and the methods of computing the processes. A hierarchy of climate models has therefore been created, each type of model using a different set of approximations and thus simulating processes on a particular temporal and spatial scale.

In the following section the major divisions of the present hierarchy of climate models will be described, and their application to the study of the impacts of energy systems will be discussed.

The simplest models of climate are essentially one-dimensional, with dependence on other dimensions being either parameterized or neglected. In a horizontally averaged one-dimensional vertical model, the various radiative fluxes are determined as a function of the vertical coordinate, and the mean vertical temperature profile is often specified. These models have been used to examine the effects of increases in atmospheric CO_2 and aerosol concentrations on the vertical temperature distribution (Manabe and Wetherald, 1967; Rasool and Schneider, 1971).

It is important to realize that because of the enormous range of scales of interacting processes in relation to the limited resolution of computational grids, it is neither technically nor economically feasible (yet) to calculate explicitly the effects of small-scale processes. But, because the small-scale processes are important, it is necessary to either relate their statistical effects to conditions on larger scales, or to specify their effects more or less arbitrarily. It is generally desirable to parameterize these effects, that is, to express the statistical effects of various small-scale transport and transfer processes in terms of the large-scale variables explicitly resolved by the model.

Energy balance models emphasize the calculation of the surface temperature in terms of a balance between incoming solar and outgoing infrared radiation. This type of model is applied to the zero-, one-, and two-dimensional cases. The most well known examples of the energy balance model are those of Budyko (1969) and Sellers (1969). This type of model can be used to study the impacts of energy systems on climate, providing results usually in terms of the ultimate impact upon global temperature. Penner (1976) has used a Budyko-type model to examine the impact of waste heat on the average temperature of the earth.

Zonally symmetric dynamic models of the atmosphere derive the zonal structure of the atmosphere from an observationally prescribed distribution of thermal and momentum sources. An example of this type of model is described by Saltzman and Vernekar (1971).

Experiments have been made to investigate the effects of changes in the amount of incoming solar radiation, but no published examples exist of the use of these models to examine the effects of energy systems.

Since the longitudinal variations of pressure, rainfall, temperature, etc., are also of interest, atmospheric dynamic models have been developed in which the longitudinal variation of quasi-stationary patterns are quantitatively modeled. This kind of model could be used to examine the impact of large-scale thermal sources (see for example Egger (1976)).

The coupling of models that describe zonal dynamics as a function of latitude and altitude with detailed models of the zonal surface energy balance is achieved in zonally symmetric models of the earth-atmosphere system. The best example of this type of model is the recently upgraded zonal atmospheric model developed by MacCracken (MacCracken and Luther, 1974). This model has been used to look at the effects of tropical and subtropical albedo and surface hydrology changes (Ellsaesser et al., 1976; Potter et al., 1975); it has also been used in a preliminary attempt to evaluate the impact of large-scale use of SEC systems (see Potter and MacCracken in these Proceedings).

Modeling the three-dimensional mean atmospheric circulation involves simulating the atmospheric circulation over a long period with an atmospheric general circulation model (GCM). Such a model is a set of time-dependent equations that describe the detailed evolution of the dynamic and thermodynamic state of the atmosphere. The resolution of a GCM is usually a few degrees of latitude and longitude horizontally and a few kilometers vertically. Atmospheric GCMs are currently able to simulate many of the observed large-scale features of the atmosphere and consequently have been used to investigate the sensitivity of the system to a variety of perturbations. With reference to the effects of energy systems, GCMs have been used to investigate the impacts of waste heat releases (Washington, 1971, 1972; Murphy et al., 1975, 1976) and the impacts of atmospheric CO_2 increases (Manabe and Wetherald, 1975).

One of the limitations of atmospheric GCMs is that they assume fixed sea surface temperatures rather than compute them. The top model of the hierarchy is therefore a three-dimensional circulation model of the earth-atmosphere system in which sea surface temperatures are calculated from a GCM of the ocean, coupled directly to the atmospheric GCM. Manabe and Bryan (1969) made the first attempts at jointly modeling the earth-atmosphere system, but such joint models are not yet sufficiently well developed to permit a study of the system's sensitivity to perturbations.

We see that the hierarchy of climate models ranges from simple computations of the effects of isolated processes on average conditions over the entire globe, to space and time dependent computer simulations of the nonlinear interactive earth-atmosphere system. The very simple models can be used to estimate the sensitivity of long-term conditions of the whole system to changes in thermodynamic and transport processes. This could be a useful step before employing the more detailed two- and three-dimensional models of the atmosphere or of the earth-atmosphere system. Table 2 shows characteristics of some climate models from which it is possible to make an assessment of the model applicability for studying the impact of SEC systems in terms of both the input required and the type of information given.

Regional Models

The concept of a regional scale developed from the application of atmospheric pollution models for predicting or diagnosing air quality. Randerson (1976) has given an overview of regional models in which it is proposed to include in the scale phenomena with horizontal wavelengths of 25 to 2500 km. Regional models can be subdivided into two basic categories: those developed to forecast general weather conditions, and those used in atmospheric pollution or air quality studies. In both cases, the physics of the regional scale seem to be dominated by boundary layer forcing an organized convection, although it is becoming clear that if necessary this scale can be controlled by macroscale processes and the nesting of regional models in macroscale models. Randerson (1976), in addition to describing the major regional models, has indicated how such models can be used to assess the impact of energy technologies.

Table 2. Characteristics of climate models for solar conversion sensitivity experiments.

VARIABLE	United Kingdom Meteorological Organization (UKMO)	National Center for Atmospheric Research (NCAR) Version used by Williams et al. (1974)	Goddard Institute for Space Studies (GISS) Version used by Somerville et al. (1974)	Geophysical Fluid Dynamics Laboratory (GFDL)
Albedo	Observed values used one value for each latitude band	Observed values specified for all non-ocean grid points	0.07 for oceans 0.14 for land 0.70 for snow or ice	Observed values used except over snow where albedo is function of snow depth
Surface Roughness	Four values of C_D used depending on stability and whether point is over land or sea	C_D constraint at 0.003 for all grid points	Drag coefficients computed as function of wind speed, static stability surface type and surface height	C_D calculated, with roughness parameter z_o assumed to be 1 cm
Hydrology	No soil moisture budget computed	Bowen ratio of 1 assumed, no other surface hydrology computed	Soil moisture specified	Simplified hydrological processes, including evaporation, soil moisture and snow cover calculations
Surface Temperature	Computed for land surfaces	Computed for land surfaces	Computed for land surfaces	Computed for land surfaces
Clouds	Specified according to observed distribution	Computed as a function of relative humidity and vertical velocity, i.e., only large scale	Eight cloud types and subtypes may be generated depending on process and atmospheric layer	Specified as input according to observed distribution
Precipitation	Rain computed	Rain computed	Rain computed	Rain and snow computed
Ocean Temperature	In all these GCMs at the present time the distribution of sea surface temperatures are specified according to observed data. Coupled ocean circulation models are being developed.			
Atmospheric CO_2	CO_2 not included but could be in radiation scheme used	Infrared radiation treated using absorption functions of gases, including CO_2, as analytical functions	Detailed calculations of energy transfer by solar and terrestrial radiation, including CO_2	Same radiation scheme as Manabe and Wetherald (1967); therefore includes CO_2

Table 2. (continued)

	One-Dimensional Vertical eg. Manabe and Wetherald (Model (1967)	Energy Balance Model eg. Budyko (1969) Sellers (1969)	Zonal Atmospheric Model eg. Potter et al. (1975)
Albedo	Vertical distributions of radiative convective equilibrium can be computed for different values of surface albedo; was run for α = .00, .20, .40 and .60	Coupling between planetary albedo and temperature of atmosphere near earth's surface is an important component of these models	Detailed specification depending on surface type, wetness. MacCracken and Luther (1974)
Surface Roughness	Model computes radiative convective equilibrium at a point	Model deals with zonally averaged heat balance of earth-atmosphere	Four values of C_D used depending on surface type; altered by convective instability of atmosphere
Hydrology	Surface hydrology but water vapor in atmosphere is treated	None	Ground may become wetter or drier, snow may build up and sea ice may form or melt
Surface Temperature	Computed	Calculated in terms of balance between incoming and outgoing radiation	Calculated separately for each surface type and depends on energy fluxes from atmosphere and layers below
Clouds	Are included in model as input variables	Not considered except as component of planetary albedo	Empirical representation depending on relative humidity
Precipitation	Not computed	Not computed	Rain and snow computed
Ocean Temperature	Not relevant	Not explicitly included except in more advanced versions	Assumed well mixed to specified thermocline depth. Fluxes of sensible heat specified from observed data. Ocean temperature computed from radiation sensible and latent heat fluxes
Atmospheric CO_2	The impacts of different levels of atmospheric CO_2 have been investigated	Not explicitly included	Longwave radiation scheme includes cooling to space for CO_2

Mesoscale Models

For studying the impact of energy conversion and use on a scale of 2.5 to 25 km, a mesoscale model dealing with the weather or climate of a region with greater resolution than a global model is more appropriate. Mesoscale models have been developed to describe the changes in atmospheric circulation caused by cities and ocean-islands. The contrast in albedo, heat capacity, and hence heating and cooling rates, heat generation, and surface roughness between the city or ocean-island and its more uniform surroundings results in the generation of localized weather processes. Garstang et al. (1975) have summarized the observed characteristics of so-called "heat-islands". Under calm conditions there is rising motion above land (during the day in the case of the ocean-island) and above the built-up area (during the night in the case of the urban heat-island), with compensating descending motion in adjacent areas. The intensity of the heat-island is a function of latitude, altitude, radiation balance (and therefore the composition of central and surrounding surfaces), the local composition of the atmosphere, geographic location with respect to terrain, and the degree of artificial heat input to the atmosphere. (The boundaries of a heat-island can be defined by surface horizontal temperature gradients which are large in comparison with gradients occurring over surrounding regions.)

The observed characteristics of heat-islands can be presented in terms of various numerical models. There are four broad categories of such models: statistical, energy balance, turbulent mixing, and dynamic. The methods used in each of these categories and the results of each approach have been reviewed in more detail by Garstang et al. (1975).

Statistical models of heat-islands are based on statistical relationships of the strength of the heat-island and meteorological variables (cloudiness, wind speed, temperature, water vapor pressure, and lapse rate). Statistical models have been used to describe urban heat-islands but not ocean heat-islands.

Energy balance models are based on the assumption that a heat-island results from distinctive energy transformation over urban and adjacent rural surfaces. The models therefore consider the available net radiation and other terms of the energy balance such as artificial heat generated in a city, sensible and latent heat transfers, heat storage, and advection of energy from rural to urban environments.

Mixing depth models consider the change in airflow over a surface in which there is a change in surface roughness; a layer of the atmosphere influenced by the change in surface conditions is examined. For example, Summers (1965) assumed that advection of stable rural air over a warm "rough" city would result in a particular form of boundary layer over the city (adiabatically mixed with a constant wind profile); using this model he demonstrated that the growth of this layer was a function of the stability upwind of the city, the heat sources within the city, and the wind speed in the mixed layer.

Dynamic models solve a set of differential equations (equations of motion and continuity, a thermodynamic equation, and an equation of state). Individual models differ primarily because of assumptions regarding term importance, initial conditions, and computer solution schemes. The models are solved using some type of finite differencing scheme.

SOLAR ENERGY CONVERSION AS A GLOBAL ENERGY OPTION

World Energy Needs and the Transition to New Sources

The present rate of consumption of primary sources of energy worldwide is 7.5 TW(th). This corresponds to an average per capita use of roughly 2 kW(th), and for much of the population of the world, the average use is much less.

A decent world will probably require much more energy in the future. A world of ten billion people living at the 5 kW(th) per capita standard of Western Europe would correspond to an order of magnitude increase to 50 TW(th) worldwide. This would occur if the product of population and per capita energy use grew at a modest two percent a year over the coming century, as it has over the past 100 years.

A transition over a period of a century or so to a world with stable population and a reasonable per capita energy use would be difficult enough if there existed unlimited and cheap sources of oil and natural gas. However, during the period in which human needs will be increasingly acute, we must somehow make the transition to a world in which the secondary energy carriers are derived from long-term, abundant energy resources. (During this period, oil and gas will become increasingly scarce and have already become too expensive for most people.) While the rate and scale of such a transition will certainly vary from place to place, depending on patterns of needs, resources, wealth, industrial development, and so forth, this transition will ultimately be global and it will be essentially completed within a century. In addition, it will be characterized by the transition from cheap, constrained energy sources (fossil fuels) to unconstrained capital-intensive sources.

In principle there are four primary sources of energy which could provide the secondary energy requirements over the very long term: nuclear fusion, nuclear fission, geothermal energy, and solar energy. At this point in time only fission and solar energy are sufficiently in hand to permit, in purely technical terms, use on the required global scale of many tens of terawatts. The role of coal could be to provide much of the needed energy during the middle part of this transition.

Given all the constraints, we must inevitably consider the use of solar energy as a global energy source on the same scale as is being contemplated for fission energy via the fast breeder. It also means that we must consider very carefully the array of impacts which deployment of such a technological strategy would produce. Unless we do so now, in a few decades we may find ourselves with substantial opposition to the large-scale use of solar options.

Below we sketch the main features of a global SEC system and the rate and scale with which such a system may be deployed, under the best of technical, economic, and institutional situations. We describe the important solar technologies in sufficient detail to motivate discussion of the interaction of SEC systems and climate.

A Global Solar Energy Scenario

As oil and gas are depleted over the coming fifty years or so, other globally transportable fuels must take their place. Hydrogen, methane, alcohols, ammonia, and liquid air (the latter not strictly a fuel but a negentropy carrier) have all been proposed as the interface between the large-scale primary sources and the continually evolving patterns of end use. In addition, electricity will continue to be required as an essential ingredient of advanced societies, regardless of its ultimate primary sources.

Solar energy, in both direct and indirect forms, can be used for the production of secondary energy carriers. The majority of indirect SEC is associated with hydropower in Latin America and Africa. While such sources may be very important regionally in the future, it would appear that they are not capable of providing anything remotely approaching the 50 TW(th) or more which could be required in a century from now. The direct conversion of sunlight, at high efficiency, appears to be the solar option capable of deployment at the required level.

During the period in which solar technologies for production of electricity and synthetic fuels become available for large-scale commercial use (sometime around 1990), we can expect the bulk transport of electricity to reach continental dimensions and that of gas via pipeline to be limited only by geography. Transport of liquid fuels will continue to be highly practical in technical and economic terms at the global scale.

This means that solar power plants and fuel production facilities can be located in sunny regions and interconnected through transmission lines, pipelines, and tankers. A global scenario envisages a total of 1 million km^2 of sunny land set aside for the operation of such facilities; this corresponds to a net production rate of secondary energy at 50 $W(th)/m^2$ equivalent of land. Because the geopolitics of sunlight are more favorable than those of oil, and because the resource is non-depletable, there is the possibility to create a global energy system.

A similar strategy is envisioned for synthetic fuel production. In principle solar thermal techniques may be employed to produce hydrogen, using the basic technology of the STEC system coupled with thermochemical water disassociation techniques. Such techniques will also be required for the use of the high temperature reactor as a source of fuel; the development of commercially interesting thermochemical hydrogen production technologies ranks as one of the most important technical challenges. However, even without such technologies, the certainty of electrolysis may permit production of hydrogen and ammonia at a cost on the order of \$30 per barrel equivalent in the future (Weingart, 1977). While these costs are well above those of current oil and gas supplies, an energy efficient world could live from such a source. Under the assumption of optimistic but reasonable technological advances, thermochemical production could permit hydrogen production at prices approaching \$10 per barrel equivalent (at the "well-head").

The production of hydrogen as a secondary energy carrier has many attractive features, and a few negative ones as well. The attractive aspects include the feature that the fuel could be used with minor changes in technology in the industrialized world, phased in and mixed in with the present gaseous fuels, and stored easily in natural geological formations including aquifers and depleted oil and gas fields. This would permit decoupling of the solar source and the end use patterns both in time and in space.

We recognize that a global network view of the solar option is dissonant with the popular view of solar energy as something that permits local energy autonomy through small-scale systems. However, it is only through the direct and large-scale use of sunlight that global energy needs could be provided from this option. Of course, this does not rule out the small-scale use of solar heating, wind generation, and so forth, when the situation is favorable for these applications. However, it is from the broader point of view that we shall examine the potential climatic implications of SEC.

SOLAR ENERGY SYSTEMS TECHNOLOGIES

Introduction

The Solar Power Resource

Solar energy is a power resource available at a rate determined by the effective surface temperature (approximately 5900°K), and the angular size of the sun, the properties of the atmosphere, and the earth-sun geometry as seen from a specific place on the earth. Outside the atmosphere the solar radiation power density is 1.4 kW/m^2 (the "solar constant"), and is limited at the surface by the properties of the atmosphere, a turbulent scattering and absorbing medium. The solar radiation at the surface will be a mixture of direct and diffuse (or atmospherically scattered) radiation; the ratio will depend on the state of the atmosphere. Under the best of clear atmospheric conditions, the maximum direct beam radiation can be as high as 1.0 kW/m^2, and constitute as much as 90 percent of the total irradiance.

The annual average global insolation (total diffuse and direct radiation on a horizontal surface) ranges from between 2 and 6 $kWh/m^2/d$, the former figure typical of northern Europe and similar regions, the latter typical of the sunny arid regions. In clear sky environments the direct beam radiation on a surface continuously oriented towards the sun can average annually from 7 to 8 $kWh/m^2/d$; this is the solar energy resource that will be important to the global solar energy scheme described later.

Direct Conversion

Many possible combinations of processes can be used to convert sunlight into other forms of energy required by an industrial society. All these processes will be carried out through combinations of energy conversion, storage, and transmission elements plus power conditioning components, combined into integrated energy systems. The "front end" of such a system will consist of units for converting solar energy into some other energy form.

Indirect Conversion

Through the climatic system, solar energy also manifests itself indirectly as winds, waves, and thermal gradients in the oceans as well as hydraulic potential energy through the hydrological cycle. Energy systems harnessing these indirect forms invariably produce mechanical energy at the initial conversion stage; other forms of energy including electricity are then produced in subsequent processes.

Options for Large-Scale Use

We will briefly describe the following technologies, which are presently considered candidates for large-scale commercial use in the future:

- Solar thermal electric conversion (STEC),

- Photovoltaic Conversion (PV),

- Ocean thermal energy conversion (OTEC),

- Bioconversion,

- Wind energy conversion (WEC),

- Solar satellite power stations (SSPS).

We will not consider solar heating and cooling of buildings, agricultural process heat or industrial process heat by solar conversion; they represent a small component of total energy demand and, particularly in the case of solar space conditioning and water heating, will be embedded in settlements which constitute a far greater disruption to the climate system than is solar hardware. Rather, we confine ourselves to systems that could be globally deployed to constitute the bulk of the secondary energy production at the 50 TW level of primary energy displacement.

The discussions that follow make use of the reference designs for SEC systems used in the current EPRI solar environmental studies (EPRI, 1976). These were developed by EPRI as technical guidelines for preliminary environmental studies of solar technologies being carried out under EPRI sponsorship.

Solar Thermal Electric Conversion (STEC)

Physical Characteristics

The STEC process involves the absorption of concentrated direct solar radiation in order to produce superheated steam or hot gases for turbogenerators. Work going on in the USA emphasizes the central receiver concept in which a field of steerable mirrors (heliostats) concentrates solar radiation on a thermal absorber on top of a tower. Two basic types of a thermodynamic cycle are considered: conventional Rankine cycle turbines (540°C steam), and high temperature Brayton cycle turbines (1000°C inlet), either in open cycle (air) or in closed cycle (air or helium) configurations. Current engineering work is oriented towards unit sizes for such plants in the 50 to 150 MW(e) busbar rating range.

The overall efficiency of converting direct beam radiation incident on the heliostats to electricity at the busbar will depend on the details of the thermodynamic cycle and, in the case of the steam cycle, on the type of cooling system employed (wet- or dry-cooling towers). In general, the overall efficiencies are expected to be in the range of 18 to 25 percent. For a 20 percent net efficiency, 5 m^2 of mirror area would be required for each kW(e) of busbar capacity. This means that for a busbar rating of 100 Mw(e) the total mirror area would be 0.5 km^2. To minimize shading and blocking of adjacent heliostats, the land required for the mirror field will have to be considerably larger than the reflecting surface area. Current engineering studies indicate that the ratio of total reflecting surface area to dedicated land area (for the mirror field) will be between 0.3 and 0.6. (This ratio is known as the ground cover ratio.) Hence the land area requirements including the balance of the plant will be roughly 1.5 km^2 per 100 Mw(e) capacity rating. (This is the value for STEC plants operating in the "sun-following" mode.)

The steam systems will require cooling in the form of wet- or dry-cooling towers or by other means such as "once through" cooling.

The high temperature systems will either eject hot air (600°C) directly into the atmosphere (open cycle) without heat exchangers, or employ heat exchangers (closed cycle) for this purpose. In both cases, heated dry air will be ejected at the rate of 1 kW(th) per 1 kW(e) production capacity. An overall Brayton cycle efficiency of 0.47 has been assumed.)

The most dramatic feature of such systems will be the heliostat fields. Each heliostat will be as much as 10 m high with reflecting surface as much as 6 m on one side. The orientation of the heliostats will be a function of both their individiual position relative to the tower position and the solar elevation and azimuth. Such elements will be rigid, in contrast to vegetative canopies, and may create additional turbulence and vorticity in the region.

Physical Effects

In general, a STEC plant partitions the incoming solar energy, which normally would be absorbed or reflected at the ground, into additional components. Some of the incident radiation will be directly reflected, some absorbed and reflected by the ground, some converted into secondary energy which may be transported out of the region, and some released as latent or sensible waste heat. The albedo of such plants will have a unique characteristic. The mirrors will reflect the majority of diffuse radiation, but the system is highly absorbing for direct radiation; hence the albedo is a two-parameter function of the local physical variables.

The major changes in boundary conditions of the local climatic system would be as follows,

- *The albedo* of the region containing the plant will change in a complex way depending on the mirror field configuration, the percentage of direct beam radiation, the solar elevation and azimuth, and on the modification of the ground beneath the heliostats.
- *Surface roughness* will almost certainly increase owing to the presence of the heliostats.
- *Surface porosity* will decrease substantially if the region is paved.
- *Surface emissivity* will change, depending on the paving materials.
- *The Bowen ratio* will shift owing to a suppresion of the transpiration.

- *The surface thermal conductivity* will be modified.
- *The surface heat capacity* will be altered.
- *The local energy balance* will be affected owing to the partitioning of incident solar energy into waste heat (latent or sensible) and secondary energy.
- *The re-emission ratio* (the ratio of energy absorbed and re-released in the presence of the solar facilities to that in the absence of the facilities) will be affected. The amount depends on the details of the surface albedo, plant efficiency, ground cover ratio, and other characteristics.

Climatic Implications

The effects of the STEC plant on the climate will depend on the scale of implementation of the technology, but for a large scenario well within the realm of possibility, local, meso, and global changes might occur. The implications of changes in the radiative balance in deserts have been studied recently by a number of researchers within the context of global and mesoscale models of the atmosphere (see Williams, 1975, Table 1). The general consensus is that a decrease in the albedo will be accompanied by a corresponding increase in precipitation. Since solar thermal plants would decrease the albedo of the desert, we might expect some increase in precipitation with their construction. Potter and MacCracken (in these Proceedings) give the results of a model simulation of this effect for a particular SEC scenario. These results support this conclusion. Model results also suggest modification of the poleward transport of sensible and latent heat. It has been suggested by Bhumralkar (these Proceedings) that, during the operation of a solar plant, convective and diffusive heat transport will become more important relative to radiative processes. This is likely to modify convective motion and could affect cloud formation, similar to the effects experienced from urban heat-islands.

We can be fairly certain that roughness length will be increased as a result of the presence of the heliostat fields, and that this in turn will modify the flux of horizontal momentum. In addition, modification of the drag coefficient, which depends on the surface roughness and the height above the surface, will cause both modification of the turbulent fluxes of energy and water vapor between the surface and the atmosphere.

Widespread areas of changed albedo, surface roughness and/or surface hydrology, can be expected to produce climatic effects. Examples will be discussed later in which sea surface temperature anomalies (SSTAs) can influence such features as the tracks of depressions or the strength of the Hadley circulation, and thus have effects elsewhere in the hemisphere. Similarly, Namias (1960) showed that abnormal heat sources or sinks, such as extensive areas of abnormally moist land or the presence of snow in areas and at times when snow is uncommon, could influence atmospheric behavior. Radiation balance, surface roughness, and temperature patterns on the microscale climate are not known. Before these effects can be evaluated, considerable work needs to be carried out on estimating appropriate modifications of inputs to existing microscale models. Although no perfect analogies exist for STEC systems, irrigated agricultural and urban developments in desert areas have affected the climate in comparable ways; this should be examined in more detail.

Photovoltaic Conversion (PV)

Physical Characteristics

Photovoltaic conversion (PV) involves the direct conversion of solar radiation, either direct or diffuse, into DC electricity by solid state (solar cell) means. Materials including silicon, gallium arsenide, and CdS/CuS are important candidates for use in arrays to accomplish this conversion.

Air Mass One (AM1) conversion efficiencies will range from 0.10 to 0.20 for single band-gap devices; in theory, more complex multiband-gap solar cells can have even higher conversion efficiencies.

Plant configurations are considered at the 50 to 200 MW(e) level, although in principle modules can be quite small even in large, integrated systems (from 20 kW(e) rooftop arrays to 1 MW and larger local arrays). In addition to the collectors, hardware for storage and power conditioning (DC/AC conversion, frequency and phase stabilization, etc.) is required. The arrays themselves may be either mounted on some type of support structures or "paved" into the ground. The ground cover ratio is expected to vary from 0.5 to as much as 0.95. The devices have a very high absorption for AM1 solar radiation, typically on the order of 0.90 (except at very large angles of incidence). In general, the effect of the plants will be to decrease the albedo of a region.

Physical Effects

In general, the *albedo* decreases substantially, particularly if the ground cover ratio is high (see Weingart in these Proceedings).

Surface roughness will probably increase in the case of large structures supporting PV elements, and may remain the same or decrease for the "paving" techniques.

Surface physics including reflectivity, porosity, emissivity, will all change if the region is paved, as discussed for the STEC systems. The change will be less dramatic if the conversion elements are supported above the ground.

The climatic effects have been discussed in the previous section.

Ocean Thermal Energy Conversion (OTEC)

Ocean thermal plants would use the vertical thermal gradients (20°C) of the tropical oceans to produce shaft horsepower in low temperature difference turbines, which could then be used to produce electricity, synthetic fuels, or liquid air. Unit sizes under consideration are as large as 480 MW. In the EPRI reference OTEC plant, the flow rate of water through the heat exchangers would be on the order of 4000 m^3/s. Cold water at 4.4°C would be withdrawn at a depth of 500 m; warm water at a temperature of 26°C would be withdrawn from a depth of 24 m. The cold water would be discharged near the surface (70 m depth) at a temperature of 7.2°C, and the warm water would be discharged at a temperature of 23.9°C at a depth of 29 m.

Physical Effects

Zener (1973) has calculated that by siting OTEC plants all through the oceans between 20° N and S latitude (one half the earth's surface in this region is covered by tropical oceans suitable for such installations), a total of 60 TW(e) or 180 TW (thermal equivalent) could be generated. He estimates that this would result in a persistent 1°C decrease in the ocean surface temperature over this zone.

Nutrients may be brought to the surface from deeper levels, resulting in an algal bloom. CO_2 might be released into the atmosphere at the surface. Deep water temperature will increase but estimates for the increase have not been made. The ocean surface albedo could increase as a result of a phytoplankton bloom. In addition, ocean circulation patterns could be modified either directly, due to the physical presence of the plants, or indirectly as a result of changes in atmospheric circulation.

Climatic Implications

The largest effect on climate likely to arise from OTEC systems would be caused by OTEC-induced SSTAs. The latter are considered likely to be the most important single influence in causing long-term weather anomalies (Sawyer, 1965), provided that such anomalies cover significant areas (1000 km or more across), they are sufficiently strong to raise or lower the total heat input (sensible plus latent) to the atmosphere by at least 50 $cal/cm^2/d$, and persist with little change during the period concerned.

Ratcliffe and Murray (1970) have shown how the SSTA distribution in the North Atlantic affects the behavior of the atmospheric circulation for at least a month ahead. The largest anomalies that they examined were in the region of the Newfoundland Banks and were on the order of +1.5 to 2.0°C. Anomalies of this magnitude and in this area were sufficiently large to cause statistically significant pressure deviations over Europe. The general explanation proposed for the effects observed (Lamb, 1972) is that the anomalies change the thermal gradient across the Atlantic Ocean and therefore change the heat and moisture input into the depressions crossing the Atlantic, which in turn influence the strength of the upper westerly wind circulation.

The role of areas of anomalous ocean temperature distributions in causing persistence of particular synoptic types over a period of a few years is illustrated by the occurrence of blocking (anticyclonic) patterns over Northern Europe during the period 1958-1960 (Namias, 1964). These were associated with below-normal sea temperatures in the western Atlantic and above-normal temperatures in the eastern Atlantic. Likewise Namias (1969) has suggested that large-scale ocean-atmosphere interactions which occurred from 1961 until the winter of 1967-68 led to a special climatic "regime" over the North Pacific and North America. The regime was characterized by a pool of warm water over the central Pacific, which generated strong and southward-displaced cyclone generation downstream, resulting in a climatic cooling over the eastern two-thirds of the USA.

Bjerknes (1966, 1969) has shown that ocean-atmosphere interaction may operate on a hemispheric or even a global scale. SSTAs in the central and eastern Pacific alter the amount of heat supplied from the equatorial ocean to the rising branch of the atmospheric Hadley circulation, which leads to a change in the poleward flux of angular momentum, thereby influencing the mid-latitude belt of westerly winds.

These and other examples in the climate literature serve to illustrate that SSTAs can affect regional and global climate. In discussing the relevance of such effects to those possible from the presence of OTEC plants, we should remember that anomalies introduced by such plants will not be transitory features. Rather, they can be expected to persist as long as the plants are in operation. Because of this persistence, the possibility of long-term climatic changes on a global scale is enhanced relative to the effect of similar physical changes of short-term duration (months). Normally, SSTAs are eventually eliminated in the ocean-atmosphere system by some process of negative feedback, and the entire climate system thereby exhibits fluctuations due to the temporally and spatially varying distributions of anomalies.

In addition to observation of the effects of SSTAs on the atmospheric circulation, the effects have also been modeled. Table 3 summarizes the results of various model experiments that investigated the effects of large-scale SSTAs on the simulated atmospheric circulation. The results indicate that SSTAs in the tropical oceans and large SSTAs in the mid-latitude oceans can have significant effects on simulated global or hemispheric climate.

Table 3. Sea surface temperature anomaly experiments.

Author and Model	Anomaly	Comments
Rowntree (1972) (GFDL)	Warm and cool anomalies of maximum differences of 3.5°C in tropical eastern Pacific	Tropical and extratropical effects found; Bjerknes (1969) hypothesis is confirmed
Spar (1973a,b,c) (Mintz-Arakawa)	Anomaly of 2-6°C in North Pacific at 22°-42°N, 140°-180°W	Hemispheric and interhemispheric effects noted
	Anomaly of 2-6°C in South Pacific at 22-42°S, 140°-180°W	
Houghton et al. (1974) (NCAR)	Anomaly of 1-2°C in western North Atlantic	Small changes that are difficult to evaluate quantitatively
Gilchrist (1975a) (UKMO)	Anomaly of maximum of 2°C in western Atlantic, off Newfoundland	Consistent effects on surface pressure only near anomaly area
Chervin et al. (1976) (NCAR)	Anomalies with maxima of ±4°C in extratropical North Pacific	Statistically significant response in vicinity of anomalies but no downstream effects
Rowntree (1976) (UKMO)	Anomaly of maximum 2°C in tropical Atlantic, as observed in January 1963	Tropical and extratropical effects found; agreement with observed patterns
Gilchrist (1975b) (UKMO)	Cooling of up to 2°C in tropical Atlantic	Effects on rainfall over Sahara and surface pressure over North Atlantic noted
Shukla (1975) (GFDL)	Cold anomaly in Indian Ocean of -3°C	Changes in Indian summer monsoon noted

Increases in atmospheric CO_2 levels will cause an increase of the earth's surface temperature, because CO_2 absorbs the long wave radiation from the earth's surface and reradiates a portion of this energy to the surface. In the absence of CO_2, that heat would be radiated directly to space. Models for estimating the extent of surface temperature increases resulting from increased CO_2 are reviewed by Schneider (1975) who concludes that an order of magnitude estimate is 1.5 to 3.0°C for a doubling of the atmospheric CO_2 content. In addition, he expects an amplification of this increase in the polar zones. Of course this estimate could be high or low by a factor of several fold, if climatic feedback mechanisms have not been properly accounted for in the models.

Since the temperature increase due to an increase in atmospheric CO_2 is not likely to be uniform over the globe, changes in climate patterns are also likely as a consequence of changes in the thermal gradient structure. Williams (1975) has estimated the increase in atmospheric CO_2 as a result of the operation of ocean thermal plants. He calculates that production of 3 kWh(e) from such a facility would result in CO_2 liberation equivalent to the production 1 kWh(e) from fossil fuel combustion. In other words, the CO_2 produced from ocean thermal plants would be one-third that produced from fossil plants producing the same amount of electricity.

It is also possible that the upwelling due to OTEC plants would create phytoplankton blooms. Siemerling (1974) has suggested that a denser phytoplankton population leads to a higher albedo value for the ocean, and thus leads to a heat loss of the ocean water and atmosphere. Whether this albedo change could occur in the regions of OTEC plants on an extent substantial enough to cause climatic change on any scale is not known and has not been investigated in detail.

Finally, the physical presence of OTEC plants could have effects on the ocean currents and their associated eddies, and this in turn could lead to changes in the oceanic poleward heat transport and to changes in the distribution of ocean surface temperature. The latter effect would manifest itself through climatic changes such as those discussed above in connection with SSTAs. The poleward transport of energy by ocean currents plays an important role in the climate; Vonder Haar and Oort (1973) estimate that in the region of maximum net northward energy transport (30°N to 35°N) the oceans transport 47 percent of the required energy. At 20°N the peak ocean transport accounts for 74 percent at that latitude; for the region 0 to 70°N, the ocean contribution averages 40 percent. It is clear that interference with this northward transport of energy by the oceans could have large-scale climatic effects.

Wind Energy Conversion (WEC)

The EPRI reference wind turbine is a machine rated at 2 MW(e) at a wind speed of 13.4 m/s (30 mph). The device would be a horizontal axis machine with a rotor diameter of 67 m. The support tower would be a shell tube structure 56 m high (18 m ground clearance).

A grid of such units would make up a power plant unit. The EPRI studies consider power plant units of 20, 100, and 500 MW(e). The actual array configuration would depend on the wind patterns of the site. If the winds were primarily from one direction over the year, lateral spacing between wind units could be reduced to a few diameters; more space would be required if the winds were essentially omnidirectional. In any case, the spacing downwind would be on the order of 15 to 20 diameters, roughly 1 km apart.

In such configurations, the maximum output per unit area of land would be about 5 MW(e)/km^2. Even under conditions of steady winds 24 hours a day, the annual output would be roughly an order of magnitude less than that for STEC systems, per unit area of set-aside land. In the case of WEC, however, the land between the turbines could be used for other purposes, provided that the potential hazards from flying blades were sufficiently low.

Physical Effects

Arrays of wind turbines would affect the boundary layer of the atmosphere, primarily by changing the roughness length and therefore the wind profile. Momentum fluxes would be changed as the roughness length increased. The generation of electricity by WEC produces essentially no waste heat.

Climatic Implications

The main effects would be on a local scale. Hewson (1975), in assessing the impact of large-scale use of wind power, states that it is improbable that any appreciable impact on climate could be detected. He suggests that the possible effects on climate may be thought of as growing a number of groves of tall trees. In a wind the branches of the trees extract energy from the wind (as shown by their swing) as do the rotating blades of a wind turbine. There might be a slight slowing of the winds for a short distance downwind from an array of windmills, but the winds would rapidly accelerate because of downward transport of momentum from the stronger winds aloft. Crafoord (1975) has developed a simple model for estimating the interaction of an array of windmills and suggests that a two- or three-dimensional boundary layer model would be ideal for studying this problem.

An array of wind turbines might be simulated by modifying the drag coefficient in existing mesoscale models or GCMs. The effects of increasing the drag coefficient at all points in the NCAR GCM is described by Williams in these Proceedings. It would be more valuable to study this problem in a mesoscale model where the regional atmospheric circulation could be examined in greater detail.

Bioconversion

Physical Characteristics

A variety of biological processes can be used to produce synthetic fuels. Photosynthesis can be used directly through the growth, harvesting, preparation, and combustion of various plants. Other processes include microbiological conversion of plant materials to useful fuels, including methane, alcohols, hydrogen, and acetone. Algae can also be used to produce methane probably with much higher efficiency than any photoproduction technique can provide fuels.

Photoproduction systems would consist of large-scale farms of high yielding plants such as exotic forage sorghum or sugercane, plus a thermal power plant to combust the materials. The EPRI photoproduction reference system assumes the use of sorghum (specifically sudan grass) with an expected sustained yield of 60 Mt/ha/a dry biomass, with a total of three harvests a year. Approximately 1100 km^2 would be required to provide the input to a base-loaded 1000 MW(e) power plant, 50 times greater than for the equivalent electricity generation from STEC plants with storage.

Physical Effects

Large-scale use of such photoproduction facilities would result in substantial changes in the albedo, transpiration, local hydrology, and soil temperature. The relative change in these variables would of course depend on the characteristics of the site prior to development of the plant. Possible atmospheric aerosol increases from cultivation, fertilization, harvesting, and conversion are also involved.

Climatic Implications

Biomass systems would be located in temperate rather than in subtropical zones. The effects of albedo change and change in evapotranspiration over large temperature zone regions would have to be considered. As shown by the studies of Namias (1960), extensive areas of anomalous surface conditions (e.g., wetter or dryer than usual) will cause changes in atmospheric behavior. Namias found relationships between spring precipitation and temperature in the southern plains of the USA and the subsequent summer conditions. He suggested that the relationship arose from the condition of the ground in the spring. For example, following a wet spring, some of the heat normally used to raise the temperature of the ground surface might be used to evaporate the excess water so as not to be available for sensible heating of the air. The lack of sensible heating could lead to the lack of formation of an upper level anticyclone associated with a warm, dry summer.

It is therefore possible that large-scale mid-latitude changes in surface conditions could act to produce climatic changes through the kind of mechanisms suggested by Namias. Also, since these changes would be on a long-term scale, and will not be eliminated by feedback mechanisms as natural anomalies are, we might expect more than just local climatic effects after some time. As shown in the SMIC (1971) report, a change from forest to wet arable land increases the latent heat flux and decreases the sensible heat flux. The Bowen ratio reacts sensitively to such changes. For irrigated land, the Bowen ratio even becomes negative (up to -0.5 according to Flohn (1973)), because the wet soil absorbs heat from the air above (oasis effect).

Aerosol increases can modify both short- and long-wavelength radiation budgets, and could affect precipitation in areas where condensation nuclei are limiting factors. The impact upon climate of an increase in atmospheric particulates due to the burning of biomass can be assessed using models. Whether the particles will cause a heating or cooling (or neither) of the earth-atmosphere system depends on their complicated absorption and scattering characteristics (a function of composition, particle size and shape, and refractive index) and also on cloud and surface reflectivity. Mitchell (1975) states that the net thermal impact of increasing man-made aerosols cannot be reliably assessed, but that the net effect will probably be small or a net warming. The actual increase of aerosols from biomass is not known, but Bach (1976) estimates that at the present time 62 × 10^6 t of particulates are produced annually from grassland fires and agricultural burning in the tropics. This can be compared with an estimated natural production of 773 to 3690 × 10^6 t/a. Burning of cropland and grassland also introduces other pollutants into the atmosphere (e.g., CO_2, CO, HC, and NO_X). The effects of these emissions on the radiation balance should also be considered. Lastly, particles will be emitted into the lower atmosphere where they have a warming effect; in middle latitudes they will be rained out fairly quickly and thus not be transported to higher atmospheric levels.

Solar Satellite Power Stations (SSPS)

Physical Characteristics

In this concept a geosynchronous satellite would convert solar radiation to microwave energy using photovoltaic or central receiver conversion units. The microwaves would be beamed to a terrestrial receiver. Beam fluxes would be in the range of 50 to 200 W/m^2, at the level of 10,000 MW(e) per satellite. Microwave to electricity conversion on the earth would be 85 to 90 percent efficient. The materials for construction would be transported to orbit by space shuttle.

Physical Effects

There will be a net heat input to the earth unless modification (increase) of the surface albedo is also carried out.

Rocket exhaust during the construction phase would be injected into all layers of the atmosphere. Microwaves will pass through all layers of the atmosphere.

Climatic Implications

The increased heat input would have effects identical to those of other nonlatent thermal injection systems. The effects of rocket exhaust are not known, but presumably the composition of the different layers of the atmopshere would be modified. Particularly sensitive would be the upper layers of the atmosphere where the rocket exhaust might represent a perturbation. An analogous study was that of the effects of the super sonic transport or the space shuttle on the stratosphere. (See for example the Climatic Impact Assessment Program (CIAP) report (Grobecker et al., 1975).) The potential effects of microwaves in the upper atmosphere are not known and should be explored.

COMMENTS, CONCLUSIONS, AND RECOMMENDATIONS

Introduction

The main objectives of the Workshop have been defined; the first objective was largely realized before the Workshop began inasmuch as each participant arrived with some knowledge of the possible impacts of SEC systems on climate. For each of the SEC technologies considered, we attempted to identify the physical characteristics of the system, the physical effects, and their climatic implications.

The physical characteristics of the various technologies are now sufficiently well known to permit specification, at least in adequate detail, for the subsequent steps of our inquiry. In many cases the necessary analysis and/or physical measurements have not been carried out. Hence some of the physical consequences of the conversion systems must be inferred in a semiquantitative or semiqualitative manner through recourse to analogies.

The climatic implications of the physical effects of the solar systems is even less quantifiable. Estimates must be made on the basis of results from climate models or observations of analogous perturbations in the climatic system. An example is our speculation on the possible climatic impacts of OTEC plants using the results of analysis and observation on the effects of large-scale SSTAs. So, identification of possible climatic impacts has proceeded from a highly quantitative engineering description of the technologies to a semiquantitative description of the physical effects of such systems, to a qualitative description of climatic implications. The second objective was to determine the effects that should be investigated and to what extent. Clearly there are two areas to be investigated:

the direct physical effects of solar facilities, and the subsequent climatic implications of these effects.

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

The identification of available tools and their suitability for such investigations (the third objective) has been previously discussed. A large number of models exists, each type being suited (designed) for a particular kind of investigation. For example, a one-dimensional vertical radiative-convective model is very suitable for studying the effects of changes in atmospheric composition (e.g. CO_2, water vapor, aerosols) or in surface albedo, but cannot be used to study the effects of changes in surface roughness. The papers by Williams, Potter and MacCracken, and Fraedrich in these Proceedings provide further descriptions of the use of different models for studying climatic change. Later, we will give some recommendations based on the Workshop discussions regarding the use of various models for studying climatic implications of SEC.

The fourth objective, to review the work of relevence to the solar energy/climate issue, has been discussed in the section on solar energy systems technologies and in the contributed papers.

The final objectives were the formulation of further work required, identification of research that could be carried out by IIASA, and the establishment of cooperative arrangements among IIASA and other research centers. Discussions are continuing between IIASA and other institutions as regards appropriate research programs.

General Comments

Persistence and the Scale of Climatic Change

There is an important relationship between the temporal persistence of a change in the boundary conditions of the climatic system and in the size of the effect. Fraedrich has pointed out that a localized (and persistent) change in boundary conditions can lead to changes in the climatic system that increase until they are at the synoptic or even global scale. This is important in considering the effects of SEC systems designed to operate essentially in perpetuity. For example, OTEC systems may result in a decrease in the surface temperature of the tropical oceans. Such a persistent change in the sea surface temperature in a specific region may well lead to global changes in climate. This is clearly more serious than the case where there are SSTAs.

We must therefore study the effects of persistent and transient changes in the climatic system boundary conditions in order to assess the possible implications of a long-term commitment to SEC facilities on the global scale.

Relationship Among Climate Models

During the Workshop, it was suggested that the results of a calculation involving models less detailed than the GCMs could provide guidelines for the use of larger models for studying the various changes in the climatic system boundary conditions. For example, the zonal atmospheric model ZAM2 is more than an order of magnitude cheaper to run (as well as much faster) than the large GCMs, and a small or a null result of an experiment might indicate that a more detailed GCM run would not be useful. However, the relationship between such models is not known. Hence what appears to be a small effect on the results of a calculation using a model like ZAM2 could nevertheless correspond to a rather large regional or mesoscale effect when modeled on a GCM. This problem is not confined to the specific models considered at the Workshop; it extends to the use of a hierarchy of climate models for studying a given problem.

Further climatological research is required to develop techniques for using a hierarchy of models in this way and for determining when it is appropriate to use the next more complex level of models.

Recommendations

Global Solar Conversion Siting Atlas

The location of a perturbation in the climatic system boundary conditions is extremely important for determining the nature and extent of the resulting climatic changes, if any. In the case of SEC systems, different technologies will have very different siting requirements. OTEC systems will require tropical ocean sites; solar thermal electricity and fuel production facilities will probably be sited primarily in arid and desert lands; PV systems could be sited virtually everywhere on the land; WEC systems require "windy" locations, and so forth.

Specification of the perturbed boundary conditions requires reasonable knowledge of the best sites for the various technologies. A preliminary and rough attempt to estimate the location of large-scale electricity and fuel production facilities is presented by Davidson, Grether, and Weingart in these Proceedings.

In general, we would like to have a global SEC atlas; no such atlas currently exists, and the information required to develop one is only partly available.

Such an atlas would be the basis for at least initial scenarios for a global SEC system, and would permit the use of a specific set of location models required for any climatic studies.

Data Needs

There are three general approaches to obtaining data on SEC technologies for use in various types of climate studies: analytic (usually computer-based) computational procedures, physical or scale-modeling (e.g., wind tunnel tests, OTEC flow distribution models), and physical measurements of actual full-sized facilities. An example of the latter is a set of measurements of wind profile characteristics and ground temperature distributions within the heliostat canopy at the new 5 MW(th) solar thermal test facility under construction in the USA at Sandia, Albuquerque, New Mexico.

Data are required for a number of reasons. First, in the USA and elsewhere there will be legal requirements for assessing the environmental impact of solar facilities. At present, there appears to be little basis, either empirical or theoretical, for carrying out a detailed (i.e., useful) assessment of this kind. In addition, measurements and calculations of both the parameters characterizing solar facilities and the resulting modifications of the local physical environment are prerequisites for any kind of detailed climate or ecological modeling activities. For these reasons micrometeorological studies and experiments are likely to have the highest priority, since the results of these will be needed both for environmental assessments and for establishing the input parameter values for regional and global climate models.

The following section outlines the parameters that must be measured for various solar technologies.

SEC Systems--Parameters Relevant to Climate Studies

In addition to the determination of the engineering characteristics of actual solar installations using measurements indicated above, measurements of the meteorological parameters of a region with and without such facilities are needed to determine the extent to which the presence (and operation) of the facility has resulted in climatic changes, and to permit refinement of the data used as input to various climate models. Table 4 lists the parameters which, in our opinion, should be determined through a comprehensive and long-term measurement program.

Table 4. System parameters.

STEC and PV Systems

Direct and diffuse radiation as a function of time.

Surface albedo as a function of time, angle of incidence.

Surface hydrology characteristics.

Data on dew formation, atmospheric water vapor.

Thermal capacity and conductivity of the soil.

Wind characteristics, including diffusion coefficients over the region, wind profile, and surface roughness.

Dust generation.

Cloud cover.

Ground surface temperature as a function of time and space in the vicinity of the facility.

Wind Systems

Wind profiles and wind statistics.

Surface roughness before and after installation of wind machines.

Momentum transfer rates, as a function of surface roughness.

Vorticity.

Downwind effect on hydrology and evaporation.

Statistics on clouds, for example, to determine whether there are effects on cloud formation.

OTEC Systems

Sea surface temperature distributions.

Current distributions.

Local CO_2 in the water and the atmosphere in the vicinity of the plants.

Deep water nutrients--effects of upwelling on ocean surface albedo via changes in organism concentration in surface layer.

SSPS

Rocket exhaust effects on the atmosphere, especially on the upper atmosphere.

Effects of microwaves on the upper atmosphere.

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PAPERS BY WORKSHOP PARTICIPANTS

Estimating Variations of the Earth's Climate

Klaus Fraedrich

INTRODUCTION

If the real climate system (cryosphere-ocean-atmosphere-biomass-land surface) were replaced by an idealized mathematical system to simulate the climate and its fluctuations, a precise definition of climate would be needed. According to observations, the climate can be determined from the statistical behavior of the real system in terms of a relatively long time average over consecutive realizations. However, there is no consensus on the appropriate averaging interval: different time periods add different aspects to the climate problem. Therefore one attempts to separate the climate system into an internal and an external system interacting with each other. Such a distinction of two or more systems is possible if there is a separating gap of the spectral variance density of the climate variables. Now, the border between an internal and an external system can be appropriately chosen, depending on the problem to be solved. For example, for studies of the ice age, the internal system should include processes of the time scale of 10^4 to 10^5 a (cryosphere); for agricultural problems it may be sufficient to use a gap at the period of decades, if it exists.

In the following, some basic aspects of a climate simulation of the geophysical fluid system are discussed and some models are deduced from first principles. This paper is not intended to replace the recent review articles on climate modeling (e.g., Schneider and Dickinson, 1974), but to extend these with respect to the most simple models.

BASIC CONCEPT

A Hierarchy of Climate Models

The hierarchy of climate models can most simply be described by the geometrical dimensions of the field of the geophysical fluid variables. From these the related climate variables can be deduced by appropriate statistical averaging procedures (barycentric averages, time averages, filter processes, etc.) in order to separate the high frequency weather processes (internal system) from a slowly varying external system. Local changes of the basic (dependent) hydrothermodynamic variables are described by the balance equation

$$\frac{\partial}{\partial t}(\rho a) + \underset{\sim}{\nabla} \cdot (\rho a \underset{\sim}{v} + \underset{\sim}{F}_a) = \sigma(a) \quad , \tag{1}$$

where a is the specific quantity (that is, specific mass, momentum, energy, entropy), ρa its density, $A = {}_v\!\int \rho a \, dv$, is the related extensive quantity, $\sigma(a)$ is the local source, and $(\rho \underset{\sim}{v} a)$ and $\underset{\sim}{F}_a$ are the convective and non-convective (conductive, turbulent) fluxes, respectively.

The zonal integration $[\;]_\lambda$ of (1) over a closed latitude circle leads to a balance equation describing the two-dimensional meridional cross-section of a climate system:

$$\frac{\partial}{\partial t}[\rho a]_\lambda + \underset{\sim}{\nabla}_{\phi,z} \cdot [\rho a \underset{\sim}{v} + \underset{\sim}{F}_a]_\lambda = [\sigma(a)]_\lambda \quad . \tag{1a}$$

The vertical integration $[\;]_z$ of (1a) over the total depth of the system gives a one-dimensional picture:

$$\frac{\partial}{\partial t}[\rho a]_{\lambda z} + \underset{\sim}{\nabla}_{\phi} \cdot [\rho a \underset{\sim}{v} + \underset{\sim}{F}_a]_{\lambda,z} + [\rho \underset{\sim}{v} a + \underset{\sim}{F}_a]_\lambda \cdot \underset{\sim}{K}\Big|_{bottom}^{top} = [\sigma(a)]_{\lambda,z} \quad , \tag{1b}$$

where $\underset{\sim}{K}$ is the vertical unit vector.

Finally, the meridional integration $[\;]_\phi$ of (1b) over the longitude with symmetric boundaries at the North and South poles yields a zero-dimensional balance equation for the extensive quantity A (mass, momentum, energy, entropy):

$$A = [\rho a]_{\lambda,z,\phi} = [\rho a] = {}_v\!\int \rho a \, dv \quad . \tag{1c}$$

In a more general form the balance equation for A can be directly obtained after integration of (1) over the volume v of the system

$$\frac{dA}{dt} + {}_o\!\oint \underset{\sim}{n} \cdot (\rho a \underset{\sim}{v} + \underset{\sim}{F}_a) do = [\sigma(a)] \quad , \tag{2}$$

where $\underset{\sim}{n}$ is the exterior unit normal at the boundary o of the volume. The sequence of the integration processes may be changed, which leads to additional and different types of climate models as for example a vertically integrated but horizontally varying system. However, the above outline is common in the literature.

Properties of a Climate Model

The basic extensive hydro-thermodynamic quantities, including the related sources and fluxes that describe a climate system, are presented in Table 1.

Table 1. Balance equations of the density of mass, momentum, energy, entropy.

Quantity	a	$\underset{\sim}{F}_a$	σ (a)
Mass M:	1	0	0
Momentum J:	$\underset{\sim}{v}$	$\underset{\sim}{P}$	$-\rho\underset{\sim}{\nabla}\phi - 2\underset{\sim}{\Omega} \times \rho\underset{\sim}{v}$
Energy U:	$u = e + \phi + k$	$\underset{\sim}{W} + \underset{\sim}{P} \cdot v$	0
Internal E:	$e = c_v T$	$\underset{\sim}{W}$	$-\underset{\sim}{P}\cdot\cdot\underset{\sim\sim}{\nabla v}$
Kinetic K:	$k = \underset{\sim}{v}^2/2$	$\underset{\sim}{P} \cdot v$	$+\underset{\sim}{P}\cdot\cdot\underset{\sim\sim}{\nabla v} + \underset{\sim}{v} \cdot \sigma(\underset{\sim}{v})$
Entropy S:	$s = c_p \ln \Theta$	$\underset{\sim}{W}\, T^{-1}$	$\underset{\sim}{W} \cdot \underset{\sim}{\nabla} T^{-1} + d$

$\underset{\sim}{P} = p\underset{\sim}{E} - \underset{\sim}{F}$: pressure-, unit-, stress-tensor,

$d = \underset{\sim\sim}{\nabla v}\cdot\cdot\underset{\sim}{F}$: dissipation,

$\underset{\sim}{P}\cdot\cdot\underset{\sim\sim}{\nabla v} = p\underset{\sim}{\nabla} \cdot \underset{\sim}{v} - d,$

$\underset{\sim}{W}, \underset{\sim}{W}T^{-1}$: heat, entropy flow,

$\phi = gz$: potential energy,

$\underset{\sim}{\Omega}$: earth's rotation.

Under hydrostatic conditions the internal and potential energy are given by

$$E = \int_V c_v T \rho dv \quad \text{and} \quad \Phi = \int_V gz\rho dv = \int_V RT\rho dv \quad ,$$

and the mass (per unit area) $M/F = M_0 = P_0/g$ depends on the surface pressure p_0. The enthalpy is given by

$$E + \Phi = \int_V c_p T \rho dv \quad , \tag{3}$$

where an appropriate isothermal state $c_p \; MT_{oo}$ defines a motionless hydrostatic equilibrium state of maximum entropy which is associated with any atmosphere of the same mass M and total energy U (Dutton, 1973; Livezey, Dutton, 1976). This leads to the concept of entropic energy which is related to the Second Law (Table 1), as compared with the concept of available potential energy (Table 2).

Table 2. Balance equations for the Oberbeck-Boussinesq approximation.

Quantity	a	$\underset{\sim}{F}_a$	$\sigma(a)$
Mass:	1	0	0
Momentum:	$\underset{\sim}{v}$	$\underset{\sim}{P}$	$(\frac{\delta\theta}{\theta_0} \underset{\sim}{\nabla}\phi - 2\underset{\sim}{\Omega} \times \underset{\sim}{v})\rho_0$
Kinetic energy K:	$k = \underset{\sim}{v}^2/2$	$\underset{\sim}{P} \bullet \underset{\sim}{v}$	$\rho_0 \, wg \frac{\delta\theta}{\theta_0} - d$
Entropy S:	$s = c_p \frac{\delta\theta}{\theta_0}$	$\underset{\sim}{W} \, T_0^{-1}$	$-\rho_0 \, wc_p \, B_0 + dT_0^{-1}$
Kinetic + available potential energy:	$\frac{\underset{\sim}{v}^2}{2} + \frac{g}{2B_0} (\frac{\delta\theta}{\theta_0})^2$	$T_0^{-1}(d - \underset{\sim}{\nabla} \bullet \underset{\sim}{W})$	$\frac{g}{c_p} \frac{1}{B_0} \frac{\delta\theta}{\theta_0} - d$

$\rho = \rho_0(Z)$: mass density is a function of z only,

$\underset{\sim}{P} = \delta_p \underset{\sim}{E} - \underset{\sim}{F}$: pressure tensor,

$\theta, B_0 = \frac{\partial \; \rho n \; \theta_0}{\partial z}$: potential temperature, static stability,

δ : deviation from a reference state $|_0$,

g : earth's acceleration,

w : vertical velocity.

Conditions on the Fluid System and Simplifications

The following conditions are introduced to define precisely an internal climate system and its interaction with the external environment. Additionally, the system must be ensured to conserve the sum of the kinetic, potential, and internal energy with a nondecreasing entropy. This leads to the following global (and mainly thermodynamic) conditions:

The system is assumed to be closed, i.e. without an exchange of substance

$$\int_V \underset{\sim}{\nabla} \cdot \rho \underset{\sim}{v} dv = \oint_O \underset{\sim}{n} \cdot (\rho \underset{\sim}{v}) do = 0 \quad , \quad \text{i.e. } \dot{M} = 0 \quad ,$$

and in energetic and entropic isolation

$$\int_V \underset{\sim}{\nabla} \cdot (\rho u \underset{\sim}{v} + \underset{\sim}{F}_u) dv = 0 \qquad \text{i.e. } \dot{U} = 0$$

$$\int_V \underset{\sim}{\nabla} \cdot (\rho s \underset{\sim}{v} + \underset{\sim}{F}_s) dv = 0 \qquad \text{i.e. } \dot{S} \geq 0 \quad .$$

Dynamic constraints are defined by boundary conditions for the specific momentum (i.e. the velocity $\underset{\sim}{v} = \underset{\sim}{n}\, v_n + \underset{\sim}{t}\, v_t$ with components normal and tangential to the boundary): a rigid boundary $v_n = \partial v_t / \partial t = 0$: a non-slip condition $v_n = v_t = 0$ (used here); and a free-slip condition $v_n = \partial v_t / \partial n = 0$.

For practical purposes an alternative and simplified system of balance equations appears to be more useful for describing the geophysical fluid than the basic set (Table 1): the Oberbeck-Boussinesq-approximation (see e.g. Dutton, Fichtl, 1969) is sufficiently accurate to realistically simulate the most important atmospheric and oceanic processes (Table 2). The main approximation is a linearization of the thermodynamic variables, that is, assuming the deviations δ from an optimally realistic hydrostatic reference state (index 0) to be small. The closed and isolated Boussinesq system under steady state conditions yields some very useful relations for the kinetic and available potential energy:

$$K + A = [\rho_0 \frac{\underset{\sim}{v}^2}{2} + \rho_0 \frac{g}{2B_0} (\frac{\delta\theta}{\theta_0})^2] = \text{const.} \tag{4}$$

This gives a direct measure of the kinetic energy which is not possible using the energy equation of the basic set (Table 1) because $E + \Phi \gg K$. A "local" efficiency of this Boussinesq system may be defined by

$$\frac{d}{d - \underset{\sim}{\nabla} \cdot \underset{\sim}{W}} \sim \frac{g}{c_p T_0 B_0} \frac{\delta\theta}{\theta_0} \quad . \qquad (5)$$

For an isothermal basic state T_{oo} the static stability yields $B_0 = q/c_p T_{oo}$ and $\delta\theta/\theta_0$; T_0 must be replaced by $\delta T/T_{oo}$; T_{oo}.

CLIMATE ESTIMATES FROM FIRST PRINCIPLES

For practical application of climate models one may distinguish two kinds of prediction (Lorenz, in WMO, 1975) with the first kind the time dependent behavior of the model is interpreted, which is transitive if a unique statistic exists for an infinite time average; otherwise the system is intransitive. For almost intransitive systems there exist different statistics for finite time averages with the solution depending on the time interval. Prediction of the second kind is not necessarily connected with the model chronology: sensitivity tests ("All other factors being constant.") describe the reaction of the internal model system to artificial perturbations of internal or external parameters. The signal-to-noise ratio characterizes the significance of the reaction. Finally, this procedure may lead to an analysis of model stability where the internal or external (structural) stability depends on variations of the internal or external model parameters.

In the following, extremely simplified climate models are presented to which the prediction of the second kind has been applied. The models are essentially zero-dimensional, i.e. the balance equation (2) holds. The notations refer to area (F) averages:

$$A = \frac{1}{F} \int_V \rho \alpha dv \quad .$$

A Simple Energy Balance Model

Energy balance models emphasize the calculation of the surface temperature T

$$C \frac{dT}{dT} = W\downarrow - W\uparrow \quad , \qquad (6)$$

in terms of a balance of the heat fluxes through the boundary of the earth-atmosphere-ocean system, where C is an appropriate coefficient of the thermal inertia. The heat fluxes are prescribed by the total incoming solar and outgoing longwave radiative flux densities at the top of the atmosphere:

$$W\downarrow = \eta I \qquad \text{and} \qquad W\uparrow = \varepsilon \sigma T^4 \quad , \tag{7}$$

where the total energy input I is given by the incoming solar radiation and varies with η:

$$I = \frac{I_0}{4}(1 - a_p) \quad , \tag{8}$$

where the solar constant I_0 equals 1360 W m^{-2}, the solar "inconstant" is ηI_0, the ratio (=4) is that of the actual surface area of the earth to the projected area as seen by the sun, the emissivity $\varepsilon \sim 0.5$, and the Stefan-Boltzmann constant $\sigma = 5.76 \times 10^{-8}$ W m^{-2} K^{-4}. The planetary albedo a_p is parameterized to incorporate the radiational feedback with the snow and ice cover of the earth's surface given by

$$a_p = a_1 - c_1(T-T_1) \tag{9}$$

$$0.25 \leq a_p \leq 0.85 \text{ for all } T \quad ;$$

that is, a_p is assumed to be a function of temperature only. The ("adjustment") parameters are defined by $a_1 = 0.486$, $c_1 = 0.007$ K^{-1}, and $T_1 = 285$ K.

This zero-dimensional model is much simpler than the one-dimensional energy balance models from which it can be derived by meridional integration (1c, 2). It incorporates essentially the same parameterizations (e.g. Sellers, 1969, 1973; Budyko, 1969; Faegre, 1972; Schneider and Gal-Chen, 1973; Ghil, 1976) and leads without much computational effort to similar results regarding the sensitivity and stability of the climate system.

The steady state solutions of (6-9) are described by a fourth order polynomial: Figure 1 shows the dependence of earth's temperature (internal variable) on a variation of the solar radiation ηI_0 (external parameter). It exhibits two solutions bifurcating at (277 K, $\eta = 0.98$) which can be interpreted as the interglacial (present day) and glacial (ice-age) climate. Sensitivity tests show the present day climate to be internally stable (but structurally unstable). The third solution of a totally ice-covered earth (a_p = 0.85) seems to be structurally and internally stable (see Ghil, 1976). Periodic orbits (beyond the bifurcation point) and a separatrix between the stable solutions have not yet been identified.

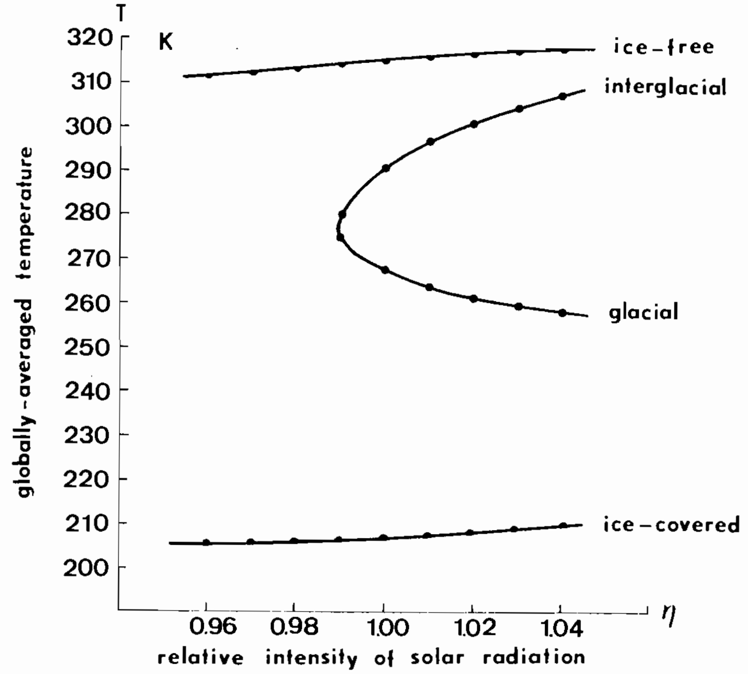

Figure 1. Steady state solutions of a zero-dimensional energy-balance model with surface albedo feedback.

Incorporation of Cloudiness

The basic steady state version of this energy balance model is of the same nature as described in the preceding section. But different feedback mechanisms are introduced which lead to the following parameterizations. The planetary albedo incorporates the cloud cover feedback so that (9) is to be replaced by

$$a_p = a_n n + a_g (1 - n) \quad , \tag{10}$$

where n is the fractional cloud cover, and a_g = 0.18, a_n = 0.5 are the planetary albedo of the cloud-free and cloud-covered earth, respectively. This leads to the steady state energy balance of the whole system:

$$\eta \frac{I_0}{4} (1 - a_p) - \varepsilon \sigma T^4 = 0 \quad , \tag{11}$$

with $\varepsilon \sim (0.5-0.6)$. An additional physical relationship for the energy fluxes is required to incorporate the cloud cover n as the second internal variable besides the surface temperature T. This is provided by the energy balance of the earth's surface

$$LE + H = \eta \frac{I_0}{4} (1 - a_p - m) - (\varepsilon_g - fn)\sigma T^4 \quad , \qquad (12)$$

where m = 0.17 is the absorption of solar radiation by gases, and $(\varepsilon_g - fn)$ is the effective emissivity of the surface (with $\varepsilon_g = 0.3$) which also accounts for the longwave counterradiation from the clouds (f = 0.8). The latent plus sensible heat fluxes (LE + H) balance the net radiation of the earth's surface and can be parameterized by

$$k\sigma T^4 (1 - n) = LE + H \quad , \qquad (13)$$

where k = 0.54, based on (a) the Bowen ratio concept depending on the temperature only (Priestley, Taylor, 1972, Paltridge, 1974); and (b) the heat fluxes being most effective during cloudfree conditions (Paltridge, 1975).

The global mean surface temperature of the system (3.5-3.8) is given by an eighth order polynomial, two solutions of which are shown in Figure 2. The computed values for temperature and cloud

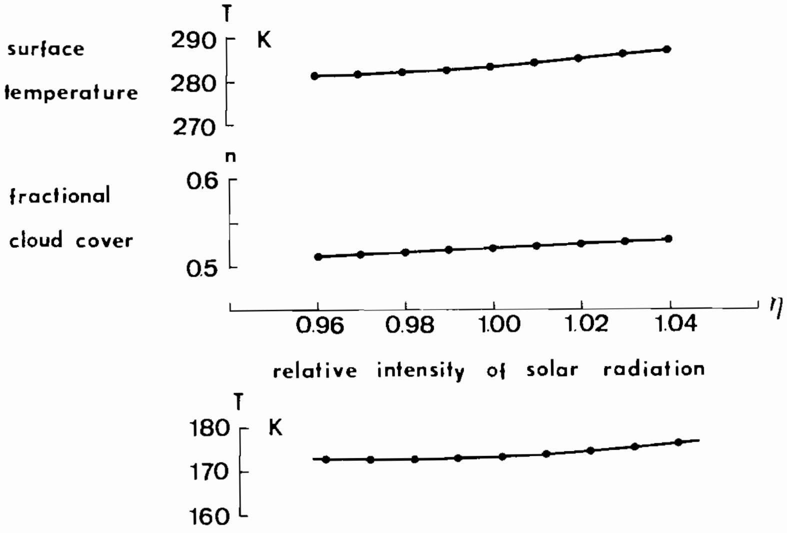

Figure 2. Steady state solutions of a zero-dimensional energy-balance model with cloudiness feedback.

cover of the physically reasonable solution as well as their sensitivities are quite realistic: observations indicate a seasonal cloud cover change of 5 percent varying with 6 percent of the incoming solar radiation I_0, depending on the earth-sun distance.

Incorporation of Dynamic Aspects

A closed and isolated system is assumed to be separable into two adjacent boxes (index 1,2) coupled by the fluxes through one surface that they have in common. One box represents the heat source, the other a heat sink, e.g. the tropical (1) separated from the middle latitude plus polar (2) atmosphere. For simplicity each box is characterized by an isothermal basic state $T_{1,2} = T_{oo} \pm \delta T/2$; a net heat input $W_{1,2} = \pm \Delta Q$ (i.e. the system is isolated: $W_1 + W_2 = 0$), a net (outward > 0) mass flux $M_0V_1 = M_0V_2$ (i.e. the total system is closed) where $V = V_1 = V_2$ is a representative meridional transport velocity. Thus the energy flux (neglecting kinetic energy) through the surface separating the boxes yields:

$$\Delta Q = (c_p + R)MV\delta T \quad , \tag{14}$$

where δT is the temperature difference between the boxes, and R the gas constant. The constraint of energetic isolation leads to a measure of the equilibrium temperature T_{oo} (see (6-8)), of the total system, i.e. its thermal level:

$$\varepsilon\sigma T_{oo}^4 = \eta I \quad . \tag{15}$$

The kinetic energy can be estimated using the concept of available potential energy that is steadily converted into kinetic energy by large-scale overturning. From (4) one obtains

$$2K = \frac{g}{12B_0}\left(\frac{\delta\theta}{\theta_0}\right)^2 = c_pT_{oo}\left(\frac{\delta T}{T_{oo}}\right)^2\left(\frac{1}{12}\right) \quad , \tag{16}$$

assuming negligibly small changes of the static stability B_0 during this process, and a linear horizontal gradient $\partial \ell n\, \theta_0/\partial y$ within the whole system (Green, 1970). A combination of (14-16) leads to the internal climate variables T, T_{oo}, and $V \sim K^{\frac{1}{2}}$ depending on the external parameters given by the net heat input into one box ΔQ and the total heat input into the whole system ηI:

$$\begin{aligned} \delta T &\sim (\Delta Q)^{1/2}(\eta I)^{1/16} \\ T_{oo} &\sim (\eta I)^{1/4} \qquad\qquad (17) \\ V &\sim (\Delta Q)^{1/2}(\eta I)^{-1/16} \quad . \end{aligned}$$

the constants of proportionality are omitted. Similar but not identical results can be obtained by a similarity analysis of the hydro-thermodynamic equations using the Buckingham T-Theorem (see Zilintinkevich and Monin, 1973, who also discuss the following examples).

The sensitivity of this model is being tested by a few special cases:

(i) Seasonal variations of the solar heat input into the summer hemisphere are assumed to be $\eta = 1 + \alpha$ times greater than the average (with $\eta = 1$) falling basically on the polar region, so that $\Delta = 1 - \alpha$. Linearizing (13) by assuming α to be small yields

$$\delta T \sim 1 - \frac{7}{16}\alpha \quad , \quad T_{oo} \sim 1 + \frac{1}{4}\alpha \quad , \quad V \sim 1 + \frac{7}{16}\alpha \quad .$$

(ii) An increasing of the solar constant by a factor of $\eta = 1 + \alpha$ (which is assumed to concentrate in the tropics $\Delta = 1 + \alpha$) gives

$$\delta T \sim 1 + \frac{9}{16}\alpha \quad , \quad T_{oo} \sim 1 + \frac{1}{4}\alpha \quad , \quad V \sim 1 + \frac{7}{16}\alpha \quad .$$

(iii) Artificial heat sources of the power αI may be introduced which are uniformly distributed over the surface, i.e. $\eta = 1 + \alpha$, $\Delta = 1$:

$$\delta T \sim 1 + \frac{1}{16}\alpha \quad , \quad T_{oo} \sim 1 + \frac{1}{4}\alpha \quad , \quad V \sim 1 - \frac{1}{16}\alpha \quad .$$

(iv) Artificial heat sources of the power αI concentrated at the pole are characterized by (i); at the equator by (ii).

These results may be completed by incorporating additional dynamic aspects with the use of a baroclinic instability criterion (Smagorinsky, 1963; see also Flohn 1964; Bryson, 1974; Korff and Flohn,1969). It describes the latitudinal position ρ_s of the subtropical high pressure belt

$$\cot \rho_s = -\frac{r}{H} \frac{\partial \, \ell n \, \theta_0 / \partial y}{B_0} = -\frac{c_p}{R} \frac{\delta T}{T_{oo}} \quad , \qquad (18)$$

where r is the radius of the earth, and $H = RT_{oo}/g$ the scale height of the atmosphere. The relative changes can be deduced with the results of the sensitivity tests (i-iv). Additionally, the related variations of the efficiency of the atmospheric heat engine may be calculated from (5).

CONCLUSIONS

It cannot be overemphazised that results from models of this simple nature should be very critically viewed. They serve mainly as a more elaborate scale analysis to clarify some important feedback processes, and provide direct first order estimates. Such drawbacks are also their advantage because it is the simplicity that allows clear identification of the physical mechanisms that lead the signal through the system. Tracing the signal is often obscured in the more complex and realistic (?) models. Finally, these simple models are a nice toy to play with.

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Experiments to Study the Effects on Simulated Changes In Albedo, Surface Roughness, and Surface Hydrology

Jill Williams

This paper reviews some experiments made with computer models of the climatic system. These are climate predictions *of the second kind* [1] in which a model is run for a control case and then with perturbed boundary conditions and the differences between the results of the two model runs are investigated. Experiments involving changes in the albedo, surface roughness, and surface hydrology are described in order to show the kinds of responses that might be found in model experiments to investigate the effects on climate of solar energy conversion (SEC) systems.

CHANGES IN SURFACE ALBEDO

The impetus for the series of experiments in which albedo changes were imposed came when scientists were trying to explain the origins of the Sahel drought, which occurred in the early 1970s. Charney [2] proposed a bio-geophysical feedback mechanism to explain the drought. He argued that the reduction of vegetation, with consequent increase in the albedo in the Sahel region would cause sinking motion and additional drying, and would therefore perpetuate the arid conditions. To test this hypothesis Charney used the general circulation model (GCM). A control integration had been made with a surface albedo over the entire Sahara of 0.14. The albedo north of 18°N was then increased to 0.35 and a six week run was made. A drop in precipitation of about 40 percent occurred north of 18°N (Figure 1), and there was a corresponding decrease of about 40 percent in convective cloud cover. The distribution of precipitation over North Africa averaged for July for the control run and the increased albedo run shows the mean position of the intertropical convergence zone (ITCZ) shifted some 4° or more south (Figure 2).

Ellsaesser et al. [3] tested Charney's hypothesis using the ZAM2 model; they made one run with an albedo of 35 percent over the Sahara and the other with an albedo of 14 percent. The changes were inserted over that fraction of the latitude band centered at 20°N which is occupied by the Sahara (i.e. 30 percent). The difference $A_{35}-A_{14}$ (Figure 3) shows a precipitation reduction of 22 percent over land at 20°N, which can be compared with 43 percent reduction reported by Charney for the Sahara for July. There was also a slight southward shift of the ITCZ with the higher albedo of the Sahara.

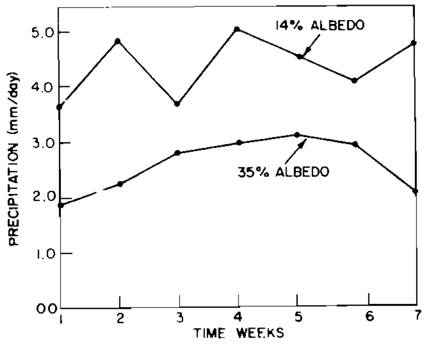

Figure 1. Precipitation in mm/day north of 18° N over Africa for albedos of 14% and 35%.

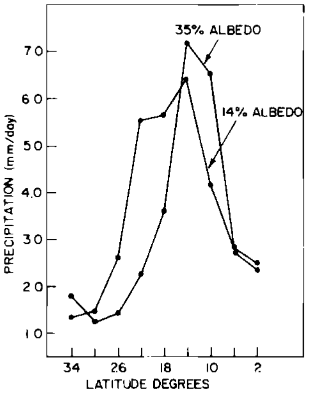

Figure 2. Average precipitation as a function of latitude for albedos of 14% and 35%.

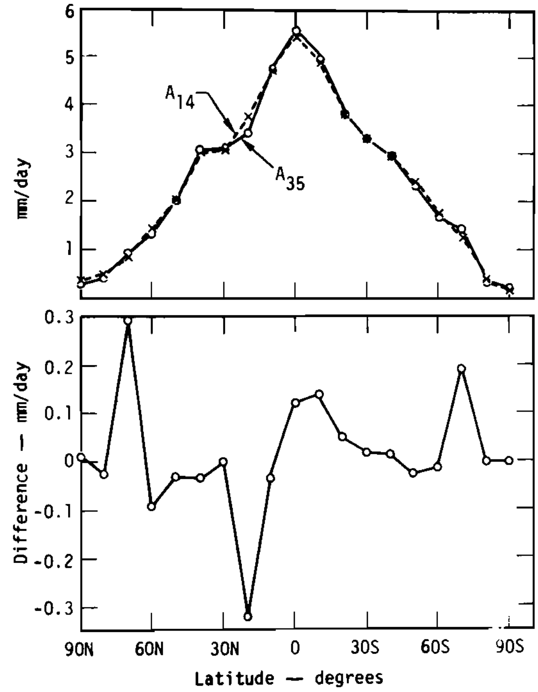

Figure 3. Latitudinal profiles of zonal average precipitation (mm/day) computed for Sahara surface albedos of 14 and 35% with the difference ($A_{35} - A_{14}$) below on an expanded scale.

The albedo of 35 percent over the Sahara strengthened the Hadley cell and the subsidence at 20°N, but the tropospheric lapse rate was increased. The high albedo of the denuded Sahara caused a cooling and reduced water content of the complete troposphere. The increased meridional temperature gradient in low latitudes strengthened the northern Hadley cell and displaced the ITCZ slightly southward.

This experiment represents a drastic impact on the surface characteristics and heat budget of the earth, an increase in surface albedo of 21 percent over 30 percent of the tropical latitude band. The area of albedo increase represents 8.4 percent of the land surface or 2.4 percent of the total surface of the globe--causing a 0.5 percent change in planetary albedo.

Two albedo feedback mechanisms for tropical latitudes can therefore be proposed:

- Increased albedo→reduced rainfall→less plant growth→ further increased albedo→enhanced desertification;
- Increased albedo→greater rejection of solar energy→ lower temperature→reduced evapotranspiration→desert moderating itself.

A second set of experiments was made with ZAM2 [4] to investigate the effects of tropical deforestation. Three runs were made: a control run with the rain forest albedo equal to 0.07; a complete removal of the rain forest by increasing the albedo to 0.25 together with an increased runoff rate and decreased evaporation rate; a "wet" deforestation by increasing the albedo to 0.25 but not including the other changes. The changes found were basically the same in both perturbation cases and were somewhat larger for the case of increased surface albedo only, which pointed to the importance of surface albedo and also to the tendency for self-compensation of geophysical processes in the real world. The feedback loops following the tropical deforestation are illustrated in Table 1.

Two experiments have been made with albedo changes with the NCAR GCM (Chervin, personal communication). In the first experiment the albedo was increased to 45 percent over the Sahara and the High Plains area of the USA. In this perturbation experiment the precipitation was reduced over the area of albedo change, and increased to the north and south of that area. A significance ratio has been computed on the basis of 5 July control experiments, and the precipitation changes are significant over the albedo change area and elsewhere (e.g. over the Indian Ocean and the Atlantic upstream from the Sahara, and off Peru). There was an increase in downward motion over the albedo change area; the changes suggest changes in east-west circulations.

In the second experiment, the albedo was changed to 30 percent over a smaller area than in the first experiment (in particular, over only one row of grid points over the Sahara). The effects were qualitatively equivalent over the High Plains, but washed out over the Sahara.

Table 1. Tropical deforestation--chain of consequences.

Deforestation
↓
Increased surface albedo
↓
Reduced surface absorption of solar energy
↓
Surface cooling
↓
Reduced evaporation and sensible heat flux from surface
↓
Reduced convective activity and rainfall
↓
Reduced release of latent heat, weakened Hadley circulation,
and cooling in the middle and upper tropical troposphere
↓
Increased tropical lapse rates
↓
Increased precipitation in latitude bands 5° to 25°N and
5° to 25°S and decrease in equator to pole temperature gradient
↓
Reduced meridional transport of heat and
moisture out of equatorial regions
↓
Global cooling and a decrease in precipitation
between 45° and 85°N and at 40° and 60°N

Source: [4]

In the first experiment, over the albedo change area there was decreased temperature (at 1.5 km) and increased surface pressure. The largest temperature decrease was 3.5°K. The pattern was consistent with the precipitation and vertical velocity changes. In the second experiment, there was an increase in pressure over the Sahara albedo change strip and a hint of the same effect as in the first experiment in the precipitation changes. There was a temperature decrease over the albedo change area, but not very much at 1.5 km (1/10 of the change in the first experiment).

In the second experiment, there were significant changes in surface pressure. The changes in ground temperature were significant but were almost washed out in the temperature field at 1.5 km. If the temperature change is not carried very high then no effect on the precipitation pattern can occur.

Over the High Plains albedo change area there was more change in the temperature at 1.5 km in the second experiment.

Apparently the role of the shape and orientation of the albedo change area is important in determining the effects. For example, a solid block of changed grid points is more effective than a row of changed points. We should therefore note, for the purposes of evaluating the effects of SEC systems, that the *geographical location and orientation of the albedo change areas are significant.*

CHANGES IN SURFACE ROUGHNESS

In GCMs of the atmosphere, the drag coefficient is used in computations of the horizontal stress components and the vertical fluxes of sensible heat and water vapor in the surface boundary layer (see, for example [5, p.17].

Two experiments have been made with the NCAR GCM in which the drag coefficient (C_D) was changed (Chervin, personal communication). In one experiment C_D was doubled at all grid points; in the second it was halved. With the increased drag coefficient the surface winds were reduced but the upper winds were increased. This occurred because there was an increased surface moisture flux in the tropics, giving an increased Hadley circulation which causes increased northward momentum transport and thus stronger upper westerlies. The effect of the increased drag coefficient was complicated because of the minimum surface velocity of 5 m/s assumed by the NCAR GCM for surface flux computations.

Delsol et al. [6] experimented with a GCM to find out how the formulation of the boundary layer processes affects the results of gross scale atmospheric circulation experiments. They experimented with C_D constant everywhere with a value of 2×10^{-3} and then with $C_D = 4.3 \times 10^{-3}$ over land and $C_D = 1.1 \times 10^{-3}$ over ocean. The complexity of the problem was emphasized by Delsol et al. with a consideration of the influence of the change of C_D on the precipitation rate. An increase in C_D contributes to the filling of depressions and therefore to a reduction in precipitation. On the other hand, a large value of C_D intensifies upward currents as well as the pumping of water vapor at the top of the boundary layer, and this could favor an increase in precipitation. Delsol et al. emphasize that the processes are completely nonlinear; some completely counteract each other. They found that the larger surface drag suppresses the baroclinic instability more, and that the use of values of C_D varying between land and sea produced a somewhat larger effect than a more detailed specification of turbulent transfer processes.

Schneider and Washington (personal communication) changed the value of C_{DW} $(= 0.7 \times C_D)$, the drag coefficient used in calculating the vertical flux of water vapor [5, p.17], in the NCAR GCM from 0.7 to 1.0. This would firstly influence r, the moisture flux in the boundary layer, and subsequently other properties. Precipitation increased at most latitudes, presumably because of the increased upward moisture flux. Changes in cloudiness were random, but large changes did occur in the high latitudes (poleward of 70°N, where the noise level is higher too). Ground temperatures also increased at nearly all latitudes.

CHANGES IN SOIL MOISTURE CONTENT

Walker and Rowntree [7] have examined the sensitivity of a tropical model to changes in soil moisture content, using a simplified version of the UK Meteorological Office eleven-layer model. The model area represented a zonally-symmetric version of West Africa. In one experiment there was desert in the same latitudes as the Sahara; in another experiment the desert was replaced by wet land. Results suggested that once the land was moist it maintained itself in this state for at least several weeks, whereas initial aridity north of 14°N was sustained, suggesting that ground dryness alone can cause deserts to persist.

Barry and Williams [8] noted that the absolute values of precipitation computed by the NCAR GCM were almost consistently too large, primarily because of the assumption of a Bowen ratio equal to unity. They therefore made a run with the Bowen ratio increased to ten, which corresponds to greatly reduced evaporation, and found much more realistic (i.e. compared with observed data) values of released latent heat (and presumably therefore precipitation) at 1500 m over arid areas of the world.

SUMMARY AND CONCLUSIONS

Table 2 summarizes the results of model experiments made to investigate the impacts of changes in surface albedo, surface roughness, and surface moisture content upon simulated climate. The albedo changes were made in the tropics or subtropics, and it is of interest to note that albedo changes due to the introduction of SEC systems would also occur in the subtropics. Clearly, feedback mechanisms between the albedo, the local energy balance, latent heat releases, etc., mean that these albedo changes exert their effects on the local or regional climate, and also force changes in components of the global atmospheric circulation such as the Hadley circulation, thereby causing global climatic changes. Changes in the surface drag coefficient lead to changes in the surface fluxes of heat, moisture, and momentum, and large-scale anomalies of these fluxes are seen to influence climate. The availability of soil moisture at the surface in subtropical climates appear, from model experiments, to play an important role in the precipitation distribution and, through changes in energy balance, in the atmospheric circulation as well.

It should be pointed out that in only one set of experiments were the results evaluated statistically to determine whether the differences between the control and perturbation cases were greater than the noise level (or inherent variability) of the model. In other words, for all except the albedo experiments made with the

Table 2.

Author	Model	Change	Results
Charney	GISS	Changed albedo over Sahara north of 18°N from 14% to 35%.	Drop in precipitation of about 40% mean position of ITCZ shifted 4° or more south.
Ellsaesser et al.	ZAM2	One run with albedo 14%, one with albedo 35% over 30% of latitude band at 20°N.	Precipitation reduced 22% over land. Southward shift of ITCZ. Strengthened Hadley Cell + subsidence at 20°N but tropospheric lapse rates increased not decreased.
Potter et al.	ZAM2	One run with tropical rain forest albedo at 0.07, removal of tropical rainfall (new albedo 0.25) and changed hydrology, third run of 'wet' deforestation (ie only albedo change to 0.25).	Changes larger when only albedo charge.
Chervin (pers. comm.)	NCAR	1) Increased albedo to 45% over Sahara Sahara and High Plains, USA.	Precipitation reduced over area of albedo change increased to north and south. Temperature decreased pressure increased.
		2) Increased albedo to 30% over one row of grid points of Sahara and block of High Plains, USA.	Effects much smaller over Sahara.
		3) Double drag coefficient at all grid points.	Increased westerly winds.
Schneider & Washington	NCAR	Changed value of C_{DW} from 0.7 to 1.0.	Precipitation increased at most latitudes, because of increased upward moisture flux. Ground temperatures also increased at nearly all latitudes.
Delsol et al.	GFDL	1) C_D constant everywhere $= 2 \times 10^{-3}$ 2) $C_D = 4.3 \times 10^{-3}$ over land $C_D = 1.1 \times 10^{-3}$ over ocean	Suppressed baroclinic instability.
Walker & Rowntree	Zonally aved. UKMO tropical	Latitudes of Sahara replaced desert by moist land.	Once land was moist it maintained itself. Ground dryness appeared to cause deserts to persist.
Barry & Williams	NCAR	Bowen ratio changed from 1 to 10 (effectively reduced surface evaporation).	Reduced precipitation (and therefore latent heat release).

NCAR GCM, it is not clear whether the differences between the control and the perturbation cases are a result of the perturbation, and there remains the possibility that a second perturbation experiment, differing in a very small and random way from the first experiment, would not produce the same results.

We can conclude that large-scale changes of albedo, surface roughness, and surface moisture content, have been shown with climate models to produce climatic changes, and several feedback mechanisms have been elaborated. In the case of albedo changes, the orientation and geographical location of the albedo change area have been found to be significant. An increase in the albedo is associated with a local decrease in precipitation and with consequent climatic changes. An increase in surface roughness produces complicated and opposing effects, but in one experiment it was shown to produce an increase in the upper surface westerlies. Decreases in surface moisture content are associated with decreases in evaporation and precipitation.

The results of model experiments carried out so far do suggest that changes in the characteristics of the earth's surface caused by SEC systems could have significant impacts on global climate if they were introduced over large areas.

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Local Energy Balance of Solar Thermal Electric and Photovoltaic Power Plants

Jerome Weingart

INTRODUCTION

The purpose of this paper is to report on the results of a preliminary examination of the effect of solar thermal electric conversion (STEC) and photovoltaic (PV) power plants on local energy exchange dynamics and climatic boundary conditions. In this exercise an explicit, although highly simplified, physical framework is developed for possible use in examining the potential effects of SEC on weather and climate. A simple (and incomplete) model of both STEC and PV power plants has been designed that takes into account changes in reflected, absorbed and processed solar energy when solar plants are introduced into a region. In the model, the geographical region is characterized only in terms of the surface reflectivity of the ground.

Effects other than those on the albedo of a region and their relative importance for possible climate modification are not discussed here.

There are many available or potentially available technologies that can convert solar energy in its direct and indirect forms (e.g. winds, ocean thermal gradients, waves) to useful energy. It is generally assumed that the use of SEC technologies will entail no significant environmental consequences, although this assumption is open to serious challenge. Many technologies appear benign when used on a relatively small scale and exhibit serious perceived or actual environmental and societal liabilities only when used on a large scale. This has been clearly demonstrated in the case of nuclear power.

As part of the debate on energy strategies it will be important to understand the various types of effects of large-scale use of many potentially important energy technologies. Perhaps because SEC is regarded as "clean", it is important to examine the possible environmental and societal impacts of large-scale SEC systems.

Among the effects we are concerned with in the evaluation or assessment of any new technology (especially when its use or contemplated use is on a very large scale) are changes in patterns of weather and climate. SEC facilities, such as STEC and PV power plants, modify the physical nature of the region in which they are located, and this modification will result in local change in the meteorological dynamics of the local region. Whether or not such effects have important consequences for climatic change is a matter very much open for discussion by the scientific community.

Exchanges of heat, momentum, and water vapor between the surface of the earth and the atmosphere are determined in part by surface temperature, surface roughness, surface albedo, soil moisture, and surface snow or ice cover. SEC systems will modify both the climatic boundary conditions and the local exchange dynamics. For example, a solar power plant will generally alter the albedo of the region in which it is located. Also, the use of a steam turbine conversion cycle in a STEC power plant results in a portion of the absorbed solar energy being released into the atmosphere as sensible and/or latent heat from a cooling tower, rather than as longwave infrared radiation from the ground.

SOLAR ENERGY CONVERSION SYSTEMS

Introduction

The large number of possible systems for converting solar energy to useful secondary energy carriers has been described elsewhere in these Proceedings. With the exception of ocean thermal electric conversion (OTEC) systems, only the high efficiency land-based direct conversion systems (e.g., STEC, solar thermal hydrogen production, PV and possibly photochemical conversion) appear capable of producing secondary energy at strategically significant (> 10 TW(th)) rates.

In this paper we consider two special cases: STEC in the central receiver configuration, and PV conversion. Solar thermochemical production of hydrogen is assumed to proceed from heat generated by the same technologies used to produce heat for thermal electric generation. The analysis of the physical effects on the region will be the same as for the STEC systems, except that a wider range of conversion efficiencies must be used for the hydrogen systems.

Solar thermal electric technology development activities in the USA, France, the Federal Republic of Germany, and Italy are aimed principally at the central receiver configuration. To a lesser extent, distributed systems employing linear concentrating systems are also being studied and developed. The central receiver system shown in a highly schematic form in Figure 1 consists of an array of two-axis steerable reflectors (heliostats) which focus sunlight onto a receiver located at the top of a tower. The receiver produces either superheated steam (560°C) for operating a steam turbine of conventional design, or very hot air (1000°C) or other gases (e.g. helium) for operating a high temperature Brayton cycle gas turbine. A system with a rated capacity of 100 MW(e) operating in the "sun-following" operating mode (producing electricity for roughly 8 hours per day in sunny locales) would require roughly 0.5 km^2 of reflective heliostat surface.

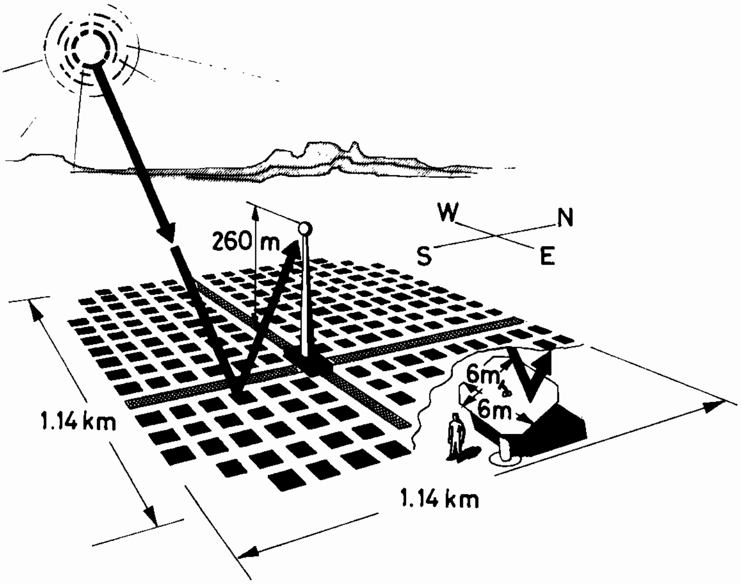

Figure 1. Central receiver or "tower power" configuration for solar thermal electric conversion.

Current heliostat development efforts suggest that each heliostat will have approximately 40 m^2 of reflecting surface. The tower in this example would be roughly 200 m in height. The expected *ground cover ratio* (GCR) or the fraction of the ground covered by the reflecting surface is in the range of 0.4 to 0.6, to minimize the blocking and shading of heliostats. Table 1 summarizes the main characteristics of a typical central receiver STEC system.

Table 1. Characteristics of a 60 MW(e) hybrid open cycle gas turbine STEC power plant. (Based on the EPRI sponsored work of Black and Veatch (1977).)

Nominal Plant Capacity	60 MW(e)
Nominal Turbine Heat Rate	9300 BTU/kWh(e)
Heliostat Field/Receiver Characteristics	
Required land area	0.64 km^2
Individual heliostat area	37.2 m^2
Total heliostats	6990
Total heliostat area	0.26 km^2
Effective ground cover ratio	0.41
Receiver type	Air heating, cavity configuration
Overall efficiency (direct beam insolation incident on heliostats to electricity at the busbar)	0.178

For STEC systems, only the direct beam or focusable (unscattered) solar radiation can be used. Approximately 10 to 15 percent of the direct beam and the diffuse radiation incident on the reflecting surfaces is absorbed, owing to the finite reflectivity of even very thin second surface glass mirrors. About 97 percent of the direct radiation reflected onto the absorber is converted to steam or hot air. In the case of a steam system, about two-thirds of the focused solar radiation is converted into waste heat and released into the atmosphere as latent and/or sensible heat, and about one-third is converted to electricity. The overall efficiency of converting direct beam solar radiation incident on the heliostats to electricity at the busbar is in the range of 0.17 to 0.23, depending on engineering design details (e.g., whether a wet or dry cooling tower is used). By contrast, most of the diffuse radiation (85 to 90 percent) is reflected back to the sky. Hence we have a solar facility that has the unusual property of a double valued albedo--that is, it is almost black for direct beam radiation and shiny for diffuse radiation. Also, the albedo will change with solar azimuth and elevation in a manner different from that of soil or vegetation.

In the case of a STEC system, one effect will be to bring into closer phase the processes of absorption and re-emission of solar radiation, the latter in the form of latent and sensible heat. In the absence of the solar power plant, the finite heat capacity of the surface would result in much of the absorbed solar radiation being lost at night by reradiation and convective cooling.

Such a STEC design will also have two different GCRs: one for *direct beam radiation*, and one for *diffuse radiation*. For example, when the sun is low in the sky, a very high percentage of the ground will be shaded from direct beam radiation, but the heliostats will shade very little of the ground from the diffuse sky radiation. Both GCRs are explicit functions of the solar elevation and of the geometry of the heliostat field. For our calculations we have used time-averaged daily assumed values in the range indicated by the more detailed calculations of the heliostat field shading that have appeared elsewhere (Martin Marietta, 1975)).

Figure 2 is a rendering of a 60 MW(e) open cycle gas turbine solar electric plant. While this is not intended as a completely accurate portrait, it is realistic enough to suggest the extent to which the surface features of the region will be modified. Certainly the most dramatic feature of such plants will be the enormous area devoted to the heliostats.

There are several types of changes in aerodynamic properties that will occur in the vicinity of a large central receiver STEC facility. The author is not aware of any attempts to determine the change in local surface roughness length--an aerodynamic parameter which determines, among other things, the rate of turbulent transfer of energy from the ground to the atmosphere. The

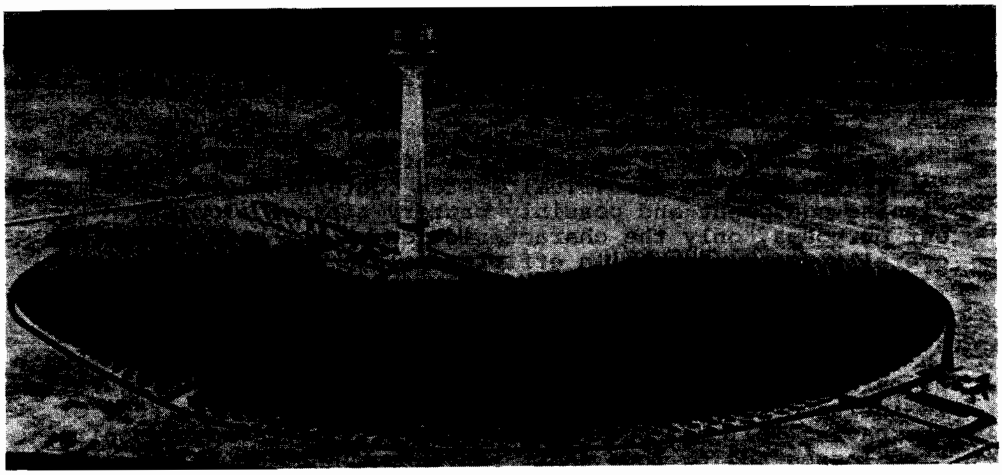

Figure 2. 60 MWe open cycle gas turbine solar electric plant. (Courtesy of the Electric Power Research Institute, Palo Alto, California)

Source: Black and Veatch (1977)

fixed mirror concentrator system--an alternative to the central receiver system--would have less of an impact on surface roughness changes.

Thermochemical conversion of hydrogen is a possibility that has been extensively discussed; see for example Veziroglu (1975), and Jet Propulsion Laboratory (1975). For our purposes, we can assume that the thermochemical cycle, or hybrid cycles requiring both electricity and heat, will operate from a central receiver facility. We make no distinction between the STEC systems and the thermochemical systems except to include in our analyses the possibility of higher overall conversion efficiencies (possibly as high as 60 percent).

PHOTOVOLTAIC (PV) CONVERSION

From a meteorological point of view, a PV power plant is less complex than a STEC system. Flat sheet photovoltaic convertors (solar cells) are highly absorbing when properly coated with an antireflection layer--the absorptivity can reach 0.95 for the AM1 solar spectrum. They exhibit a single valued absorption since they operate by individual photon-initiated processes rather than by thermal processes requiring focusing optics. Of course, PV conversion elements can be used in conjunction with focusing optics, such as plastic Fresnel lenses, especially if the combined system can produce electricity at lower costs than a nonconcentrating system. From the climatic point of view, the concentrating PV systems will behave in the same manner as the STEC facilities; we will therefore not explicitly consider concentrating PV systems in this paper.

The conversion efficiency of available PV elements ranges from about 5 percent (AM1) for CdS thin film cells to about 20 percent for GaAs/GaA1As cells in concentrated AM1 illumination. Silicon solar cells have exhibited efficiencies as high as 18 percent (AM1).

A PV power plant will consist of arrays of PV convertors integrated into an electrical system containing power conditioning equipment and possibly battery storage elements. For our purposes, only the characteristics of the array, plus the overall system conversion efficiency, are of interest.

The cheapest way to deploy such conversion elements may be to pave a large region with PV convertors, embedding them in the ground rather than on structures, with a ground coverage of perhaps 95 percent. The possibility of such a configuration is included in the analysis below. Of course, the effect of the paving will be to eliminate virtually all evapotranspiration losses and to thus shift the energy balance in the region (provided that evapotranspiration had been an important local cooling mechanism). While this will not be an important consideration for arid lands, PV devices will be suitable for regions which, because of considerable atmospheric scattering, may be unsuitable for STEC or other focusing systems.

LOCAL PHYSICAL EFFECTS OF SOLAR FACILITIES*

Introduction

A simplified description of the effect of the surface on incoming solar radiation would be a combination of direct reflection, absorption, and re-emission. Of course radiative exchange between the surface and the surroundings takes place continuously and depends on the surface temperature of the ground and on the radiation temperature of the atmosphere.

Other energy exchange mechanisms include advective cooling of the surface (wind), turbulent transfer of sensible heat, and evaporative losses via evapotranspiration. By placing a SEC facility in a region, some fraction of the incoming solar radiation will be converted to a secondary energy form and (generally), transported out of the region. Some of the energy will be ejected as waste heat; some will be absorbed by the mechanical elements of the plant and re-emitted into the local environment (e.g., the mirrors will absorb 10 to 15 percent of incident radiation). Some fraction of the sunlight will reach the ground which itself may have been modified through paving or soil stabilization techniques.

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*Symbols used in the discussion of energy balance effects are given in Table 2.

Table 2. Symbols used in discussion of energy balance effects.

I: Solar radiation incident on a horizontal surface ($= I(t)$).

I_1: Direct beam radiation incident on a horizontal surface ($= I_D \sin \phi$).

I_D: Direct beam normal solar radiation.

ϕ: Solar elevation angle ($= \phi(t)$).

I_2: Diffuse (scattered) solar radiation on a horizontal surface.

$E_1 = \int I_1(t)dt$ (24 hour average)

$E_2 = \int I_2(t)dt$ (24 hour average)

$A = E_1/(E_1 + E_2)$, the fraction of average *direct* beam radiation incident on the ground.

$B = E_2/(E_1 + E_2)$, the fraction of average *diffuse* radiation incident on the ground.

$R_g(\lambda)$: Spectral reflectivity of the ground.

R_g: Average ground reflectivity ($= \int R_g(\lambda)I(\lambda)d\lambda \, / \int I(\lambda)d\lambda$)

$\alpha_g(\lambda)$: Spectral absorptivity of the ground ($= 1 - R_g(\lambda)$).

α_g: Average ground absorptivity.

α_{m1}: Absorptivity of solar facility for *direct beam* radiation.

α_{m2}: Absorptivity of solar facility for *diffuse* radiation.

R_{m1}: Reflectivity of solar facility for *direct beam* radiation.

R_{m2}: Reflectivity of solar facility for *diffuse* radiation.

g_1: Time averaged ground cover ratio for *direct beam* radiation.

g_2: Time averaged ground cover ratio for *diffuse* radiation.

ε_1: Efficiency of conversion of *direct beam* radiation.

ε_2: Efficiency of conversion of *diffuse* radiation.

The equilibrium conditions where no solar facility exists and those that exist where there is a solar facility are as follows.

No Solar Facility

Incoming solar energy = Energy directly reflected + Energy absorbed by surface and re-emitted (radiation, sensible and latent heat flux).

Solar Facility

Incoming solar energy = Energy reflected from solar facility + Energy reflected from unshaded surface + Waste heat (latent and/or sensible) + Secondary energy + ground absorptivity/re-emission.

The parameters important in describing the effect of a SEC facility on the energy flow in a region include:

- The total solar radiation and the percentage of direct and diffuse components;
- The GCRs associated with each of these components;
- The reflectivity of the system (solar facility plus ground) for each of the components; and
- The conversion efficiency of the facility.

In terms of these key parameters, the energy balance equation for a region with a solar facility is as follows.

$$\left.\begin{aligned} E_{in} = {} & E_1(R_g(1 - g_1)) + E_2(R_g(1 - g_2)) \\ & + E_1(R_{m1}\ g_1) + E_2(R_{m2}\ g_2) \end{aligned}\right\} \text{Direct reflection}$$

$$\left. + E_1\ g_1\ \alpha_{m1}(1 - \varepsilon_1) + E_2\ g_2\ \alpha_{m2}(1 - \varepsilon_2) \right\} \text{Waste heat from solar facility}$$

$$\left. + E_1\ g_1\ \alpha_{m1}\ \varepsilon_2 + E_2\ g_2\ \alpha_{m2}\ \varepsilon_2 \right\} \text{Secondary energy produced}$$

$$+ E_1(1 - g_1)\,\alpha_g + E_2(1 - g_2)\,\alpha_g \quad . \quad \Bigg\}\begin{array}{l}\text{Absorbed and}\\ \text{rereleased to}\\ \text{the ground}\end{array}$$

The various terms in the equation correspond to time averages--that is $E_1(R_g(1 - g_1))$ stands for

$$\int dt\; I_1(t)\; R_g(t)(1 - g_1(t)) \equiv \langle I_1\; R_g(1 - g_1)\rangle_T$$

where T = 24 hours. We are now able to calculate two ratios. The *reflectance ratio* (R) is the ratio of energy reflected by the region when a solar plant is present, to that reflected in the absence of a plant. This is simply a calculation of the change in albedo in the optical regime. The reflectance ratio is given by

$$R = A(1 - g_1) + B(1 - g_2) + Ag_1(R_{m1}/R_g + Bg_2\;(R_{m2})/R_g$$

The *re-emission* ratio is the ratio of energy absorbed and locally re-emitted by a SEC system (plus the latent and sensible heat emission) in the presence of the solar plant, to that absorbed and re-emitted (at the same surface albedo) in the absence of a solar plant. The re-emission ratio R_e is as follows:

$$R_e = \frac{\begin{array}{l} I_1\, g_1\, \alpha_{m1}(1 - \varepsilon_1) + I_2\, g_2\, \alpha_{m2}(1 - \varepsilon_2) + \\ \quad I_1(1 - g_1)\,\alpha_g + I_2(1 - g_2)\,\alpha_g \end{array}}{(I_1 + I_2)\,\alpha_g}$$

$$= Ag_1\left(\frac{\alpha_{m1}}{\alpha_g}\right)(1 - \varepsilon_1) + Bg_2\left(\frac{\alpha_{m2}}{\alpha_g}\right)(1 - \varepsilon_2)$$

$$+ A(1 - g_1) + B(1 - g_2) \quad .$$

Note that both ratios do not contain information about the temporal distribution of energy flows (since we are taking 24 hour averages) or about the thermodynamic quality of the various energy components. We assume that in the case of sensible heating, the hot reject air from a thermal cycle thermalizes quickly with the surrounding atmosphere. This is not the case for latent heating where the energy removed by evaporation can be transported many hundreds of kilometers from the original site.

There is a considerable difference, for example, between the absorption of sunlight by the surface and the re-emission in the longwave infrared all during the night, and the re-emission of absorbed (by a STEC facility) solar radiation promptly and in the form of sensible heat (dry-cooling tower), latent heat (wet-cooling tower) or as 400°C air (in the case of a central receiver using a high temperature gas turbine). The implications of these differences need to be thoroughly investigated; this is outside the scope of this paper.

Reflectance Ratio (Albedo Shifts)

The reflectance ratio was computed for a number of cases in which the key parameters were varied over their physically meaningful ranges; these ranges are shown in Table 3.

Table 3. Parameters for calculations of the reflectance ratio for STEC and PV systems.

Figure	Technology	A	g_1	g_2	R_{m1}	R_{m2}	ε_1	ε_2	# Examples
3	STEC	0.5- 0.8	0.5	0.5	0.0	1.0	n/a	n/a	4
4	STEC	0.6 0.8	0.6 0.5 0.6 0.5	0.4 0.5 0.4 0.5	0.0	1.0	n/a	n/a	4
5	STEC	0.8	0.1- 0.9	0.1- 0.9	0.0	1.0	n/a	n/a	9
6	STEC	0.4 0.6 0.8	0.5	0.5	0.0 & 0.1	1.0 & 0.85	n/a	n/a	6
7	PV	n/a n/a	0.5 0.95	0.5 0.95	0.1 0.3	0.1 0.3			2
8		n/a	0.95	0.95	0.0- 0.3	0.0- 0.3			6
9	PV	n/a	0.7 0.9	0.7 0.9	0.1	0.1			2
	STEC	0.6 0.8	0.6 0.6	0.4 0.4	0.0	1.0			2

Table 4 summarizes the range of albedo values for various surfaces.

Table 4. Albedo values of various surfaces.

Source: Lamb (1972)

Surface	Albedo %	Surface	Albedo %
New-fallen snow (90% has been observed in Antarctica)	85	Grain crops, depending on ripeness	10-25
Old snow	70	Clay (blue), dry	23
Thawing snow	30-65	Ploughed fields, dry	12-20
Salt deposits from dried up lakes	50	Pine forest	6-19
White chalk or lime	45	Oak tree crowns	18
Yellow deciduous forest in autumn	33-38	Granite	12-18
		Other rocks, generally	12-15
Quartz sands, white or yellow	34-35	Stubble fields	15-17
Clayey desert	29-31	Clay (blue), wet	16
Parched grassland	16-30	Spruce tree crowns	14
River sands (quartz), wet	29	Wet fields, not ploughed	5-14
Green deciduous forest	16-27	Fir tree crowns	10
Green grass	8-27	Water, depending on angle of incidence	2-78

Figure 3 shows the effect of changing the percentage of direct beam solar radiation for a STEC facility with an absorptivity of unity for direct radiation and an absorptivity of zero for diffuse radiation. The average GCR for both the direct and the diffuse components was taken as 0.5. In fact, the GCR will be somewhat different for direct and diffuse solar radiation components. For example, if the sun is low in the sky, the heliostats will be close to vertical in the north segment (the Northern Hemisphere) of the heliostat field. In this case, a smaller fraction of the surface will be shadowed from diffuse radiation than from direct beam radiation. The relative amount of direct and diffuse ground cover will depend on the specific layout of the plant (i.e., there may only be a north field of heliostats, or the central receiver may be in the center of a field) as well as on the angular position of the sun. The effect of changing the direct beam GCR to 0.6 and the diffuse GCR simultaneously to 0.4 are shown in Figure 4.

The reflectance ratio is a decreasing function of the reflectivity of the surface beneath the heliostats. For very low values of surface reflectivity, the solar facility reflects more solar radiation than does the ground. Also, as the fraction of diffuse radiation increases, the reflectance ratio naturally increases

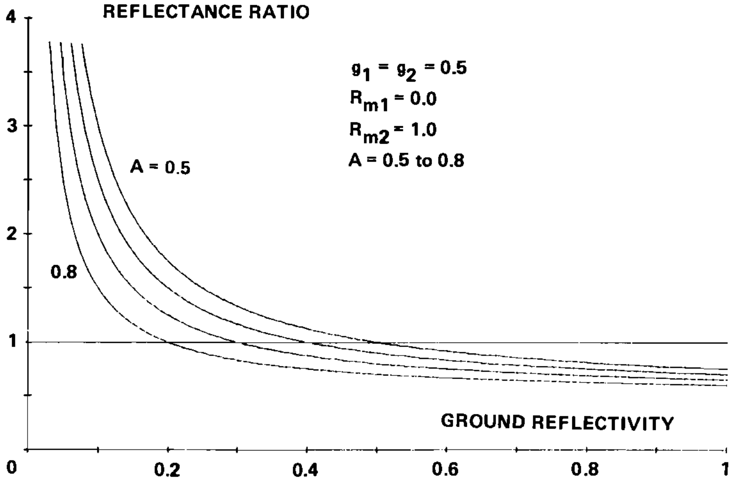

Figure 3. Effect of shift in percentage of direct beam solar radiation for a STEC facility.

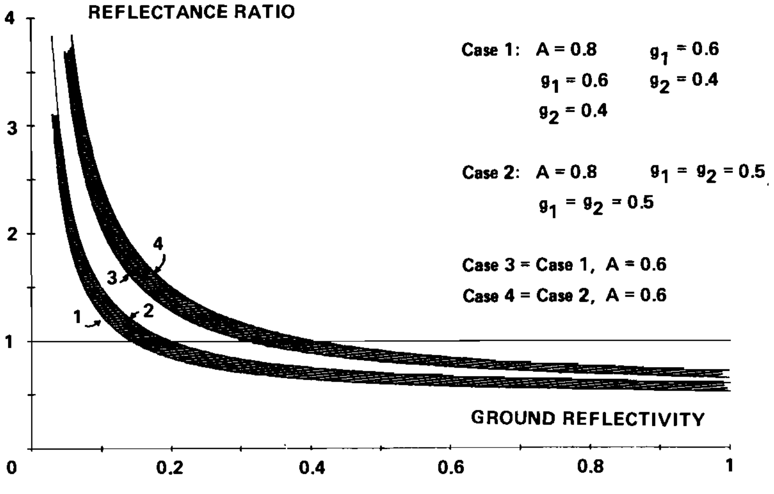

Figure 4. Effect of different ground cover ratios, STEC system.

since only the diffuse component is reflected from the solar facility in this example. The reflectance ratio is unity for 0.2 to 0.5 surface reflectivity for the values of A between 0.5 and 0.8. Arid lands tend to have albedo values in the range of 0.2 to 0.35. Hence there is a combination of GCR, percentage direct beam radiation, and solar absorptivity values for which there is no net change in optical albedo. This is a point which others have made by "back of the envelope" calculations. Such calculations have generally been designed to support the assertion that there will be no important effects on weather and climate due to the presence of a SEC facility in an arid region. This reasoning, however, is erroneous as we have shown, and is discussed elsewhere in these Proceedings.

Figure 5 shows the same calculations with different GCRs.

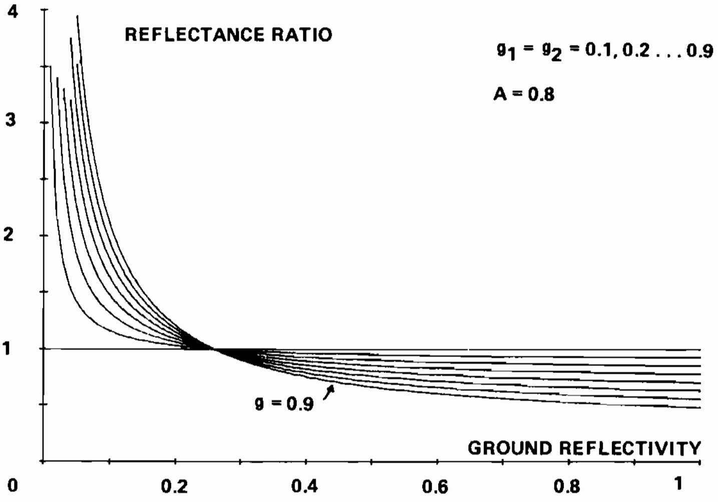

Figure 5. Effect of change in ground cover ratio, STEC system.

By decreasing the GCR for direct beam radiation, and holding the other key parameters fixed, it is possible to increase the albedo of the solar facility plus ground to that resembling the reflectivity of arid lands, for values of ground reflectivity below 0.2. The opposite effect occurs above this value; a decreased GCR increases the effective albedo of the ground plus the solar facility. However, in all cases where A = 0.8, the net albedo of the combined system (solar facility plus ground) is less than that for the ground alone, for ground reflectivity above 0.2 alternating the ground beneath the heliostats is in principle another method for controlling the effective albedo of the region.

We can see that there are some combinations of surface reflectivity and solar power plant characteristics for which the change in the local albedo is zero (i.e., the reflectance ratio is unity). However, as can be seen for Figure 5, in the case of a STEC facility with typical characteristics in a region of high direct radiation component (e.g., the New Mexico environment) the effective albedo of the region will be reduced by 30 to 40 percent relative to typical arid lands. Furthermore, the albedo of the region containing the SEC system is *a function of the percentage of direct beam radiation;* thus the albedo will not be constant with time. Hence even if we could design the plant in such a way that under clear sky conditions the regional albedo was unchanged, with a STEC facility we cannot have a constant albedo with changing climatic conditions.

From an economic point of view one would like to design a STEC plant for minimum cost and not have to tailor the physical characteristics of the plant to meet some climatic constraints. Obviously, then, we would need to know whether there really will be any climatic consequences of ignoring the inevitable shift in regional albedo when such facilities are introduced.

Figure 6 indicates the effect of modifying the reflectivities of a STEC system for direct and diffuse radiation from 1.0 to

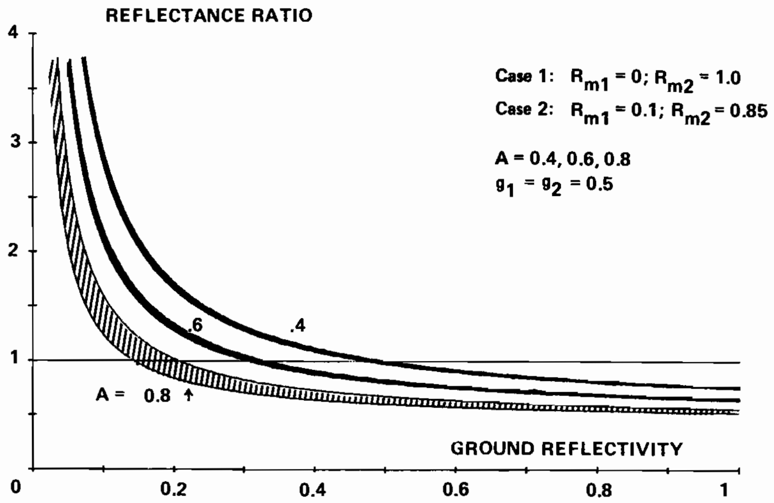

Figure 6. Effect of change in reflectivity, STEC system.

0.1 and from 1.0 to 0.85, respectively. In both cases, the higher values are more realistic; however we can see that only in the case of the highest expected percentage of direct beam radiation (0.8 = A) does this have any effect on the reflectance ratio. Thus the simple assumptions that the reflectivity $R_{m1} = 0$, and $R_{m2} = 1.0$, are reasonable.

Figure 7 summarizes results of similar modifications to a PV system. Because PV systems have a high absorptivity for direct and diffuse incident radiation and, in general, have high GCRs, the reflectance ratio is below unity at low values of surface reflectivity, for low system reflectivity. Figure 7 indicates that the reflectance ratio curve will shift to the right (i.e., towards higher values) when the reflectivity of the PV system is unusally high (0.3). When both a STEC and a PV system have the same reflectivity, the reflectance ratio will obviously be unity. With both a low reflectance ratio and high GCR the surface albedo will be significantly reduced from that characteristic of arid lands.

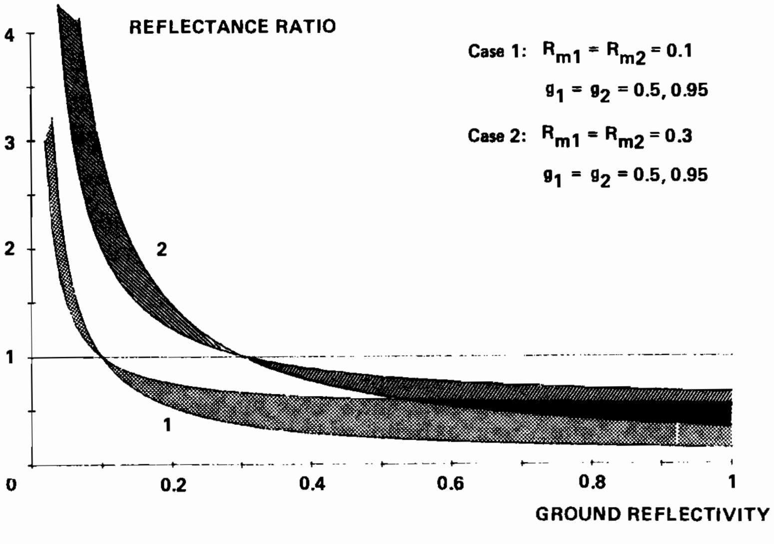

Figure 7. Reflectance ratio, PV system.

Figure 8 indicates dramatically the effect of a change in reflectivity for a PV system covering 95 percent of the surface, and again demonstrates that for the expected values of PV array reflectivity (0.03 to 0.10) the net albedo of the region will be substantially decreased, unless the region was formerly a pine forest (which is unlikely).

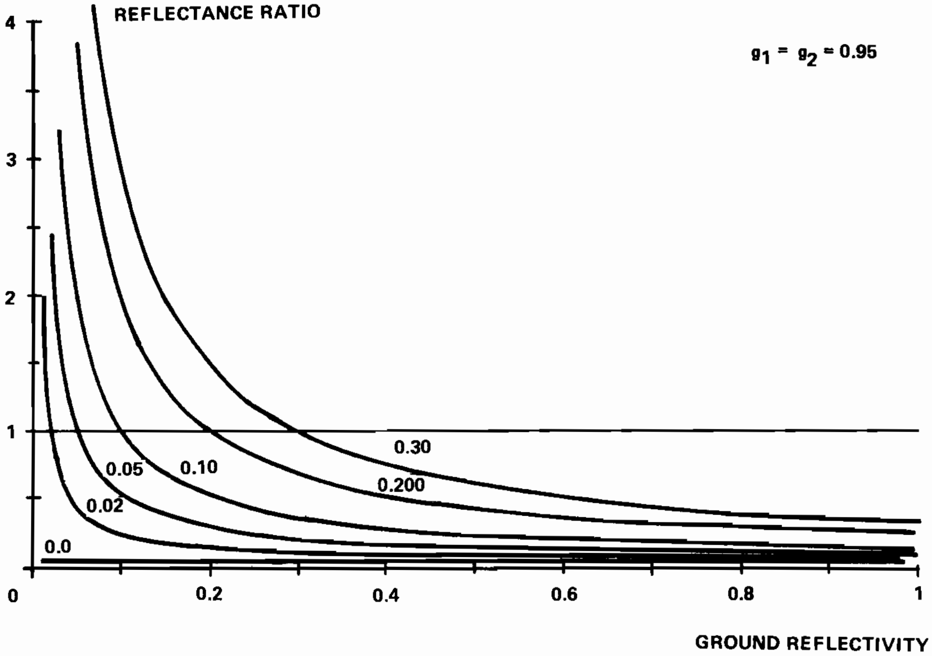

Figure 8. Effect of change in reflectivity from 0.0 to 0.3, PV system.

Figure 9 compares albedo shifts expected from STEC and PV systems, under reasonable assumptions regarding their physical characteristics. Here we see that the PV system invariably results in much lower net albedo values than those of the STEC system, owing partly to the much higher GCR possible with PV systems, which do not require tracking and can lie essentially flat on the surface.

Of course, the maximum annual output of PV systems will depend on the slope of the arrays. The optimum slope in turn depends on the latitude. Hence, at the equator, the GCR is likely to be very high, while in northern latitudes it may be reduced because of the need to maximize the total amount of incident solar radiation over the year.

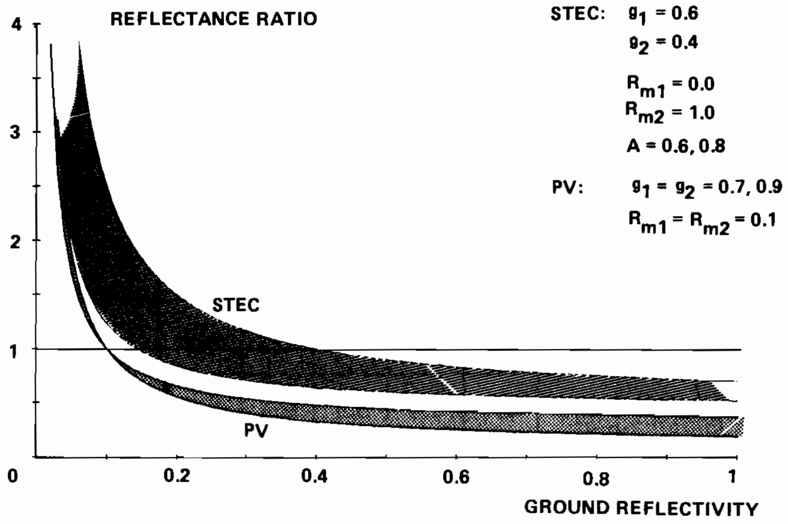

Figure 9. Comparison for STEC and PV systems.

Re-Emission Ratio

The range of key parameters explored in the analysis below is summarized in Table 5.

Figure 10 shows the dependence of the re-emission ratio on the surface reflectance and the system conversion efficiency for a STEC system in an environment of 80 percent direct beam radiation, with GCRs of 0.6 (direct) and 0.4 (diffuse). The conversion efficiency ranges from 0.0 to 0.25. A conversion efficiency of zero means that the plant is converting all of the absorbed direct beam radiation into waste heat (sensible and/or latent). For this example, we can see that in purely numerical terms, the amount of energy re-emitted from the region containing the solar plant is unchanged due to the presence of the plant over a wide range of surface albedo (0.2 to 0.35) typical of arid lands. Of course, the thermodynamic quality of this re-released energy is substantially altered through the "processing" by the SEC system of sunlight into waste heat and secondary energy production.

Figure 11 shows the same situation over a wider range of conversion system efficiencies. This plot extends over conversion efficiencies much larger than those expected (or possible) with available technologies.

Table 5. Parameters for calculations of the re-emission ratio for STEC and PV systems.

Figure	Technology	A	g_1	g_2	R_{m1}	R_{m2}	ε_1	ε_2	Computed # Examples
10	STEC	0.8	0.6	0.4	0.0	1.0	0 - 0.25	0.0	continuum
11	STEC	0.8	0.6	0.4	0.0	1.0	0 - 1.0	0.0	10
12	STEC	0.3-0.8	0.6	0.4	0.0	1.0	0.25	0.0	6
13	PV	n/a	0.9	0.9	0.1	0.1	0 - 0.3	0 - 0.3	3
14	PV	n/a	0.4-1.0	0.4-1.0	0.1	0.1	0.2	0.2	7
15	PV	n/a	0.9	0.9	0.1	0.1	0.1 0.2	0.1 0.2	2
	STEC	0.6 0.8	0.5	0.5	0.0	1.0	0.2	0.0	2

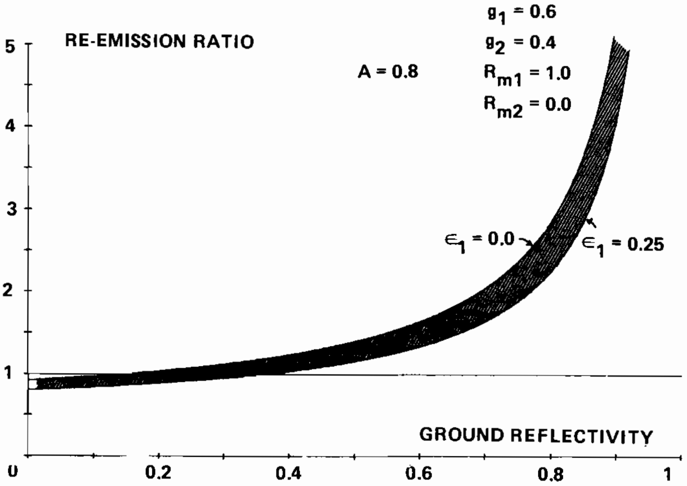

Figure 10. Dependence of STEC system re-emission ratio on conversion efficiency (realistic range).

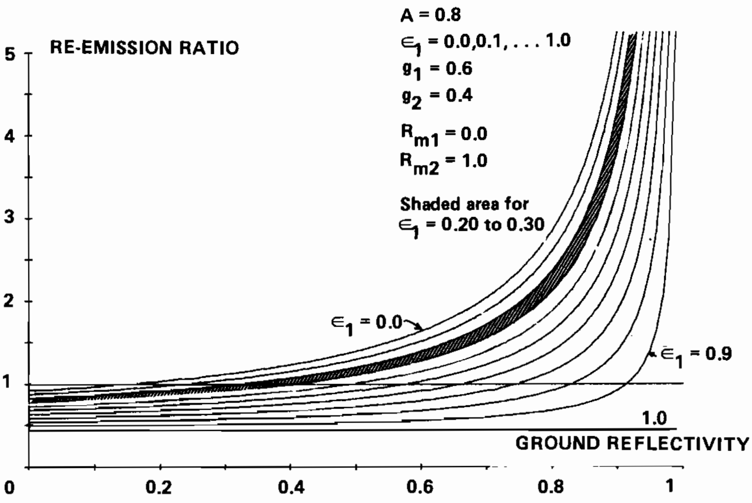

Figure 11. Effect of conversion efficiency on STEC system re-emission ratio.

Figure 12 shows the effect of a shift in the percentage of direct beam radiation for a STEC plant of 0.25 conversion efficiency. Here we see that a change in local atmospheric conditions results in a substantial shift in the re-emission ratio.

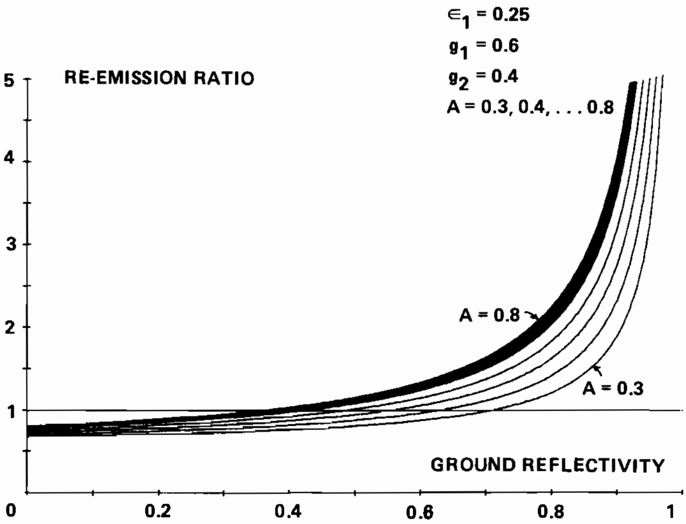

Figure 12. Effect of variations in direct beam fraction on STEC system re-emission ratio.

Figure 13 demonstrates the effect of changes in conversion efficiency on re-emission ratio for a PV system. In this case the PV system is assumed to have a GCR of 0.9 and an absorptivity of 0.90. In purely numerical terms, owing to the presence of the PV plant, the shift seems relatively small over the regime of interest for the surface albedo.

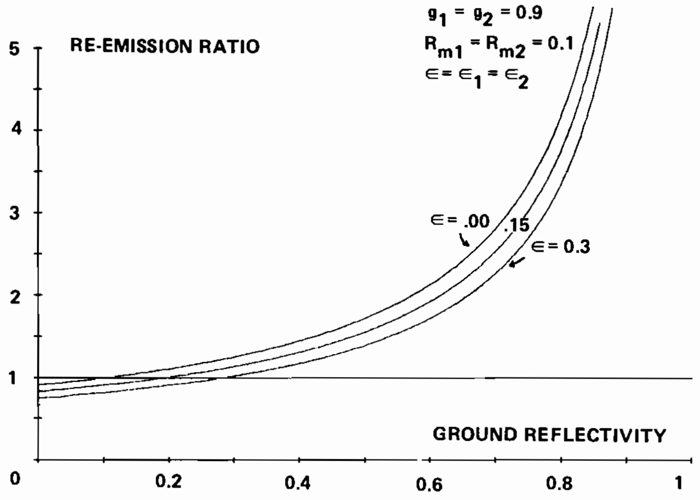

Figure 13. Effect of conversion efficiency on PV system re-emission ratio.

Figure 14 shows the effect of changing the GCR for a PV system in which the conversion efficiency is 0.20 and the absorptivity is 0.90. In this case the effect is small until we encounter large surface reflectivities.

Figure 15 compares a STEC and a PV system in terms of the effects of such systems on the re-emission ratio, assuming conditions likely for such systems used on a large commercial scale. In this case, the difference appears small over the albedo range 0.2 to 0.4.

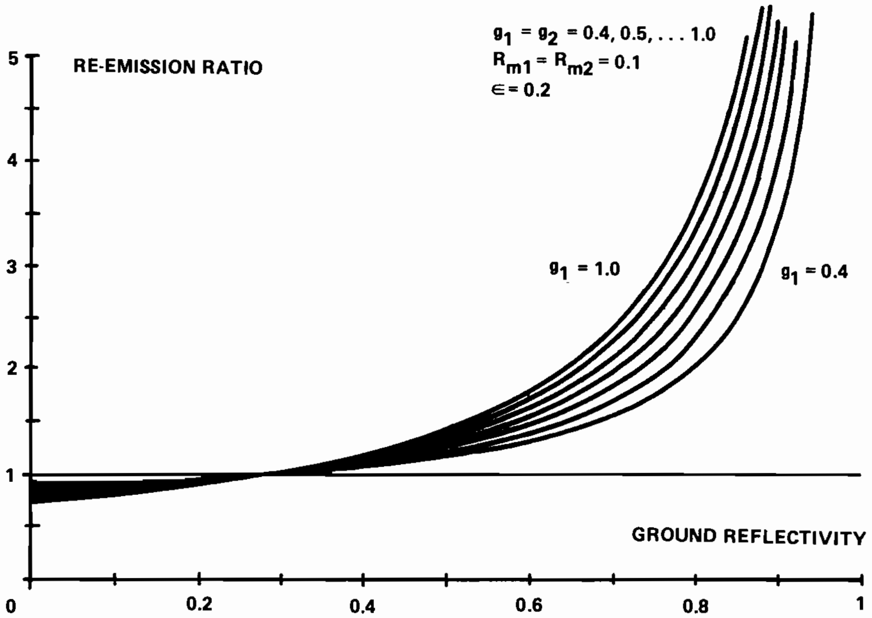

Figure 14. Effect of variation in GCR on PV system re-emission ratio.

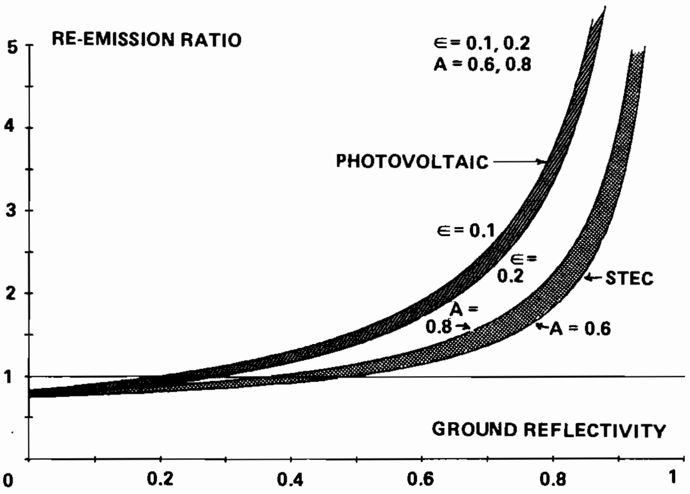

Figure 15. Comparison of re-emission ratio for STEC and PV systems.

CONCLUSIONS

These simple calculations demonstrate that the albedo of a region can change substantially in the presence of a STEC or a PV conversion system, and that the degree of change will depend on the details of local ground albedo, meteorological conditions, and on the physical characteristics of the solar conversion systems. While more detailed calculations are required to provide a more realistic picture of the physical changes in the region, the important issue remains the extent to which such physical modifications are important in terms of perturbations in weather and climate.

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The Effects of Solar Energy Conversion on Climate

Mark Davidson and Donald Grether

INTRODUCTION

Man has only recently begun to realize and worry about the possible effects of his activities on the earth's atmosphere, and to weigh options based upon environmental criteria including possible effects on climate and the atmosphere. The case for caution in dealing with climate modification has been put eloquently by Schneider with Mesirow (1976). With a burgeoning world population and increasing industrialization, man's ability to change his environment is increasing. Our energy consumption is releasing great amounts of waste heat into the climate of large metropolitan areas, and in some instances may have affected agriculture.

One main reason why climate modification is a major concern is that it can alter the agricultural output of a region. Examples of droughts are plentiful in historic times, including the recent ones in the Sahel and the Soviet Union. Schneider argues that even the highly technological agriculture of the USA is vulnerable to drought and climatic change.

There are a number of approaches to assessing the climatic impact of a given activity, ranging from qualitative reasoning, to simple analytic models, to complex computer simulations of the microscale, mesoscale, or global atmosphere. Global models vary in complexity from highly averaged zonal models to very detailed general circulation models (GCMs). One of the problems with the more detailed models is their cost and the "noise" level of the output. Zonally averaged models, on the other hand, lack geographic details of the atmospheric circulation. For assessing the possible impact of a future technology, some combination of these techniques should probably be used, provided that the importance of the question can justify the expense of running a GCM, and that the results appear to have a chance of being statistically significant.

Solar energy could have a major impact on future energy supply. The question we address here is: what are the possible climatic effects of implementing this new technology?

It might be argued that such an effort at this time is premature owing to the speculative nature of the scenario being considered, or to the very questionable economics of most solar designs. We are presently in the midst of a small revolution concerning man's attitutde towards his environment, and the importance that should be given to environmental questions as compared to economic and social ones. It is not clear what ultimate significance will be given to possible climatic results of future industrial undertakings; thus the real value of this study is difficult to assess. However, if we are to avoid potential ecological or environmental disasters, then all new technologies must be scrutinized for their possible effects. This should be done before major policy decisions have been made regarding the technology, and indeed the results of such an effort should be an important input into these decisions. In the case of most solar technologies, the point has not yet been reached where government and industry decision makers are faced with the choice of implementation of each new technology. Thus there is still time to analyze the effects of these technologies and to avoid mistakes. This task may not be easy, and many of the results may be negative or uninspiring. Nevertheless, it is important work that needs to be done.

Most of our analysis is qualitative in nature owing to the immense complexity of the atmospheric ecosystem. Much remains to be done in the way of quantifying and expanding some of the more important effects.

CHARACTERIZATION OF SOLAR TECHNOLOGIES

Potential solar energy conversion (SEC) applications range from hot water heaters for residences to geosynchronous satellites beaming microwaves to land-based receivers. The application generally considered closest to economic feasibility is the heating and cooling of buildings in existing or new urban areas. The solar devices may alter the urban heat-island effect, but will be only a part of a complex of roads, parking lots, buildings, factories, etc. Most of the other solar applications, in contrast, would be new man-made intrusions into the environment. To the extent that one or more of these latter technologies were to supply a substantial fraction of a nation's or of the world's energy requirements, they can be expected to alter the climate to some extent. This section briefly describes these technologies, with an emphasis on those aspects that could affect the climate. SEFE(1975) and Bockris (1975) provide good introductions to technical details of the applications.

SOLAR THERMAL CONVERSION

A wide variety of devices have been proposed to convert incident solar energy to thermal and then to electrical energy. Thermal to chemical conversion (to produce fuels) is an attractive alternative to electricity production, but practical processes have not yet been developed. In general, the cost per unit area of collector increases with the operating temperature. On the other hand, at least for electrical generation, the amount of collector area needed for a given power output decreases with the increasing operating temperature. For the central receiver, the efficiency of converting the light incident on the collector (mirror) to electricity would be about 25 percent (STCMA, 1974). The corresponding number for shallow solar ponds would be about 3 percent (Clark, et al. 1974). Some 3 to 4 km^2 of land (about one-half covered with mirrors) per 100 MWe (baseload) would be required for a central receiver plant. The corresponding area for a shallow solar pond would be about 25 km^2. In general, for central station power plants, economic considerations favor the high temperature devices; the higher conversion efficiency more than balances the higher unit cost of the collectors. It is perhaps fortuitous that the high temperature applications would minimize (for a given power output) the amount of land with modified albedo.

Photovoltaic Conversion

The range of possibilities for photovoltaic devices for central station power are analogous to those for solar thermal conversion. Very cheap cells might be placed in horizontal arrays (as with the solar pond) or tilted at a fixed angle (as with flat plate collectors). The cost per unit of power for expensive cells can be reduced by using one or two axis concentrators (as with the parabolic trough or the paraboloidal dish).

The relationship between economics, efficiency, and land area is less clear for photovoltaics than for solar thermal. The nonconcentrating devices are not necessarily less expensive or less efficient per unit collector area than the high concentration ones. However, for currently realizable solar cell efficiencies of $\sim$ 15 percent, a concentrating photovoltaic system should not be used for the central station power. Since the cost of the concentrators (e.g., heliostats) dominates the economics, the higher conversion efficiency of solar thermal would always be chosen. According to this argument, photovoltaic devices would be used only if the cost per unit of power of flat arrays was less than that for solar thermal energy. Thus, in terms of climatic change, it is reasonable to consider only horizontal or tilted nonconcentrating arrays. The collector area for a given power amount would $\sim$ 2 to 3 times that of a solar thermal plant, taking into account the lower efficiency and (for fixed arrays) the cosine factor.

Wind

Wind turbines of both the horizontal axis (e.g., propellor) and the vertical axis (e.g., Darrieus rotor) types have been proposed for central station electrical generation. A good wind site might have an annual average power density of 200 W/m^2 or more. The theoretical maximum of the power that can be extracted by a horizontal axis machine is 59.3 percent. Well-designed turbines can extract 40 to 45 percent of the power in the wind, with an overall efficiency for electrical generation of 30 to 35 percent (SEFE, 1975) (allowing for losses in the transmission and generator). The individual units of the central station power would be large. A horizontal axis machine might have a blade diameter of 100 m and an output rating of 2 MW(e) for winds of 7 m/s (power density of 200 W/m^2). The units must be spaced far enough apart to avoid downwind interference. A spacing of 10-blade diameters is standard.

The potential for wind power appears to be more limited than for the other solar technologies. Coty (1976) estimates that, in the USA, the annual average power in the wind below 1 km is 3.4×10^{11} kW. Coty further estimates that if large turbines were deployed in a uniform density with a spacing of 10-blade diameters, the converted electrical output would be 7.3×10^{8} kW. Using somewhat different assumptions than those of Coty (1976), Coty and Dubey (1976) estimate that about one-third of the land area is actually suitable for wind turbines, with a power output of 2.1×10^{8} kW. This number is close to the current US electrical demand. However, the total US energy consumption is about 15 times as large. Thus wind power could supply only a small fraction of the total energy demand, even if demand did not increase. While these estimates for the US are not necessarily applicable to other countries, it seems reasonable to assume that if the rest of the world is to attain a per capita energy consumption on the order of that of the US, some source other than wind will be required.

From the standpoint of large-scale, mesoscale or global climatic changes, large arrays of wind turbines might be treated by increasing the surface drag coefficient to simulate the loss of energy from the wind. Given the wide spacing of the turbines and the small fraction of the energy in the wind that is actually converted to electricity, large effects are unlikely. Local effects in the turbine arrays may be significant. The reduction of wind velocity near the ground could affect evaporation rates and heat transport. Local turbulence could be modified.

Ocean Thermal

Ocean thermal gradients have the advantage over solar thermal, photovoltaic, and wind power in that the source of power is continuously available. One possible application would be plants located in the Gulf Stream, feeding electrical power to the USA mainland by undersea cable. The best locations (with the largest gradients and lowest currents) are in the tropical oceans. Since these are remote from most areas of high energy demand, the plants would need to manufacture fuels (e.g., hydrogen by electrolysis) or to undertake energy-intensive materials processing (e.g., aluminum refining).

Current concepts of ocean thermal plants have been reviewed by Dugger et al. (1976). Typically, warm surface waters at ∿ 25° C would be heat exchanged to a working fluid and released back to the ocean ∿ 23° C. Cold, deep waters from about 750 m at ∿ 5° C would be pumped close to the surface to condense the working fluid, then released at ∿ 7° C. For 100 MW(e) (net) both the hot and the cold water flow rates would be ∿ 2 × 10^9 kg/h. The depths that hot and cold water effluents would be released depend on the design. One design described by Dugger, et al. (1976) would release both effluents at 80 m.

The conversion efficiency of ocean thermal plants is sufficiently low (2 to 2.5 percent) that, from the standpoint of the impact on the ocean, the extracted energy can probably be ignored and the plants regarded as large pumps that redistribute the ocean waters. The exact nature of this redistribution, which is not well understood, will depend on plant design. Advocates of this technology generally assume mixing of the nutrient rich cold water effluent with the surface waters. The anticipated enhanced marine life is regarded as a new source of food. By way of contrast, Harrenstien and McCluney (1976) assume that, for proper plant design, the cold effluent will descend to the depths without appreciable mixing. Based on this and other assumptions, these authors calculate that ocean thermal plants would lower the surface temperature of the Gulf Stream by 0.5° C if there were enough plants to generate the current US electrical demand of ∿ 2 × 10^5 MW(e). As they point out, it is not clear whether this reduction is "too much". The calculation (if essentially correct) does indicate that the Gulf Stream would not support plants generating the total US energy demand.

The potential for the tropical oceans is much greater than for the Gulf Stream. In an early paper, Zener (1973) estimated that the oceans between the latitudes 20° N and 20° S could support 60 × 10^6 MW(e) of conversion for a 1° C drop in surface temperature. Zener implicitly assumed that the cold effluent would descend and not mix with the surface.

If the ocean thermal plants are either advertently or inadvertently designed to mix the cold outflow, then the impact on the surface temperature of the ocean would be considerably greater than for the above quoted calculations. Natural upwellings produce local climate anomalies along with the enhanced fish population. Von Hippel and Williams (1975) suggest that the mixing will cause a net transfer of inorganic carbon to the surface waters. They estimate that an ocean thermal plant would release about one-third as much CO_2 to the atmosphere as does a fossil-fueled plant of equivalent energy production.

Biomass Production

Organic material can be converted to electricity through combustion, or it can be chemically converted to fuels. Waste material (urban, agricultural, forest) could supply a finite but small portion of the energy demand of industrialized countries. Supplying all or a large fraction of the energy demand would require deliberate growth of organic material for conversion. Biomass production has the advantage over other solar technologies of intrinsic chemical storage of energy, and is also considered to be less capital intensive (SEFE, 1975).

There are a number of uncertainties that make it difficult to characterize the land modifications needed for massive biomass production. One uncertainty is the extent to which "genetic engineering" or special agricultural practices could improve photosynthetic conversion efficiency. Another is whether the technology would take over existing crop and forest lands or whether it would be economically or politically restricted to current arid or semiarid land. A rough scenario can be made from currently realizable efficiences, based on the assumption that only semi-arid land would be used. To meet the current total US energy demand would require 6 percent of the total US land area if the crop were sugar cane which has a high conversion efficiency of 2 percent (Calef, 1976); 17, 25 and 124 percent of the land would be needed for corn, scotch pine, and cool temperate forest, respectively. For sugar cane grown in the southwest USA, Calef (1976) estimates that $9 \times 10^{11} m^3$ (7.4×10^8 acre-ft) of irrigation water per year would be needed; this is 1.5 m of water over the 6×10^5 km^2 of land area devoted to the crop.* Essentially all of this water would be released into the atmosphere through evaporation, transpiration, and crop drying.

Conversion of the biomass to other energy forms potentially has many of the air and water pollution problems. However, the atmospheric CO_2 content should not be affected under steady state conditions. The major climatic change factors would appear to be the reduced albedo and the increased water release rates of vegetation relative to semi-arid land.

CLIMATE AND DESERT SYSTEMS

Central receiver and photovoltaic plants will modify the radiation balance of the atmosphere, which could change the global or regional climate. These devices would be placed in arid zones so that an understanding of the dynamics of desert climates is necessary to investigate this subject. Many feed-backs contribute to or affect climate stability of deserts, thus complicating our understanding of the earth's arid regions. Several of these feedbacks, which it is believed can be modified by man, will be discussed here.

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*Calef points out that this amount of water is ∿ 50 times the mean annual discharge of the Colorado River, making this scenario rather unlikely.

As far as climate is concerned an important factor in many deserts is the rain shadow effect. This occurs when the desert is on the leeward side of a mountain range, or when it is a large distance from a body of water. In the first case, moist air moves over the range, rising on the windward side and experiencing cooling, condensation, and precipitation, and descending on the leeward side experiencing a decrease in relative humidity, and evaporation of water droplets and ice, thus helping to sustain the desert. In the second case, by the time the air reaches the arid region, much of its water content has precipitated out. Pure rain shadow deserts are rare; however the rain shadow effect is probably an important factor in many deserts. Some examples are most of the deserts of the USA, the Gobi and Sinkiang deserts of China, and the Patagonia of Argentina.

Most, if not all, arid regions are associated with a descending atmosphere often referred to as subsidence. Subsidence causes a decrease in relative humidity and can be accompanied by a decrease in cumulus convection. Both effects tend to decrease precipitation. In the case of a rain shadow, subsidence is increased by topographical features. However, many other factors can affect subsidence. The great deserts of the world lie in the zones of descending air of the poleward halves of the two Hadley circulation cells (Sellers, 1965). In this case subsidence is a complicated result of the global atmospheric circulation. Almost all the major deserts are in this class. Thus any changes in the Hadley cell circulation, as might be caused by changing north-south temperature gradients, may affect precipitation in these deserts. Regional or mesoscale circulation patterns may also affect subsidence and thus enhance or diminish precipitation. Desert formation is integrally linked with atmospheric circulation, and a complete understanding of this subject is therefore not possible at this time. In lieu of this, we shall discuss several feedback mechanisms which have been investigated and which relate man's activity to the desert climate.

An elegant and detailed model relating surface albedo changes to changes in precipitation has been presented by Charney (1975). Charney's ideas, roughly speaking, are as follows. Moist air rises in the intertropical convergence zones and moves poleward. Charney's calculations include viscosity in a boundary layer above the surface of the desert. Above the boundary layer the flow is assumed geostrophic (coriolis forces balance pressure forces). Inside the boundary layer the Coriolis force is assumed to balance the east-west friction force. Only radiative heat transfer is included in the model. Over the deserts, surface albedo is high (30 to 40 percent). Charney ignores evaporation at the surface, and assumes that the net shortwave energy absorbed there is equal to the net longwave energy radiated. In the model the atmosphere is transparent to shortwave radiation, but absorbs longwave radiation because it is assumed to contain water vapor. Thus the atmosphere gets energy from the longwave radiation emitted from the surface. The atmosphere also emits thermal radiation into space, and the temperature lapse rate is determined by the condition of radiative equilibrium. In this model when the albedo of the surface increases (thus decreasing the longwave radiation leaving the surface), the equilibrium temperature of the atmosphere drops, due essentially to radiative cooling. As the air cools it descends, causing a decrease in relative humidity and therefore in precipitation. Charney has tested his ideas on a global circulation model which supported his claim. It showed a net increase in precipitation in going from an albedo of 35 to 14 percent for the Sahara. The absence of vegetation and resulting high albedo helped to maintain the desert. Man's activities can affect vegetation cover by overgrazing, and Charney argues that this could reduce precipitation.

A number of questions can be raised about Charney's mechanism. First, one would expect that thermal transport processes other than radiation would be important in the lower atmosphere, particularly turbulent diffusion, free convection, and evaporation. Secondly, if albedo were decreased by plant cover then an increase in evapotranspiration would probably occur, leading to a cooler surface. In Charney's model the surface temperature increases with a decrease in albedo, presumably because he does not include evaporation.

Another idea, which is controversial but possibly applicable to some deserts, is due to Bryson and Baerreis (1967). Bryson noted large amounts of dust in the atmosphere of India's Rajasthan desert, and found evidence that the dust was important in sustaining the desert environment. He argues that the presence of aerosols causes cooling of the atmosphere by reflecting more shortwave radiation back into space. This cooling again results in subsidence and aridity. He has proposed this as an explanation of the encroachment of the Rajasthan in historic times.

Otterman has investigated a variant of the heat-island thermal mountain effect to explore the relation between aridity and albedo (Otterman, 1974). The idea is that increased albedo leads to less shortwave energy absorbed at the surface which in turn leads to a lower temperature and a "thermal depression". Since the surface is cool, the atmosphere also cools and sinks. Otterman feels that his model is consistent with Charney's. The models certainly differ radically but Charney disputes Otterman's claim.

Still another effect has been proposed by Schnell (1975) who claims that particles which are biologic in nature are important in the formation of ice nuclei. He argues that vegetation cover provides these particles and thus facilitates precipitation.

The one effect that seems to be widely accepted is that an increase in the albedo, other things being equal, decreases precipitation, and vice versa. The question then is: what effect will solar plants have on an arid region? Solar central receiver design plants and photovoltaic arrays will decrease the albedo in the region in which they are installed (unless costly preventative action is taken). About 15 to 25 percent of the collected radiation's energy will be converted either to electricity or synthetic fuels. This energy will eventually be converted to low grade heat, but this may occur some distance from the power plant. If construction of solar plants is intense, then large amounts of dust will enter the atmosphere due to construction activities and off-road vehicles. With an increase in aerosols, Bryson's effect may occur tending to make the desert more arid. The relative importance of this dust is unclear at this time.

We see that there are conflicting effects which could tend to modify precipitation. First, decreasing the albedo will tend to increase precipitation. This effect would be partially offset by transporting the energy large distances. On the other hand, human populations would tend to increase in arid regions, which could lead to decreases in the albedo. Next, the aerosol content of the atmosphere can be expected to increase, and this might tend to decrease rainfall (as well as decrease the output of the plant). Finally, we would expect a net increase in evaporation in the desert. This could be caused by several factors. First, some evaporative cooling devices might be used to condense steam for power plants. Second, the human population needed to support the energy plants will need water to live and grow crops. Increased evaporation would probably tend to increase precipitation.

The most difficult of these effects to study would probably be the aerosols. The albedo modification could be studied using existing GCMs and zonally averaged models. The results of such a model run, which was performed by Gerald Potter of Lawrence Livermore Laboratory, are present elsewhere in these Proceedings.

MICROCLIMATOLOGY OF CENTRAL RECEIVER POWER PLANTS

There are other microclimatological effects that deserve consideration as far as central receiver plants are concerned. Perhaps the most important effect will be increased dustiness of the region. In its natural state the desert surface usually forms a protective crust which retards erosion of underlying fine particles. This crust is easily broken. With the extensive construction that would be needed to build solar plants, substantial breaking of the crust and release of fine particles into the atmosphere would be unavoidable. Persistent aerosols would affect the performance of the plant. Possible effects of dust on the radiation balance were discussed briefly in a previous section. Another side effect of construction will likely be increased water runoff and erosion.

The shade under the canopy of heliostats will lead to a lower surface temperature than normally occurs. The evaporation rate under the canopy will be reduced. This will probably be most pronounced after rains when the soil-held water normally evaporates quickly. As a result of the canopy, more of this water is likely to reach the water table. After some time, the water table height may increase slightly, but this is not likely to be a large effect.

Dew can be an important source of moisture in deserts. Monteith (1957) and Baier (1966) have given reviews of the state of knowledge of dew formation in arid regions. Normally the dew which forms overnight evaporates very quickly in the morning. Under the canopy the rate of evaporation will be lower and the moisture content of the soil therefore higher, on a daily average. This moisture might lead to enhanced vegetation, which some have suggested could be used for grazing land for livestock. With increased vegetation and lower temperature there is likely to be an increase in the wildlife population living underneath the heliostat canopies.

Atmospheric turbulence in the lower atmosphere will increase because of the effective increase in surface roughness resulting form the heliostats. In the simplest approximation, the vertical transport of heat leads to the equation

$$\frac{\partial \Theta}{\partial t} = K_H \frac{\partial^2 \Theta}{\partial Z^2} \quad ,$$

(Sutton 1953), where Θ is potential, t is time, and Z is altitude, and K_H is the virtual coefficient of conduction. Although a good understanding of K_H as a function of surface roughness does not seem to exist, it presumably would increase as a result of an increase in surface roughness that would occur in the heliostat fields. With an increase in K_H, temperature lapse rates and diurnal variations would be modified. K_H can range from about 0.2 cm^2/s for still air to about 10^7 cm^2/s for very unstable stirred air (Priestly, 1959). Detailed models of K_H would be required to understand the significance of the change. The change in roughness of the desert terrain will also change the wind profile. Horizontal velocity is parametorized as (Sellers, 1965)

$$U = \frac{U^*}{K} \ln(Z/Z_o) \quad ,$$

where K is approximately 0.4 (the Von Karman constant), U* is the friction velocity, and Z_o is the roughness length. Sellers presents a table of Z_o for different terrains. For a smooth desert he gives $Z_o \simeq .03$ cm; and for a citrus forest $Z_o \simeq 198$ cm. In this table, the citrus forest is the closest terrain to a heliostat field. Thus the mean winds would be somewhat reduced above the field.

In the unlikely event that evaporative cooling devices are used with solar plants, they may cause fog or clouds. The details would depend on the type of cooling. For example, Currier et al. (1974) have taken data of fogging around the cooling pond at the four-corners power plant. Their results suggest that fogging is correlated with the parameter $I = \Delta t/(e_s - e_a)$, where Δt is the difference between water temperature and ambient air temperature, e_s is the vapor pressure of saturated air at ambient temperature, and e_a is the ambient air vapor pressure. The larger I, the more likely the occurence of fog. Usually some condensation occured for $I > 20°$ F/mb. For other types of cooling devices this index might not be suitable, but in any event we can expect fogging to become less likely with a decrease in relative humidity. Since the deserts where the solar plants are likely to be situated have, on the average, very low relative humdity, we would not expect fogging to be a major problem except at night.

FREE CONVECTION ABOUT A CENTRAL RECEIVER POWER PLANT

This section deals with the convection currents that will be caused by the operation of a central receiver power plant in an arid location. We shall discuss these currents in a grossly idealized model in order to make a first order estimate of the magnitude of this effect. This topic is of interest because if the air speed is too great in the field of heliostats, then particles from the surface will be swept into the atmosphere, and increased turbidity will result. This could decrease the efficiency of the plant and also have undesirable effects on regional climates.

The subject of convection has been studied extensively over many years; a good description is given by Sutton (1953). An important factor complicating the analysis is that under the right conditions, the convection currents become unstable or turbulent. In these conditions analytical methods do not yield exact solutions because of the great mathematical complexity of turbulent fluids.

When turbulence occurs, a parcel of air which is rising due to buoyant forces will undergo mixing (entrainment) with the surrounding air, and its motion will be nonadiabatic. The mean or average velocities in this case will deviate from purely laminar flow. Although exact methods are not available for treating this case, a number of approximate models have been developed for handling the special case of a rising plume. The model we use applies to axially symmetric boundary conditions, and to an environmental lapse rate which depends only on altitude. The equations become especially tractable when the atmosphere is neutral.

Imagine a cylindrically symmetric heat source (such as a cooling tower for a power plant) on a horizontal surface. Also consider the case where the environmental temperature is a function only of altitude, and there is no environmental wind. Various treatments of the convection caused by these conditions have been given. We shall follow a model developed by Priestly and Ball (Priestly, 1955 and 1959; Priestly and Ball, 1955). Following Priestly and Ball (PB) we write

$$\frac{\partial}{\partial Z}(rw\rho) + \frac{\partial}{\partial r}(ru\rho) = 0 \quad , \tag{1}$$

$$\frac{\partial}{\partial Z}(rw^2\rho) + \frac{\partial}{\partial r}(ruw\rho) = r\,\frac{\Theta'}{\Theta_e}\,\rho g + \frac{\partial}{\partial r}(r\tau) \quad , \tag{2}$$

which are, respectively the equations of motion and conservation for a viscous fluid in the hydrostatic approximation. These are coupled to an equation for energy conservation

$$\frac{\partial}{\partial Z}(rw\theta\rho) + \frac{\partial}{\partial r}(ru\theta\rho) = -\frac{1}{c_p}\frac{\partial}{\partial r}(rF) \tag{3}$$

where

w is vertical velocity,

u is radial velocity,

ρ is density,

θ is potential temperature,

θ_e is environmental potential temperature,

θ' is excess potential temperature $(\theta - \theta_e)$,

τ is vertical turbulent shearing stress,

F is radial (potential) turbulent heat flux,

c_p is specific heat of air (taken as a constant).

All quantities refer to mean values. PB assume the following form for a solution:

$$\frac{w}{w_m} = f\left(\frac{r}{R}\right) \quad , \quad \frac{\theta'}{\theta'_m} = h\left(\frac{r}{R}\right) \quad , \quad \frac{\tau}{1/2\rho w_m{}^2} = j\left(\frac{r}{R}\right) \quad , \tag{4}$$

where the subscript m denotes the value on the axis of symmetry. w_m, θ'_m, and R depend only on height Z. These forms do not yield an exact solution; however they conform to an intuitive picture of a rising plume whose radial dependence changes in scale but retains its relative shape.

For the special case of neutral conditions,

$$\frac{d\theta_e}{dZ} = 0 \quad ,$$

a complete solution may be obtained. PB find for neutral conditions

$$R^2 w_m \theta'_m = \text{constant} = A \quad . \tag{5}$$

Making a further approximation by assuming $f = h = \exp\left(- \frac{r^2}{2R^2}\right)$, the Gaussian approximation, they find

$$w_m = \left\{\frac{3Ag}{2\theta_e C^2 Z} + \frac{B}{Z^3}\right\}^{1/3} \quad , \tag{6}$$

$$\theta'_m = \frac{A}{C^2 Z^2} \left\{\frac{3Ag}{2\theta_e C^2 Z} + \frac{B}{Z^3}\right\}^{-1/3} \quad , \tag{7}$$

$$A = Q/\pi\rho c_p \quad , \quad \text{where Q is the source strength.} \tag{8}$$

$$R = CZ \quad . \tag{9}$$

The parameters A,B, and C are constants of integration. The point Z = 0, r = 0 has been chosen to be the concurrent point of the cone shaped plume.

For our purposes, we shall ignore the terms containing B in these expressions, since they fall off fast with altitude and are difficult to determine.

An expression for radial velocity u may be obtained from the equation of continuity (1) which can be integrated to yield

$$u(r,Z) = \frac{1}{r}\frac{\partial}{\partial Z} w_m(-R^2)\left[1 - e^{\frac{-r^2}{2R^2}}\right] \quad , \tag{10}$$

Substituting in (10) the forms for w_m and R, and taking B = 0, we find

$$u = \frac{-C^2 w_m Z}{r}\,\frac{5}{3}\left(1 - e^{\frac{-r^2}{2R^2}}\right) + w_m\frac{r}{Z}\, e^{\frac{-r^2}{2R^2}} \quad , \tag{11}$$

$$w_m = \left(\frac{3Ag}{2\theta_e C^2 Z}\right)^{1/3} , \tag{12}$$

$$\theta' = \frac{A}{C^2 Z^2}\;\frac{3Ag}{2\theta_e C^2 Z} \tag{13}$$

$$R = CZ \quad , \tag{14}$$

$$A = Q/\pi\rho c_p \quad , \tag{15}$$

$$R^2 w_m \theta'_m = A \quad . \tag{16}$$

Next we apply these equations to a solar thermal plant to analyze convection caused by its dry-cooling towers.

Consider a 100 MWe intermediate load power plant, using the central receiver design with dry-cooling towers. The waste heat ejected at the tower will be about 200 MW(th). The air at the mouth of the tower might be about 150°F. For dry cooling, all of the waste heat is sensible. This causes greater convection currents than evaporative cooling where most of the energy goes into latent heat, and so can be used to set a bound on convective effects. A rising wet plume is difficult to model because of the added degrees of freedom resulting from condensation phenomena.

As a typical example of a cooling tower for a 100 MW solar plant, we consider a cylindrical tower with 16 m radius. This dimension can be scaled simply, using the formulas given. Our model does not accurately depict convection near the ground, since the model does not meet the condition that the vertical velocity vanish at the surface. We shall therefore consider velocities at a height level with the tower, and the results are only approximate. Let Z be the vertical coordinate, and Z_o the coordinate of the top of the tower. $Z = 0$ is the level of the apex of the cone shaped heat plume. At height Z_o we must have

$$R = CZ_o = R_o \quad , \tag{17}$$

where R_o is the radius of the tower.

The total heat per unit time ejected by the tower is denoted by Q. This determines w_m at a height Z_o by equations 5 and 8

$$w_m(Z_o) = Q/(\pi R_o{}^2 \rho c_p \theta'_m) \tag{18}$$

$$= \frac{Q}{\pi R_o{}^2 \theta'} \times 8.5 \times 10^{-5} \, \frac{K^\circ cm^3}{erg} \tag{19}$$

Once C is known, equation 11 then gives u at this height. For $r \gg R$, the expression for u simplifies to

$$u \approx -\frac{5}{3} \, \frac{C^2 w_m Z}{r} \tag{20}$$

The parameter C may be solved for in terms of known quantities

$$C = \theta'_o{}^3 \, \frac{R_o{}^5}{A^2} \, \frac{3}{2} \, \frac{g}{\theta_e} = 3/2 \, \frac{\theta_o}{\theta_e} \, \frac{R_o \rho}{w_m{}^2} \tag{21}$$

$$\text{where } \theta'_o = \theta' \, \Big| \; r = 0, \quad Z = Z_o \quad . \tag{22}$$

If we take the following typical number for a solar cooling tower in an arid location

$$Q = 200 \text{ MW(th)} \quad , \tag{23}$$

$$\theta_e = 305 \text{ K} \quad , \tag{24}$$

$$\theta'_o = 35 \text{ K} \quad , \tag{25}$$

$$R_o = 16 \text{ m} \quad . \tag{26}$$

then w and u are determined in terms of these.

We find for example

$$w_m(Z_o) = 6 \text{ m/sec} = 22 \text{ km/h} \quad . \tag{27}$$

This is the velocity of the air at the mouth of the cooling tower. We find a value for C of

$$C = .75 \quad . \tag{28}$$

The Z coordinate of the tower mouth, Z_o, is equal to

$$Z_o = \frac{R_o}{C} = 21.3 \text{ m} \tag{29}$$

At this height, u(r) is given by (for $r \gg R_o$)

$$u(r,Z_o) = \frac{120}{r} \text{ m/sec} \quad , \tag{30}$$

so that at a distance of 50 m from the tower centerline

$$u(r{=}50\,\text{m}) = 8.6 \text{ km/h} \quad . \tag{31}$$

It is unlikely that this magnitude wind could cause any serious erosion problems except in the very nearest heliostats. Since our model is only approximate, it is conceivable that the actual currents could be somewhat larger than these predictions. This might occur, for example, if the heliostat field were significantly cooler than the surrounding desert, an effect which we have ignored. The cooler field would lead to somewhat larger currents. Based on this model, we may say that it would be surprising if convective erosion turns out to be a serious environmental problem.

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A Scenario for Albedo Modification Due to Intensive Solar Energy Production

Donald Grether, Mark Davidson, and Jerome Weingart

One major problem facing mankind at present and for the foreseeable future is obtaining sufficient energy to support an ever burgeoning population in a dignified manner which enables more than bare survival for each individual and nation. Fossil fuels probably cannot meet this energy demand, and even if they could temporarily, they could not sustain it for very long. In the long run, one promising alternative to fossil fuels appears to be solar energy. Although technology in this field is not far enough advanced to decide whether solar energy will be economically competitive with nuclear power, present indications suggest this possibility. For power generation, the technology closest to economic viability is solar thermal power generation. This consists of mirrors to focus the sun's light, and of collectors to transfer the radiation energy to a "working fluid" which then is used in a turbine to generate power. This scheme has the advantage of not producing unmanageable waste products and of not requiring special security arrangements. Because solar thermal energy requires a relatively large land area, environmental concerns arise.

A potential problem with large-scale solar thermal energy production is climate modification induced by altering the earth's natural radiation balance. The global scenario presented here is an attempt to estimate the maximum credible deployment of solar thermal energy in the future. The modification of the natural albedo may be estimated in this case. This change is of such a magnitude that global climatic changes appear possible. The global scenario has been used in the setting up of an experiment with the zonal atmospheric model developed at Lawrence Livermore Laboratory in California, USA. (This experiment is described by Potter and MacCracken in these Proceedings.)

The maximal solar thermal scenario being considered is strictly for studying climate modification; thus our scenario has more solar thermal production than is actually likely to occur. The climate effects caused by this can be used to bound any effects that might occur in a less extensive scenario. If it turns out that drastic atmospheric changes occur in the zonally averaged or general circulation models (GCMs), then it will be interesting to consider less extensive cases in order to get an idea of the level of solar thermal energy production needed to cause undesirable atmospheric effects.

At present world population has passed 4 billion. If trends continue, then by the year 2000 world population will be 6.5 billion. Beyond that is anybody's guess, but it is conceivable, if not likely, that the earth's population will reach 10 billion in the twenty-first century. It is unlikely that population will increase much beyond that level although it is possible. In our scenario we consider a world of 10 billion people. We do not claim that this is the most likely steady state population that earth will attain. We do feel that planning must be done with this order of magnitude in mind.

The present primary per capita energy consumption in the USA is about 10 kW. It might be argued that this level of consumption is extravagant and that the world average per capita consumption will never achieve anything near this level. For the purpose of bounding climatic changes we feel that a world per capita energy consumption of 10 kW is a reasonable upper bound. In our scenario we will assume this figure as a world average, and we will assume that all power is generated by solar thermal energy. To be more specific, we assume that for each person there exists 10 kW of base load power generating facilities.

Solar energy may be utilized differently, e.g., solar thermal power, photovoltaic power, ocean thermal power, wind energy, biomass conversion, satellite collectors, and heating and cooling of buildings, etc. Most of these technologies require relatively large areas of equipment to absorb solar radiation. Thus extensive implementation of one or more of these technologies may change the radiation balance in the earth's atmosphere. For the case of solar thermal power, reasonable estimates can be made of the size of the land area. To generate 100 MW(e) of base load power, from 1.5. to 2 km^2 of reflector surface would be required. Almost all direct radiation would be concentrated on the reflecting surfaces, to a central collector which would then absorb most of it. The effects of access roads and population increases in the vicinity of plants would also tend to decrease the albedo of the region. Thus, to account for some of these effects, and to obtain an upper bound on climate modification, we shall assume an equivalent reflector area of 3 km^2.

More land area will be needed than reflector area. A rough estimate of the ratio of land to mirror area is about 3 : 1. Thus, for a 100 MW(e) plant, we associate 9 km^2, about 6 km^2 for the plant itself, and about 3 km^2 for access roads and population related uses. The land area required to supply 10 kW(e) per person with 10 billion people would be

$$9 \times 10^6 \ \text{km}^2 = \text{total land area.}$$

Once again, this should be viewed as a rough upper bound. The change in albedo caused by installing this level of solar thermal energy is complicated by several factors. First, the solar plant affects direct and diffuse radiation in different ways. Direct radiation tends to be absorbed, whereas diffuse radiation tends to be reflected. The actual amount of radiation depends on time of day, latitude, reflector-collector geometry, season, and relative magnitude of direct to indirect insolation. For a zonal atmospheric model or a GCM, an average time independent albedo is desired. A rough estimate of the albedo change may be obtained by assuming that an area equal to the total reflector area has become perfectly black as a result of constructing the solar facility. If α denotes the new albedo and α_N the natural albedo, and if one-third of the land areas is the total reflector area, we have

$$\alpha \approx \frac{2}{3} \alpha_N \tag{1}$$

Thus, the new albedo is approximately two-thirds of the natural albedo in a region with intensive solar generation.

In order to complete our scenario we must decide how the 9×10^6 km^2 of land area is to be proportioned worldwide. We have assumed that solar energy will be used to produce fuels, such as hydrogen, which may be transported large distances. Thus intensive solar energy production need not coincide geographically with population centers. A number of factors affect the suitability of a region for solar generation. Some of these are total number of annual sunshine hours, roughness of terrain, availability of labor and capital, accessibility of markets, political stability, and availabiltiy of building material (mainly steel, glass, and concrete).

Table 1 shows how the solar energy production of this scenario might conceivably be distributed. Figure 1 shows the land area devoted to solar energy conversion in this scenario. The total area is roughly equal to that of the USA. Table 2 shows the solar land area by latitudinal zones, along with a total zonal area and a fraction thereof of solar area.

To investigate the effects of this scenario, we modified the zonally averaged land albedo of the model as follows:

- f fraction of land in the zone devoted to solar plants;
- α_s natural albedo of the solar land;
- α_u natural albedo of the remaining land;
- α_z zonally averaged land albedo.

Table 1. Solar energy production (authors' scenario).

Country/ Region	Percent	Total Mirror Area (km^2)	Land Area (km^2)
North America	15	4.5×10^5	13.5×10^5
South America	10	3.0×10^5	9×10^5
Europe	<5	1.5×10^5	4.5×10^5
Sahara	15	4.5×10^5	13.5×10^5
Arab. Penin	10	3.0×10^5	9×10^5
India	15	4.5×10^5	13.5×10^5
China	15	4.5×10^5	13.5×10^5
Australia	5	1.5×10^5	4.5×10^5
South Africa	5	1.5×10^5	4.5×10^5
USSR	5	1.5×10^5	4.5×10^5
TOTAL	100	3×10^6	9×10^6

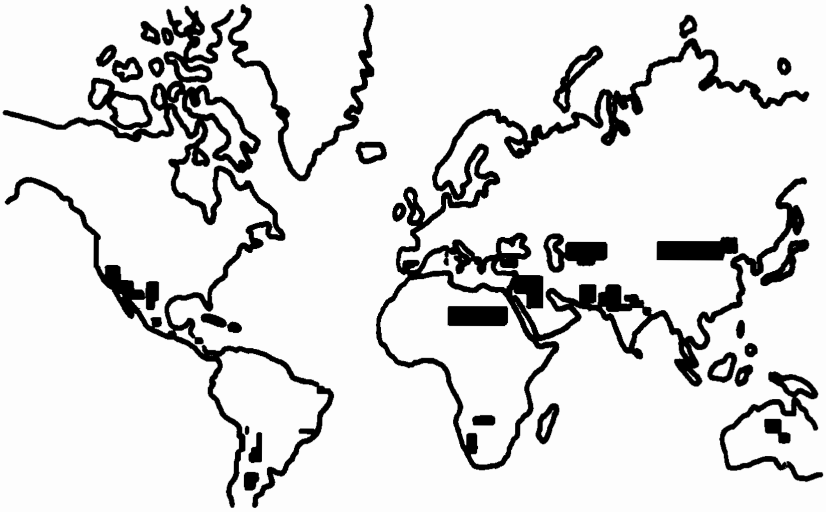

Figure 1. Land area devoted to solar energy conversion (authors' scenarios).

Table 2. Solar land area by latitudinal zones.

Latitudinal Zone	Zonal Area/R_e^2	Solar Area/R_e^2	$\frac{\text{Solar Area}}{\text{Zonal Area}}$	$\frac{\text{Solar Area}}{\text{Zonal Land Area}}$
-85 to -75	.1899	0.0	0.0	0.0
-75 to -65	.3742	0.0	0.0	0.0
-65 to -55	.5472	0.0	0.0	0.0
-55 to -45	.7036	0.0	0.0	0.0
-45 to -35	.8386	.0034	.0041	.029
-35 to -25	.9481	.0148	.0156	.061
-25 to -15	1.0288	.0236	.0230	.061
-15 to -5	1.0783	.0018	.0016	.005
-5 to 5	1.0950	.0016	.0014	.003
5 to 15	1.0785	.0009	.0008	.002
15 to 25	1.0292	.0554	.0539	.127
25 to 35	.9487	.0673	.0710	.162
35 to 45	.8393	.0617	.0736	.146
45 to 55	.7044	.0014	.0020	.003
55 to 65	.5482	0.0	0.0	0.0
65 to 75	.3753	0.0	0.0	0.0
75 to 85	.1910	0.0	0.0	0.0

Prior to the placement of the solar plants, we have (approximately)

$$\alpha_z = f\alpha_s + (1 - f)\alpha_u \quad ; \tag{2}$$

this is true only where the shortware flux striking the two land areas is approximately the same.

After the solar collectors are in place, we have (according to our approximation) a new albedo for the solar area of

$$\alpha_s' = \frac{2}{3}\,\alpha_s \quad . \tag{3}$$

The new zonally averaged albedo becomes

$$\alpha_z' = \alpha_z - \frac{1}{3}\,f\alpha_s \quad ; \tag{4}$$

a value of $\alpha_s = .35$ has been used to simulate desert albedo. Equation (2) was then used to change the zonally averaged land albedo in going from the control case to the solar case. The values for f by zone are given in Table 2.

Possible Climatic Impact of Large-Scale Solar Thermal Energy Production*

Gerald L. Potter and Michael C. MacCracken

The Lawrence Livermore Laboratory's second generation zonal atmospheric model (ZAM2), because of its particular suitability, has been applied to the scenario previously developed by Davidson, Grether and Weingart (these Proceedings). See Ellsaesser et al. (1976) for a brief description of the model. The model has recently been used to study the possible climatic impact of various surface perturbations (Potter et al., 1975; Ellsaesser et al., 1976) and of changes in the solar constant and atmospheric composition (MacCracken and Potter, 1975; MacCracken, 1975).

For this study the boundary conditions of ZAM2 were modified to simulate the alteration in the zonally averaged land surface to the extent of the large areas that might be used for solar energy production. As in previous studies, the annual average version of the model was used; the results should be viewed as preliminary, and as indications of the possible sign of the climatic changes, not as accurate quantitative changes.

Davidson, Grether and Weingart have provided ZAM2 with the appropriate fractional land coverages and the albedo values expected to be indicative of the solar thermal collectors. The sea level land surface albedos from 50° N to 40° S latitude were reduced appropriately. No other modifications of the surface were allowed even though such surface interaction coefficients as runoff, evaporation and surface roughness could also have been adjusted.

Figure 1 shows the latitude-height change in atmospheric temperatures (solar collector minus control case). As might be expected, the troposphere warmed because of the increased absorption of solar radiation. The maximum warming occurred over the latitudes of largest coverage of solar collectors (20° to 40° N and 20° S) in the upper troposphere. A similar (but opposite sign) change, reported by Ellsaesser et al. (1976) above the subtropics when he increased the subtropical desert albedo, is best explained by the effect of the warmer earth on evaporation, atmospheric water vapor content, and moist adiabatic lapse rate.

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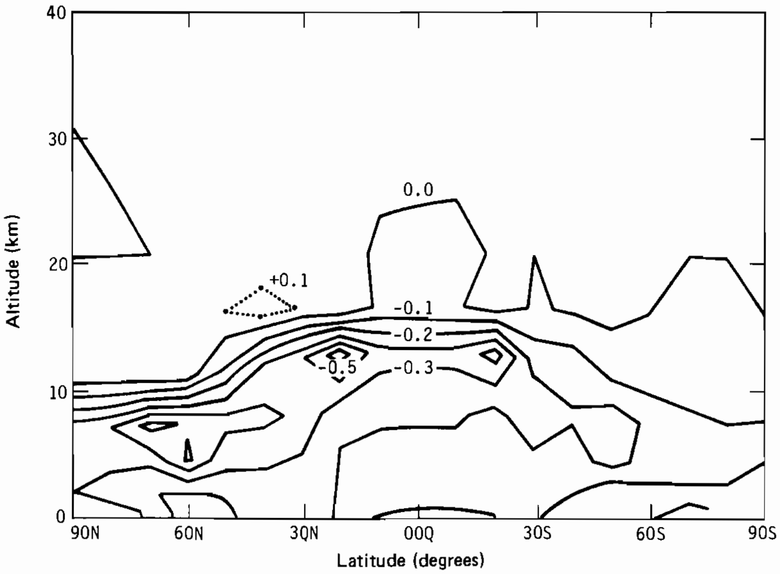

Figure 1. Temperature difference (perturbed minus control). Contour interval = 0.1.

Figure 2 shows the temperature change for the surface with the maximum increase occurring at 80° N (1.4 K). This is consistent with previous global perturbation experiments (MacCracken and Potter, 1975) where the polar regions exhibited the maximum effect, whether cooling or warming. The primary causes of polar region sensitivity are the strength of the surface inversion, water vapor feedback, and ice-albedo feedback mechanism. In the solar collector perturbation run, the sea ice at 80° N retreated, and decreased snow coverage occurred at several other latitudes. The surface warming for the latitudes 50° N to 40° S is due primarily to the increased absorbed solar radiation. The surface cooling at 50° S appears to be related to the fact that the model does not yet reach equilibrium at this latitude. This is a local effect and apparently does not influence other latitudes.

In addition to the surface temperature calculation, the model computes the temperature just above the surface at 1000 mb. Figure 3 shows the maximum warming at 30° N and 80° N. The subtropical maximum corresponds well with the surface warming.

Table 1 is a summary of the globally averaged surface energy balance components (daily values averaged over 7.5 days). For the solar collector simulation the flux of sensible heat was reduced slightly, but the evaporative flux increased. The Bowen ratio (sensible/latent heat flux) therefore decreased slightly. This corresponds to the increased capability for evaporation with warmer temperatures. The surface of the earth as a whole warmed by ∿ 0.1 K, but the effective outgoing radiation from the surface decreased slightly. This can be explained by the increased water vapor content of the atmosphere (Figure 4) and the ensuing increased atmospheric back-radiation. The slight imbalance is an indication that equilibrium was not completely achieved.

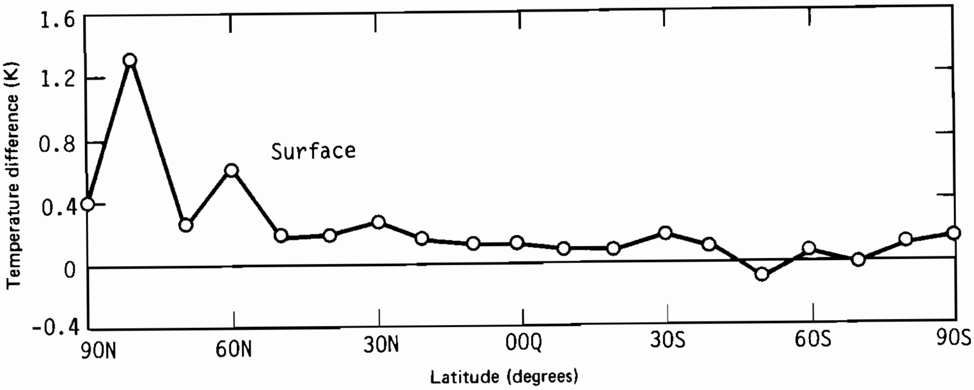

Figure 2. Temperature difference (perturbed minus control).

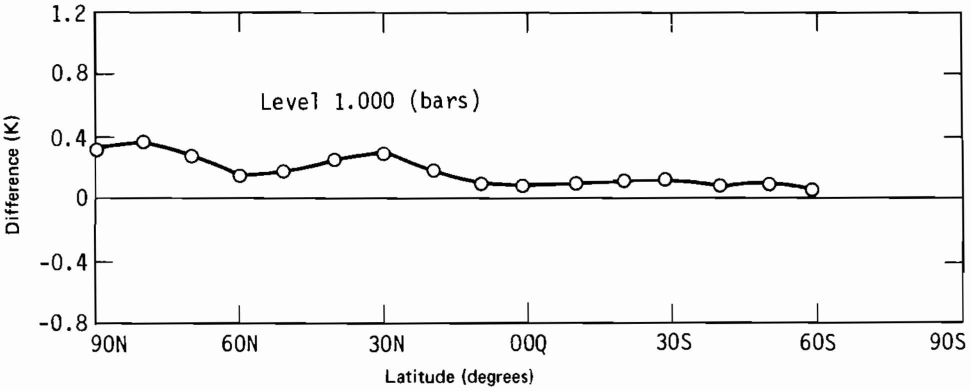

Figure 3. Temperature difference (perturbed minus control).

Table 1. Global surface energy balance (cal cm^{-2} day^{-1}).

	Control	Solar Collector
Sensible Heat	- 34.60	- 34.53
Evaporation	-199.12	-201.13
Terrestrial	-153.06	-152.72
Solar	386.59	388.02
TOTAL	- 0.19	- 0.35

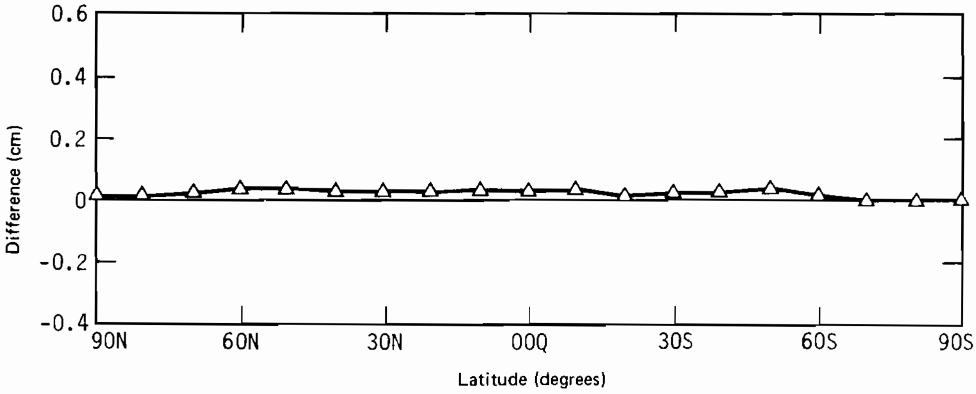

Figure 4. Precipitable water difference (perturbed minus control).

Table 2 is a summary of the global water balance. The slightly higher evaporation and precipitation rates for the solar collector case are indicative of a warmer planet. Although the model water residence time is shorter than the observed estimate (∿ 10 days), the change in residence time does show that the cycle time of water in the atmosphere is slower. It should be noted, however, that for the control case precipitation exceeds evaporation and for the solar case evaporation exceeds precipitation. This anomaly shows that the model has not quite reached a true equilibrium.

Table 2. Global water balance.

	Control	Solar Collector	
Evaporation	.332993	.336340	cm day^{-1}
Precipitation	.333124	.335948	cm day^{-1}
Total water column depth	2.4786	2.5042	cm
Residence time	7.44193	7.44662	days

Precipitation is calculated over each separate land type and then averaged to give the zonal average. Figure 5 shows the change in precipitation, with the maximum increase occurring in the latitudes having the largest area of solar thermal collection facilities (and therefore having the largest surface albedo change). The increases are due to the warmer temperatures increasing evaporation and convective activity. The increase at 50° S is probably related to the nonequilibrium conditions discussed earlier.

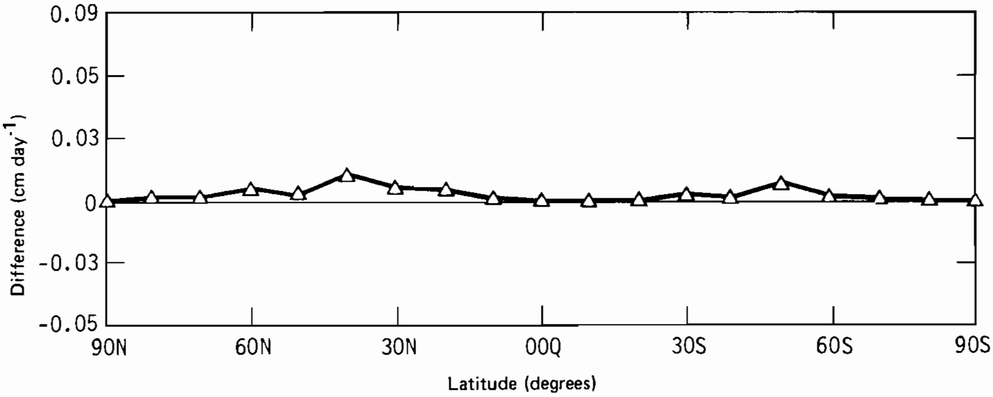

Figure 5. Difference in precipitation (perturbed minus control).

Figure 6 shows the latitude distribution of precipitation for the land fraction only. The maximum increase in precipitation occurred in the Northern Hemisphere subtropics. It is interesting to note that the data for Figure 6 represent the daily average precipitation for a period of four months. The precipitation high from Figure 5 at 50° S is not apparent from this longer record, indicating the transient nature of that local anomaly.

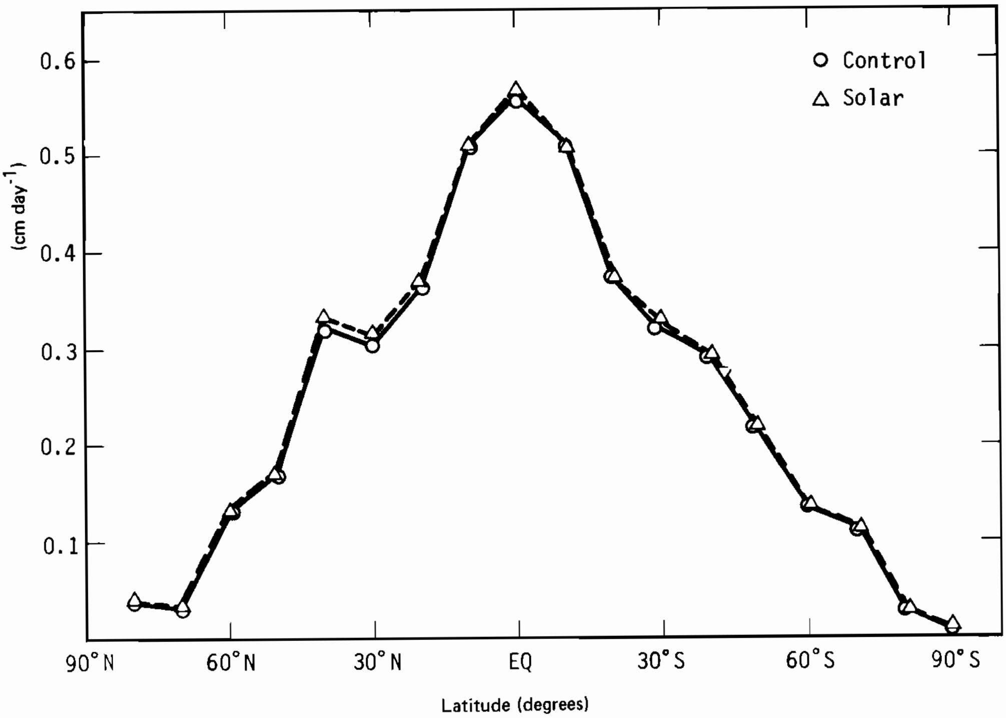

Figure 6. Daily average precipitation averaged over four months.

Significant conversion of potential to kinetic energy (indicating large upward vertical motion) in the model atmosphere occurs only in the three latitude bands 10° N, 10° S, and at the equator. Differences in the conversion of potential to kinetic energy (Figure 7) show a reduced intensity, indicating a decrease in the strength of the Hadley cell and a slight northward shift of the intertropical convergence zone (ITCZ). This is corroborated by the meridional advective transport of sensible heat (Figure 8). Sensible heat transport is considered positive northward, so that at latitudes 5° N and 15° N the equatorward heat flux across these latitudes by mean motions decreased. The northward flux in the Southern Hemisphere tropics, however, increased.

The ZAM2 model was used to estimate the climatic effects of large-scale solar thermal power facilities . The results appear to be consistent with other numerical experiments. The model response can be summarized by tracing through a feedback loop: decreased surface albedo → warmer surface → increased evaporation and increased convection → increased precipitation in the subtropics and increased water vapor in high latitudes → increased surface temperatures at high latitudes → decreased equator-to-pole temperature gradient → decreased Hadley cell intensity → possible northward shift of the ITCZ. The experiment also resulted in a warmer upper troposphere, particularly over the latitudes of maximum area of albedo change. The response was noted in Ellsaesser et al. (1976). The increased surface energy subsequently increased surface absolute humidity, which in turn displaced the convective parcel ascent curve to the right (indicating more water vapor and latent heat release), making the lapse rate less steep and warmer where the water vapor content was lowest.

It should be noted that ZAM2 has previously been shown to duplicate quite well the results of a 3-D GCM for large surface perturbations; this is important because it is questionable whether experiments looking at such small changes in local albedo as reported here would be possible given the synoptic variability inherent in 3-D models.

ACKNOWLEDGMENT

The authors wish to acknowledge Drs. Donald Grether, Mark Davidson, and Professor Jerome Weingart for providing the scenario for the model experiment.

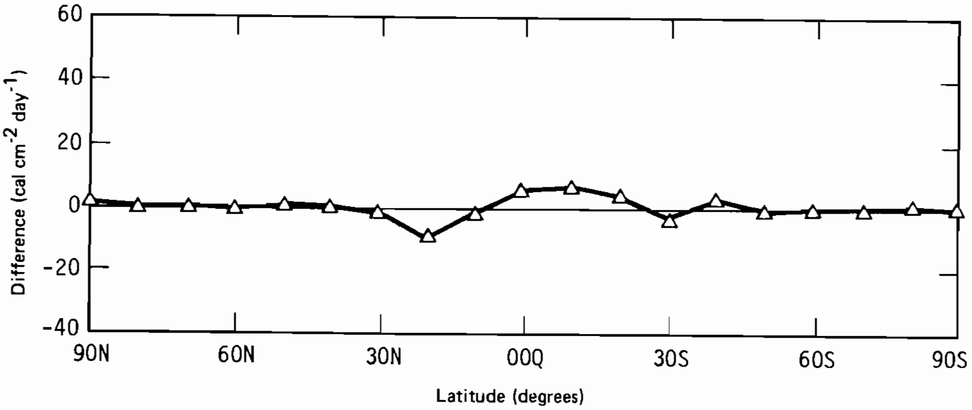

Figure 7. Difference in conversion of potential to kinetic energy (perturbed minus control).

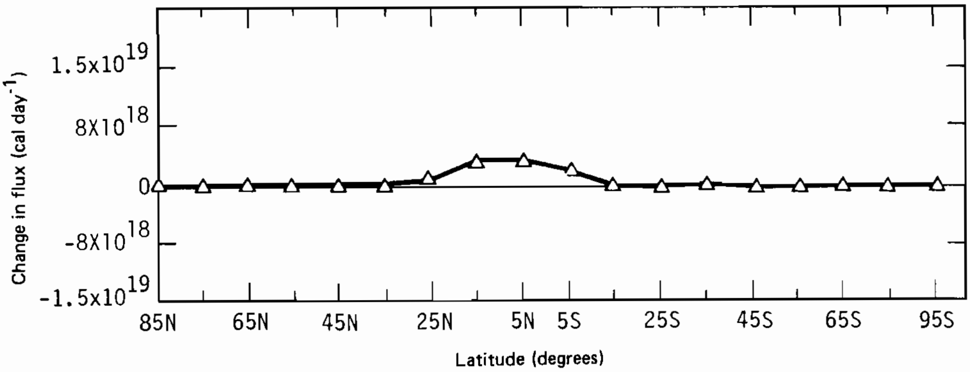

Figure 8. Difference in northward advected sensible heat (perturbed minus control).

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Possible Impacts of Large Solar Energy Systems On Local and Mesoscale Weather

Chandrakant M. Bhumralkar

INTRODUCTION

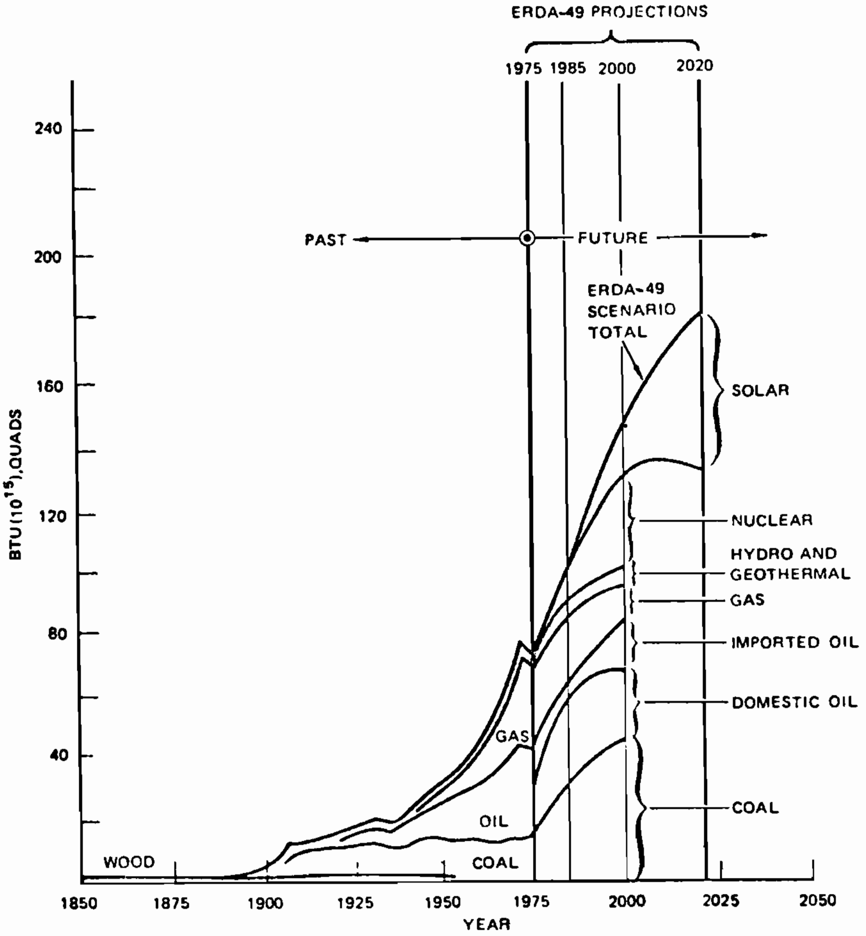
Limitations to Solar Energy Utilization

The sun's radiant energy arrives at the earth with a power density of approximately 1kW/m^2 normal to the sun. Atmospheric attenuation, clouds, and the day-night cycle reduce the long term average to less than a quarter of this figure. Nevertheless, the enormity of the total energy reaching the earth from the sun is evident. The question inevitably arises: why has solar energy been exploited only for special-purpose applications? The answer is twofold. Although solar energy is abundant, it is extremely dilute--its flux density onto the earth is only 1/500th of that onto the surfaces of a modern steam boiler. *This makes collection and conversion of solar energy a very costly process.* Moreover, the density of solar energy at any place on the earth is variable in time, which makes *energy storage an added requirement.*

Future Plans for Utilization of Solar Energy

The Energy Research and Development Administration (ERDA) in the USA, created in 1974, has prepared a comprehensive plan for energy research, development, and demonstration. The plan is designed to achieve solutions to the energy supply system and associated environmental problems in (a) the immediate and short term (to the early 1980s); (b) the middle term (the early 1980s to 2000); and (c) the long term (beyond 2000).

The research, development, demonstration, and commercialization (RDD&C) goals of ERDA for solar energy are contained in the report, ERDA-49. The program projects that 45 × 10^{15} BTUs (45 quads) could be supplied from solar energy by the year 2020. By comparison, in 1975 the USA used about 75 quads of energy total, of which more than 75 percent was derived from petroleum and natural gas. Thus, the ERDA-49 plan would require the creation of a comprehensive solar energy industry in 45 years, which will supply as much energy as that supplied by present petroleum and natural gas industries combined. In addition, the ERDA-49 plan projects a nuclear industry which will supply more than 30 quads of electricity annually as compared to 2.2. quads last year, with fossil fuels making up most of the rest. The ERDA-49 plan is depicted in Figure 1; the solar energy component is outlined in Table 1.



Note: The ERDA-49 program has projections through the year 2020 for the total scenario (180 quads), for the solar component (45 quads), and through the year 2000 for the other energy supply sources.

Figure 1. US past energy supply and projections of the ERDA-49 program.

Source: Reuyl et al., 1976

Need to Assess Atmospheric Effects of Solar Energy Systems

If implemented, the solar energy component of ERDA-49 is of such massive proportions that its potential for atmospheric and other consequences is enormous. Evidently, the implications of the solar energy program, in particular, and the entire energy program, in general, must be addressed. An assessment of the choices offered by solar energy technologies when compared with nuclear and fossil fuel alternatives should be made.

Table 1. Estimates of energy and fuels to be supplied in the US by solar energy.

Source: Energy Research and Development Administration (1975).

	1985	2000	2020
Direct Thermal Applications (in units of Q = quads = 10^{15} BTu/a)			
Heating and Cooling	0.15	2.0	15
Agricultural Applications	0.03	0.6	3
Industrial Applications (Process Heat)	0.02	0.4	2
Total	0.20	3.0	20
Fuels from Biomass Conversion	0.50	3.0	10
Solar Electric Capacity, GW(e)			
Solar Thermal	0.05	20	70
Photovoltaic	0.10	30	80
Wind	1.00	20	60
Ocean Thermal	0.10	10	40
Total Electric Capability	1.30	80	250
Equivalent Fuel Energy	0.07	5	15
Overall Energy Equivalent in quads	1	10	45
Total Projected US Energy Demand	~100	~150	~180

ASSESSMENT OF INDIVIDUAL SOLAR ENERGY TECHNOLOGIES

General

To carry out the role as mandated by the US Congress, ERDA has prepared a National Solar Energy Plan whose major goal is to develop, demonstrate, and introduce, at the earliest feasible time, economically competitive and environmentally acceptable solar energy conversion (SEC) systems to meet a significant amount of the national energy requirements. Figure 2 summarizes the alternatives for making electric power from solar energy; some of the alternatives mentioned involve the exploitation of energy stored in water, wind, or life, while others involve the exploitation of sunlight itself. The current ERDA solar energy program focuses on the following eight solar technologies: solar heating and cooling, solar thermal electricity, solar total energy systems, industrial and agricultural applications, photovoltaic (PV) cells, wind energy conversion (WEC), ocean-thermal energy conversion (OTEC), and biomass conversion.

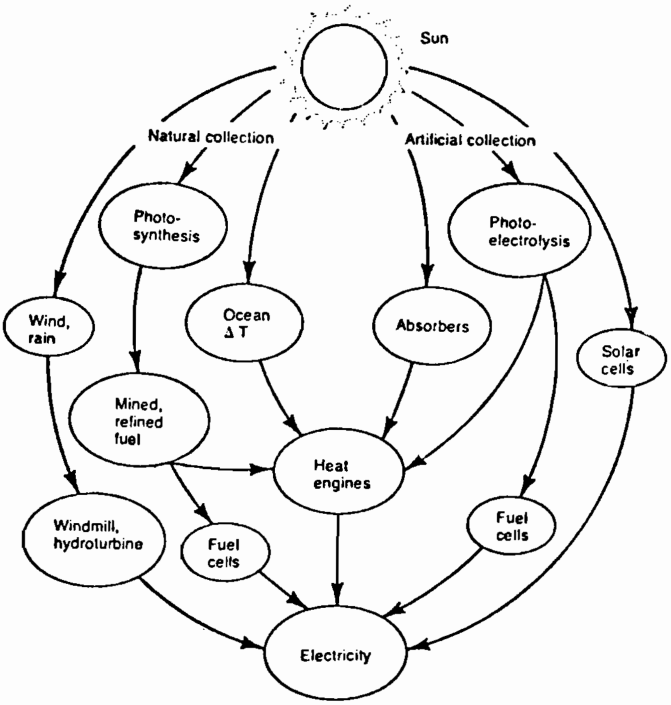


Figure 2. Alternatives for making electric power from solar energy.

Source: Goodenough, 1976

Keeping in view the potential impact of the above technologies on local and mesoscale weather/climate, I plan to consider the following four technologies in some detail: solar thermal electricity, OTEC, WEC, and bioconversion systems.

Solar Thermal Electricity

The basic concept underlying solar thermal electric power generation is the utilization of solar radiation to heat a working fluid to a high enough temperature so that it can be used either directly or indirectly to power a turbine which will in turn drive an electric generator.

To attain the high temperatures required for this application, concentrated, focused, direct solar radiation is necessary (diffuse radiation cannot be focused). Two methods exist for attaining these requisite temperatures: the central receiver system, and the distributed collector system. Both systems require the performance of all of the following functions:

- Collection and focusing of solar energy;
- Conversion of solar energy to thermal energy in a working fluid;
- Thermal energy transport to heat engine;
- Conversion of the thermal energy to electrical energy;
- Rejection of thermal energy not used in the conversion process; and
- Energy storage to cover the period when direct solar radiation is not available.

The conversion of the thermal energy to electrical energy involves the transformation of heat from the superheated steam, usually accomplished by means of a steam Rankine cycle plant. Figure 3 illustrates schematically a Rankine electric power generation plant; it also shows one of the techniques (cooling tower) by which the waste heat is ejected into the atmosphere. Evidently this is one aspect of solar energy systems that can have impact on local or mesoscale weather.

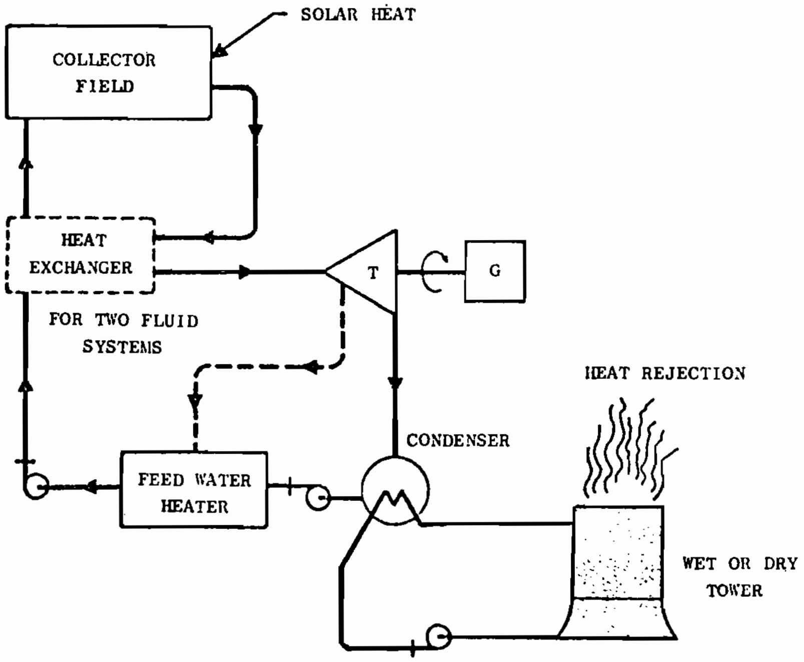


Figure 3. A Rankine electric power generation plant.

Source: Energy and Environmental Analysis, Inc., 1976

Ocean Thermal Energy Conversion (OTEC)

The ocean is a vast collector of solar energy, converting and storing it as heat. Between the tropics of Cancer and Capricorn, the surface of the ocean reaches a steady temperature of 25°C, and at depths as shallow as 1000 m in some locations, glacial melt migrating to the equator from the polar regions provides a nearly infinite heat sink at about 5°C.

The basic operating principle of an OTEC power plant makes use of this infinite heat sink by extracting electric power from a heat engine operating across part of the temperature difference between surface and deep sea water. The warm surface water is pumped through an evaporator containing a working fluid (e.g., ammonia) in a closed Rankine-cycle system. The vaporized working fluid drives a gas turbine which provides the plant's power. Having passed through the turbine, the vapor is condensed by colder water drawn up from deep in the ocean. No fuel of any kind is used; the enclosed working fluid is evaporated and continuously condensed by the warm surface and colder deep ocean water (Figure 4).

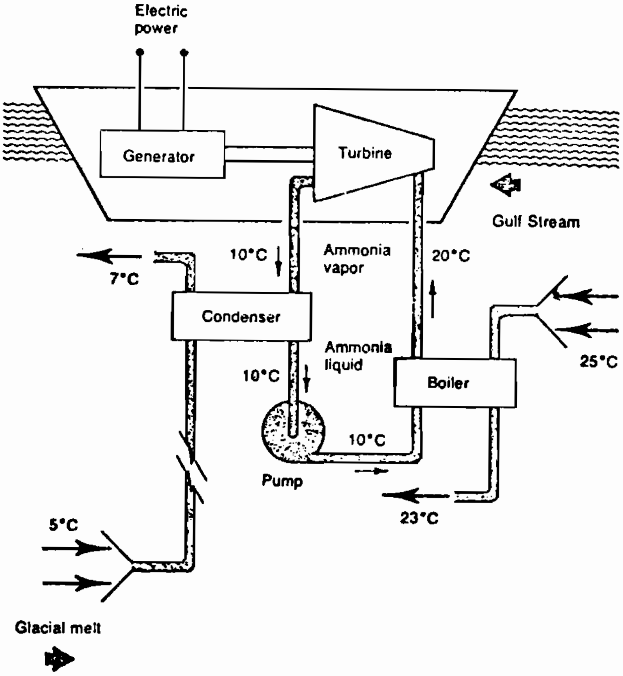


Figure 4. Ocean thermal energy conversion system.

Source: Goodenough, 1976

Though the basic thermodynamic principle underlying OTEC was established a long time ago, the OTEC technology must still be considered in its infancy, requiring more research before it can contribute significantly to the world's energy needs. The main difficulty with the OTEC technology is that, although there are enormous amounts of available energy, the conversion efficiency is very low (~5 percent at best). The temperature difference is small, implying the need for large flows of water. Also, there are a host of engineering problems.

Wind Energy Conversion (WEC) System

It is expected that by 1985, horizontal axis wind machines will be in use for electric power production. As with other solar energy applications, there are problems entailed in interfacing wind systems with existing utility grids, and with storage. WEC systems are contemplated with individual machines ranging in power output from 50 to 3000 KW(e); clusters will generate power in the multimegawatt range.

The general theory of the WEC system is that the power contained in a moving wind stream is proportional to the first power of both the air density and the area of the wind stream, as well as proportional to the third power of the wind velocity. In terms of a wind machine with blade diameter D, the power P can be calculated from the equation

$$P = k\, D^2\, V^3 \quad ,$$

where k is a parameter that depends upon the system units used, and V is the wind velocity.

Unfortunately, the maximum extractable power is considerably smaller than the total available power. The power that may actually be recovered from a wind machine is a function of a number of variables including the wind speed itself.

The theoretical maximum efficiency for a given wind speed is about 60 percent. This optimum point is found by maximizing both the volume flow and the pressure drop across the blade with respect to blade design and total area parameters. Empirical evidence has shown that actual efficiencies of 47 and 35 percent have been found for horizontal and vertical axis wind machines, respectively.

Bioconversion Systems: Fuels from Biomass

The objectives of the Fuels from Biomass Subprogram, contained in the ERDA Solar Energy Development Program, are to develop and demonstrate the economic and technical feasibility of using essentially inexhaustible agricultural and forestry residues, producing terrestrial and marine biomass which are converted into clean fuels, petrochemical substitutes, food, and other energy-intensive products. The sources and possible conversion involving three processes that concern solar technology of biomass are described below.

Sources of Biomass

There are three types of sources of biomass: terrestrial biomass growth, marine biomass growth, and biomass residues.

The cultivation of terrestrial biomass is a practice with a long history. For "farming" a biomass energy plantation, the stress is on yield and not on crop type because a pound of most dry plant matter has a heat value of 7500 to 8000 BTUs, irrespective of species. Biomass suitable for energy conversion may include agricultural crops, grasses, and trees. The use of trees for an energy feedstock holds certain advantages over the use of agricultural crops; trees are able to withstand a wide range of climates and require less intense soil preparation.

Whatever farming scheme is employed, the biomass plantation will require substantial land area. For example, to support a 100 MW electric facility with wood, an energy plantation is needed consisting of a hardwood species capable of yielding 5 dry tons of growth per acre-year. The following parameters are then assumed: utility runs at 70 percent capacity; 8500 BTU/lb (dry wood); 12,000 BTU (wood)/kWh; and trees harvested on a four-year cycle (yielding 20 tons/acre/day).

To fuel the plant for one year would require harvesting an area of 350 mi^2. Since this is only one-fourth the growing area of the plantation, the total size would be around 1400 mi^2. Four such energy plantations would occupy approximately 1 percent of the total harvested farmland of the entire US (in 1975 this was about 333×10^6 acres).

The role of the "energy farm" as a contributor to the energy needs is limited only partly by the availability of land and water resources. *Given the basic low efficiency of the photosynthetic process, and the simultaneous importance of plants as a food source, there is sufficient reason to doubt the practice of any major effort that diverts land from existing or potential food production.* While it is possible that the production of energy may compete with the production of fiber, it is economically unfavorable at this time.

Even though the oceans cover 70 percent of the earth's surface and receive over one-half its natural insolation, the farming of marine biomass has never been realized to an appreciable extent. For marine farming, seaweeds represent the principal crop that can be cultivated on open ocean rafts. Considerable difficulties stem from the design characteristics which must be able to counter stresses of open-ocean environment.

Biomass conversion schemes have made wastes (e.g. municipal and agricultural) an attractive energy source. Direct combustion of biomass continues to supply energy to such industries as paper and sugar mills. However there are practical limitations such as collection and existing utilization practices.

Conversion Processes

There are four conversion systems associated with conversion of biomass to energy: thermochemical systems, bioconversion systems, direct combustion, and direct hydrogen production.

Thermochemical processes for converting biomass to liquid or gaseous fuels essentially involve the elimination of oxygen and the addition of hydrogen to organic compounds.

Bioconversion is a term used to denote biomass conversion processes that are accomplished through action of micro-organisms. There are two types of bioconversion processes: anaerobic digestion, and alcohol fermentation. Overall, these processes consume more energy than the net energy produced.

Of all the conversion processes available for biomass conversion, direct combustion is the most familiar. The overall thermal efficiency of the direct combustion process producing electricity is about 38 percent, which implies that about 60 percent of the heat energy is dissipated into the atmosphere.

If wood is to find use as a source of electrical energy, major forest growth will be needed to supply a reasonably sized generating facility. It has been calculated that a 400 MW steam electric plant might be supported by a plantation of 370 mi^2. Estimates for a 1000 MW plant have ranged from 600 to 2000 mi^2. A self contained coal-fired facility occupies about 1.6 mi^2. A likely hindrance to the development of wood-powered electrical generating plants would be the enormous land requirements involved.

However, the use of wood is not restricted to electric generation. The forest industry normally uses 10 to 20 percent of its process steam energy for electrical production, while the remainder is used for drying, heating, and hot pressing. Not having to convert all of the BTUs from the fuel into electrical energy greatly improves the overall efficiency of the operation. Steam generated from wood or bark can be run through a turbine and then exhausted for use as process steam, rather than wasting the heat in a condenser. Under these conditions, the relative efficiency of heat recovery from fuel combustion can reach 75 percent.

CHARACTERISTICS OF SOLAR ENERGY SYSTEMS WITH POTENTIAL FOR IMPACTING LOCAL AND MESOSCALE WEATHER

Solar Thermal Electricity

Simply stated, a solar thermal plant would capture a part of the incident solar radiation and convert it to waste heat and usable electricity.

I give here some range estimates of potential energy balance effects, and compare them to known circumstances of heat balance perturbation due to human activities.

First it is important to examine the operating conditions of a "typical" plant. A typical solar thermal power plant, producing 100 MW(e), utilizes approximately 1 mi^2 of land, about 40 percent of which is covered with more then 30,000 heliostats. The heliostats intercept a considerable portion of the solar radiation incident on the plant, some of which is reflected back to the atmosphere, some is converted to useful electricity, and the rest is lost as waste heat from heliostats, cooling towers, etc. *The implication of this is that, depending on the size and number of solar thermal energy plants, local climate and terrestial conditions could be changed.*

Table 2 shows some general effects of a solar power plant on the net energy flow at the earth's surface.

Table 2. Estimated impact of solar thermal energy conversion on plantwide surface.*

Without Solar Powerplant				
Reflection,	30%	≃	shortwave radiation,	30%
Soil Absorption,	70%	→	longwave radiation,	35%
		→	heat convection and conduction,	35%
With Solar Powerplant				
Reflection,	22%	≃	shortwave radiation,	22%
Soil Absorption,	42%	→	longwave radiation,	21%
Waste Heat Generation,	28%	→	heat convection and conduction,	49%
Electricity Generated,	8%	→	off site thermal	(8%)

*Estimates are made with respect to incident solar radiation at a desert site for an intermediate load plant.

Without the power plant, the energy returned to the atmosphere is about equally split between shortwave, longwave, and heat emissions. With the solar power plant in location, it is expected that the effective reflectivity or albedo will drop from 30 to 22 percent--a large change, but perhaps not outside the range of natural limitations for sandy soil. Absorption by the soil will be lessened and the soil temperature should be somewhat lower. The balance between shortwave and longwave radiation will remain about the same, but the *relative role of convection and conduction will increase considerably*. Approximately 8 percent of the incident radiation will be converted to electricity and removed from the site via transmission lines.

To interpret these results it would be useful to identify an existing, man-made condition similar to that depicted in Table 2 for the solar power plant operation, and to review the impact under the existing situation. Putting aside about one-half of the heat convection and conduction losses of the power plant scenario, longwave, shortwave, and convective losses would be nearly equal with the baseline "no solar power plant" case, but the total amount of energy would be less. Such a condition could occur in a natural setting with inherently less incident radiation, i.e., a location further north of the equator.

However, under natural conditions such a location would not discharge the additional *convective* and *conductive* heat. The occurrence of excessive convective and conductive heat is similar to urban environments with large heat discharges due to fuel combustion. One might therefore compare the "solar power plant" heat and radiation impact to the impact of urban and industrial areas and their associated heat-island effects.

Table 3 mentions the types and magnitudes of effects of urban heat-islands which may be associated with multiplant large-scale solar thermal energy development.

Table 3. Effects of urban heat-islands.

Temperature	
Annual mean	1.0 to 1.5°F higher
Winter minima	2.0 to 3.0°F higher
Relative humidity	
Annual mean	6% lower
Winter	2% lower
Summer	8% lower
Cloudiness	5 to 10% more
Wind speed	
Annual mean	20 to 30% lower
Extreme gusts	10 to 20% lower
Calms	5 to 20% more

Of these observed effects, cloudiness and wind are likely to be significantly influenced by factors other than heat balance, such as pollution levels and structural roughness. Cities also exhibit greater precipitation and dust, yielding lower radiation.

The above calculations and interpretation should not be over-interpreted because the method used to arrive at these numbers is only approximated. It incorporated generalized assumptions about reflectivity and reradiation rates, and does not address the potential effects of diurnal patterns.

Besides the traditional environmental problems associated with any large-scale construction project (soil erosion, fugitive dust, noise pollution, and vehicle air pollution emissions), the normal operation of solar thermal energy conversion plants will impact atmosphere if wet-cooling towers are used. These towers may allow more than twenty tons of dissolved or suspended solids, including heavy metals, biocides, and other toxic substances, to be released in the atmosphere each year, depending on plant size. Localized ice or fog may also form from cooling tower drift.

The atmospheric problems associated with wet-cooling towers are not unique to solar enery; similar towers are also used with fossil fuel and nuclear plants. The technology of dry cooling has been developed as an alternative to wet-cooling applications, but dry-cooling systems are considerably more expensive.

Ocean Thermal Energy Conversion (OTEC)

The technology of OTEC is the least developed of all the solar technologies. Since French experimental plants built more than 40 years ago all failed to operate automatically, basic questions about material needs, plant design, site location, and operating efficiencies have not been clearly answered. Consequently, the potential atmospheric impacts of an operating OTEC plant are difficult to assess.

Besides the deposition of metallic and chemical elements in ocean water, the normal operation of an OTEC plant will also affect ambient water temperatures. The surface and deep ocean water that flows through an OTEC plant will be lowered or raised 1-3°C, respectively, which will cause a surface temperature drop in the ocean area surrounding the plant of possibly more than 0.5°C; such a temperature drop is well within the range of normal thermal variation. However, slightly lower ocean surface temperatures will lead to slightly lower local air temperatures owing to decreased evaporation losses. For a single OTEC plant impacting only 10 to 40 km^2 of ocean surface, the microclimatic effects would probably be insignificant. *However, if many OTEC plants were to operate in the same general ocean area, impacts on weather might be more significant.* Temperature anomalies at the air-surface interface of 2-6° over areas greater than 10^6 km^2 may affect global weather patterns. The local and mesoscale effects may be reflected in the variations in sea breeze phenomena. For example, the frequency and the time of passage of sea breeze fronts at coastal regions may be altered.

Pumping large quantities of colder deep ocean water to the surface will not only lower surface temperature but also alter the structure of oceanic mixed layer, which plays a vital role in the dynamics of air sea interaction and the consequent atmospheric oceanic phenomena.

Wind Energy Conversion (WEC) System

Microclimate Effects

Any analysis of microclimate effects must concentrate on the attenuation of the velocity of the air stream passing through the area swept out by the rotor blades. The attenuation will cover a planar area behind the rotors, which is larger than the area swept out by the rotors. Calculations for a 100 kW wind machine show that the wind reduction behind the rotors was at a maximum; for an 18 mph wind speed, it was about 6 mph. For incoming wind speeds in excess of about 25 mph, minimal wind speed reduction behind the rotors was calculated. Calculations were not performed for larger systems, but results should be similar in terms of the percentage increase in the wake area relative to the rotor diameter. Very small pressure and temperature reductions (about .07" of H_2O and .03°F, respectively) were calculated at the point of maximum wind velocity reduction.

Wind systems can act as wind barriers in a positive sense. Wind barriers are commonly erected (planted) in the Northern Great Plains states to reduce soil evaporation and erosion, and to increase soil temperature. Lowered speeds, however, can act negatively by allowing frosts to occur (due to decreased water evaporation), which would not occur under higher speed conditions. However, the computed wind reduction occurs at points high enough above ground level so that none of the impacts (beneficial or negative) discussed is likely to have much significance in the field. Reduced wind speeds at points above ground level should affect snow and rain accumulation to some degree. The magnitude of such an effect is uncertain at this time.

Biomass Conversion

Biomass conversion is a general term which encompasses several different kinds of solar technologies with widely differing environmental impacts. For the sake of simplicity, potential impacts will be divided here into those expected from the production/collection of biomass sources and those expected from the conversion of those sources into electrical or chemical energy.

The single most important environmental problem related to biomass production will be the use of limited resources. The amount of biomass available for energy conversion on any particular parcel of land is dependent on fertility; however, more fertile land will also be more valuable for food or fiber production. More than 1000 mi^2 of woodland may be needed to continuously fire a 100 MW(e) plant.

On the other hand, biomass may be collected from land primarily devoted to other purposes. For instance, steam generators could be fueled from residues from agricultural or lumbering operations. However, the collection of such residues may deplete the soil's organic content, leading to other problems such as increased erosion and decreased productivity. The impact of these on microclimate is evident.

Increased erosion will add to another serious resource problem: water pollution. Both fertilizer use and sediment runoff pose water quality problems near any large-scale agricultural activity. *Moreover, deforestation may cause thermal pollution problems on local waterways and on land because of reduced shading.*

The direct combustion of biomass, particularly the burning of wood, should present no new problems other than those normally encountered in the combustion of fossil materials. In fact, since biomass has an inherently low sulfur and ash content, direct combustion should pose less serious air quality and land use problems than coal burning. However, increased CO_2 from burning biomass will have a bearing on radiative heat balance of the atmosphere and can be expected to affect weather.

The construction of a direct combustion unit will not cause environmental problems beyond those normally associated with the construction of any boiler installation. The major pollutant arising from the operation of the biomass conversion unit will be particulate matter emitted to the ambient air. The amount and nature of the particulates will depend on both the quality of the biomass combusted and the efficiency of the particulate removal system. These may act as condensation nuclei and affect cloudiness and rain in a given region.

Summary

The preceding discussion of actual physical characteristics of four different SEC systems has indicated that there is a potential for such a system to modify weather/climate, at least on a local (micro) or mesoscale.

In general, the installation of a SEC system can result in the alternations listed in Table 4.

Table 4. Effects of solar energy systems relevant to modification of weather climate.

Nature of Effect	Solar Energy System
Land Surface Alteration	o Solar Thermal Electricity o Wind Energy Conversion o Biomass Conversion
Energy Production and Waste Heat Release	o Solar Thermal Electricity o Wind Energy Conversion o Biomass Conversion
Atmospheric Contamination (gaseous and particulates)	o Biomass Conversion
Modification of Ocean Water	o Ocean Thermal Energy Conversion

These effects of SEC systems are similar to those caused by many human activities such as urbanization, energy production and waste heat released into the atmosphere through fossil-fuel or nuclear plants, and automobile pollution.

Since there are no currently existing solar energy power plants of a large capacity, the implications of the effects of SEC systems on weather/climate will necessarily have to be based on the knowledge of the effects of other comparable characteristics.

POTENTIAL IMPACT OF SEC SYSTEMS ON LOCAL AND REGIONAL CLIMATE

General

The atmosphere is a relatively stable system. The solar radiation that is absorbed by the planet and heats it must be (almost) balanced by the emitted terrestial infrared radiation that cools it; otherwise the mean temperature would change. This nearly perfect balance is the key to the changes that do occur, since a reduction of only about 2 percent in the available energy can, in theory, lower the mean temperature by 2°C and produce an ice age.

That there have not been wider fluctuations in climate is the best evidence that the complex system of ocean and air currents, evaporation and precipitation, surface and cloud reflection and absorption forms a feedback system for keeping the global energy balance nearly constant. Because of the delicacy of this balance and the consequences of disturbing, it is important that we attempt to assess the impact of solar energy systems on the ocean atmosphere system.

The radiation balance of the atmosphere is controlled, in one way or another, by the following: alterations in surface characteristics; thermal pollution; energy production and waste heat release; CO_2 from fossil fuels; particulates in the atmosphere; clouds; cirrus clouds from jet aircraft; supersonic transports in the stratosphere; and atmospheric oxygen.

The first *three* of the above factors have been identified as direct effects of SEC systems (Table 4). Therefore, by implication, it is perhaps safe to state that the SEC systems possess the potential for affecting climate.

Climatic Effects of Alterations in the Earth's Land Surface

The most important properties of the earth's surface that have a bearing on climate are discussed below.

Albedo

Reflectivity: Modification of the albedo of the ground for shortwave radiation (as in the case of solar thermal electricity and biomass conversion systems) brings about a change in the amount of energy available to heat the ground and the atmosphere just above the earth. This, in turn, changes the overall lapse rate of the atmosphere thereby affecting its stability; this essentially controls the occurrence or non-occurrence of various weather phenomena as well as the dispersion of pollutants in the atmosphere. For example, a decrease in surface albedo, as indicated in Table 2 for a solar thermal conversion system, usually would raise the temperature on the ground and therefore of the air just above it. The atmosphere thus becomes more unstable and as a consequence experiences increased vertical mixing.

Aerodynamic Roughness

This, together with stability of the atmosphere, controls the three-dimensional turbulence within the planetary boundary layer. Considering the importance of the boundary layer dynamics to the atmospheric processes, changes in the roughness characteristics such as those that would be caused by solar thermal, WEC or biomass conversion systems, can have effects on weather phenomena on a local and regional scale.

Heat Capacity and Conductivity

The smaller the heat conductivity and capacity of the surface, the larger the surface temperature during the day; the resulting increased lapse rate can cause greater vertical dispersion of pollutants and other atmospheric properties.

Availability of Moisture

Variations in the availability of water on the surface affect the portion of the sun's energy that is available for evaporation. For example, a decrease in the amount of moisture at the land surface (which can be caused by burning biomass or by paving the land surfaces for installation of reflectors/collectors) will cause lesser evaporation, and the resulting surface temperature will be warmer. The lesser evaporation will also affect the formation of clouds and thus precipitation at or downwind from the solar power plant.

Summary

Many of the activities concerning SEC systems can result in modification of the climate. In most cases, the effects are predominantly local and regional, with some global effects as well. Of obvious importance are those that affect the amount of heat available to drive atmospheric motions. It is not easy to appraise (on the basis of the state of the art) the effects of activities such as deforestation and pavement of land surfaces. These affect the apportionment of heat release from the surface between sensible heat--which is available to drive atmospheric motions--and the latent heat--which becomes available when vapor condenses and precipitation occurs. Since comparatively large amounts of heat are involved, this area should be studied in detail.

Climatic Effects of Energy Production and Waste Heat Release into the Atmosphere

Waste Heat Problem

Following the fundamental law of thermodynamics, waste heat has to be cast off during processes of energy generation and consumption. This waste heat is as much a climatic contaminant as are air pollutants in the atmosphere.

The amount of waste heat ejected into the atmosphere is basically governed by the thermal efficiency of the power plants; according to the current estimates, the amount of waste heat is roughly inversely proportional to the cycle thermal efficiency. In most efficient fossil-fired steam plants (with 40 percent efficiency), the ratio of waste heat to useful energy is 1·5:1. For certain light water reactor nuclear plants (with 32 percent efficiency), this ratio is 2:1; this implies that the amount of waste heat ejected at such nuclear plants is twice the amount of useful energy produced. As regards solar power plants, all indications are that, due to the very low efficiency of the SEC technologies, the amount of waste heat put into the atmosphere could reach very large proportions. According to an estimate made for solar heating and cooling, the electro-generation efficiency may be as low as 12 percent, and for biomass conversion systems the ratio of waste heat to useful energy may exceed a value of 3.

Estimates of Waste Heat

Calculations have been made for an area of roughly 350,000 mi^2 covering the northeast part of the USA where 40 percent of the national energy utilization occurs. It is estimated that thermal waste heat is currently ~1 percent of the absorbed solar energy and is projected to be 5 percent by the year 2000. Similar calculations, made for a 400 mi^2 area of the Los Angeles Basin, show that (based on fractionation between waste from electric power generation and from other sources) 15 to 20 percent of the total waste heat will enter the atmosphere. In comparison to the estimates of waste heat for the above relatively larger areas we could estimate that the waste energy at individual power plants can be as much as 46 percent of the solar energy absorbed at the ground.

The above estimates are generally applicable to cooling systems commonly used by power plants that utilize cooling towers to dissipate waste heat into the atmosphere.

Impact of Waste Heat on the Atmosphere

Waste thermal power is available to the atmosphere as either sensible heat (a dry-cooling tower) or a combination of sensible and latent heat (wet evaporative cooling tower). The latent heat is produced primarily through the generation of electrical power; it is dissipated by circulation through the cooling towers and is generally available to the atmosphere at higher altitudes than sensible heat and at some distance downwind of the source.

In order to assess the impact of waste heat released into the atmosphere, it is useful to compare: (a) the energy input in the atmosphere released from cooling towers, with (b) the energy production associated with naturally occurring atmospheric processes and (c) the anthropogenic energy sources such as urban heat-islands. A comparison of these three types of energy releases shows that on a mesoscale basis the energy released from cooling towers is much more concentrated than that released from either natural atmospheric processes or anthropogenic sources. *Therefore, the waste heat rejected from cooling towers has the potential for generating significant atmospheric effects such as cloud formation, augmentation of precipitation, and increased fog formation.* In the case of large-scale power plants, at times there may be severe weather disturbances such as thunderstorms or tornadoes. While it is difficult to specify the precise impact of quantities of heat released from cooling towers over small areas, there is sufficient evidence to suggest that cooling towers will have far greater impact on the atmosphere than any other type of cooling system that rejects waste heat into the atmosphere over larger areas.

Summary

In summary, heat is released into the atmosphere from various sources. These releases are largely concentrated in a small fraction of the earth's land area. Also, this additional impact of waste heat into the atmosphere occurs mainly at the local and the regional levels. In larger industrial areas (e.g., Eastern USA ~5 × 10^4 km^2), the merging of heat source areas seems doubtful at present. However, we must envisage a large extension of existing heat sources, and the creation of major new sources.

The main effect of the waste heat output on the local/mesoscale is the creation of a stationary three-dimensional heat-island. While the effects of waste heat on local climate have been established, there are still some uncertainties about possible effects on the regional and global scales essentially as a result of uncertainties in the amounts and locations of future power generation.

The information regarding atmospheric effects of waste heat derived from nonsolar energy technologies can be applied to solar energy systems, since the effects of physical characteristics associated with these are essentially the same as those applicable to other energy-generative systems.

Climatic Effects of Atmospheric Contamination Caused By SEC

Particulates in the Atmosphere

One of the most evident effects of a biomass conversion system--particularly the direct combustion system--is atmospheric contamination. Major pollutants include particles directly emitted during combustion and those formed in the atmosphere from gases emitted during combustion. Some estimates indicate that between 5 and 45 percent of all particulate matter in the atmosphere is produced through combustion.

The particulate load in the atmosphere affects climate in two ways:

- Particles change the radiation field by scattering sunlight; they may thus change the *albedo*. Particles also radiate energy in the infrared spectrum, thereby modifying the temperature structure of the surrounding atmosphere, and may significantly affect the static stability of the atmosphere.

- Particles acting as condensation nuclei can affect the processes of condensation in the atmosphere, resulting in clouds, snow, or rain.

From known distribution of particles in the atmosphere, it is seen that while the number concentration of small particles (< 0.1 μ radius) decreases with increasing altitude, the concentration of the large particles (~1 μ radius) shows a maximum at 18 km, suggesting that the particles (predominantly sulfates) are formed and reside in the stratosphere. Thus the impact of particulates formed by solar energy conversion on micro- and mesoscale climate may be minimal.

CO_2 Produced by SEC Systems

The impacts of burning biomass (particularly wood) for energy production are similar to those currently encountered in the combustion of fossil fuels; CO_2 is one of the by-products. Although CO_2 is a trace gas with a relatively small concentration (~320 ppm), it plays an important role in determining the temperature of the planet. Since CO_2 represents one of the components affecting the earth's radiation budget, changes in CO_2 concentration caused by SEC systems can produce changes in surface temperature and consequently in the static stability of the atmosphere. For example, it is projected that a doubling of the amount of CO_2 resulting from fossil fuel combustion, to the year 2000, might increase the mean annual surface temperature by 2°C. Note that these estimates are based on a crude computer model and do not take into account the dynamics of the atmospheric processes.

In summary, though the probability of direct climate change resulting from CO_2 is small, the long-term consequences could be quite serious; therefore, we must study the effects of CO_2 on climate.

Climatic Effects of Modifying Ocean Waters

The basic operating principle of an OTEC system involves the artificial upwelling of colder water from below, thereby changing the surface layers of the ocean. Since the surface layers of ocean largely determine the direct interaction between ocean and atmosphere, the potential impact of OTEC on climate is evident. For example, mechanical mixing of the ocean mixed layer (~150 m in thickness) would typically lead to a decrease in summer surface temperature by 4°C; this would change heat transport by ocean currents. The climatic effect of creating a small artificial upwelling could be quite large locally; it could include the formation of low level summer inversion and low level summer fog. It may be that mesoscale sea and land breeze effects could also be modified by installing an OTEC system.

The deep ocean water is a large heat sink, which is warmed by an OTEC system through thermal mixing; the structure of the ocean mixed layer is thus changed considerably. Since this heat exchange in the ocean has not been removed from the earth, it will perhaps make its presence felt in some way in the overall heat balance of the earth-atmosphere system. This is, however, speculative, and more study is needed to determine the climatic impact of an OTEC system.

There are two types of oceanic variations that could have an effect on atmospheric CO_2 and thus affect climate. One is the overturning of deep waters discussed above; this could bring CO_2 to the surface and release large amounts of CO_2 into the atmosphere in a short time. A change of surface water temperature over a relatively large area could influence the CO_2 balance between ocean and atmosphere.

POTENTIAL CLIMATIC IMPACTS OF SEC SYSTEMS

Based on the foregoing discussions, it is the author's judgment that significant climatic effects (local and mesoscale) of SEC systems may be caused by *alterations in the earth's land surface*, and by *energy production and waste heat release into the atmosphere*. Both factors produce effects which are analogous to those caused by the heat-island phenomena. Note that the effects of surface anomalies depend on latitude, aridity, and essentially on the climatic zone in which the SEC system is installed.

The assessment of the impact of SEC systems on the atmosphere can be made by studying and interpreting analogous events in nature such as heat-island effects and by simulated modeling. Analogies based on heat-island effects are extremely useful because of the repetitious nature of the event. Also, since they occur in various climates, a wide range of climatic regimes is available.

Mathematical models offer the most flexible means of assessing the relative importance of various factors which produce the total affect.

Table 5 summarizes the principal characteristics of the author's model; its versatility is specially evident in the treatment of ambient environmental interaction, horizontal wind, boundary layer processes, cumulus scale processes, and cloudiness--both convective cloud and large-scale.

The model is particularly suitable for studying atmospheric effects caused by differential variations in surface characteristics, temperatures, and moisture such as those that are likely to be encountered with solar energy systems.

The model can be used to simulate and analyze the atmospheric effects of solar energy systems, to cover the following scales:

- *Mesoscale* effects extending over a distance of a few hundred kilometers with a time scale of 6 to 12 hours;

- *Cloud scale*--extending over several tens of kilometers with a time scale of 1 or 2 hours;
- *Microscale* effects extending over several hundreds of meters, with a time scale of several minutes.

Table 5. Characteristics of mesoscale mathematical model

Characteristic	Model Treatment
Geometry	Rectilinear (two-dimensional).
Domain	Variable grid mesh-length, suitable domain 12 km high by 500 km long.
Environmental Inter-Action	Implicit, total cloud/environment interaction.
Horizontal Wind	Initial ambient wind is specified.
Boundary Layer	Surface aerodynamic roughness, heat and moisture transport.
Hydrodynamic Equations	Primitive, hydrostatic.
Treatment of Cloudiness	
- Large-scale	Implicit.
- Convective	Parameterized, based on vertical stability.
Cloud Microphysics	Liquid: Kessler condensation collection and evaporation. Ice: none (subgrid scale convection does not include microphysics).
Rainfall	Convective: directly parameterized. Large-scale: is a natural extension of in-cloud microphysical processes.
Perturbation	Temperature, moisture, horizontal convergence.

The first two of the above are applicable to the energy production and waste heat release associated with SEC systems, and the third is applicable to alteration of surface characteristics likely to be caused by a prospective SEC system.

This model has been applied recently to assess the atmospheric effects of waste heat rejected from conceptual large power parks at a single site, generating a capacity of 10,000 to 50,000 MW(e) near Baton Rouge, Louisiana, USA. The preliminary results indicate that significant weather modification can result from the development of the proposed type of power center.

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APPENDIXES

Appendix 1: Glossary of Technical Terms

In compiling the following glossary, we have attempted to avoid unnecessary use of jargon. However, since certain words and phrases are part of the technical shorthand of the climate and solar energy engineering communities, we have therefore defined them where necessary.

Air mass zero (AMO), air mass one (AM1) refers specifically to the spectral distribution of unscattered radiation. AMO radiation is solar radiation outside the atmosphere. AM1 is the solar radiation after traversing a clear atmosphere at normal incidence. "Air mass" is defined as the cosecant of the zenith angle, essentially equivalent to the total pathlength through the atmosphere, with the pathlength at normal incidence normalized to unity.

Albedo of an object is its reflectivity with respect either to a specific wavelength or to some wavelength distribution of radiation (such as AMO sunlight).

Bowen ratio is the ratio of the sensible heat flux at the surface to the latent heat flux at the surface.

Busbar refers to the output terminals of a power plant (the point prior to any transmission and distribution network).

Canopy is a distributed array of elements, mechanical or vegetative, which has the general appearance of building canopies in that the elements are characterized primarily by their horizontal extent.

Convective activity, convective cloud cover. Convection involves the vertical interchange of air masses, each with its store of heat, water vapor and momentum. The motion is in discrete masses or "eddies" of different sizes. The convection is either "free" when the air mass rises due to density differences with the surroundings, or "forced" when for example an air mass passes over rough ground. Forced convection can also be an aspect of mechanical systems, such as cooling towers. *Convective cloud cover* occurs when air parcels moving upward reach a level at which condensation can occur. Clouds developed as a result of convective activity usually develop through stages of small, medium and large cumulus to cumulonimbus, and heavy, showery precipitation is associated with the final stages of development.

Cryosphere is defined as the earth's ice masses and snow deposits.

Direct beam radiation is the solar radiation that arrives at the surface without undergoing scattering, absorption, or reflection. This radiation can be focused since it is highly collimated, with a beam spread corresponding to the apparent angular size (0.5°) of the sun.

Diffuse radiation is the solar radiation at the surface, which has been scattered from the atmosphere. This radiation cannot be focused, and in general will have a different spectral distribution than direct beam radiation.

Drag coefficient is a measure of the shearing stress or drag per unit horizontal surface area, generated by a given amount of wind.

Evapotranspiration involves the combined process of evaporation of water from the ground surface and the transpiration (loss of water from the stomata) from growing plants.

General circulation model (GCM) is a three-dimensional model of the general circulation of the atmosphere, using a time-dependent set of equations describing the detailed evolution of the dynamic and thermodynamic state of the atmosphere.

Ground cover ratio is a term used in connection with solar energy conversion plants. It is based on the ratio of surface area of solar collectors (heliostats, photovoltaic arrays, etc.) to the area of the land used for the siting of these elements.

Hadley cell, Hadley circulation. When the mean meridional (north-south) circulation of the atmosphere is derived, it is possible to observe a mean mass circulation in the tropics called the *Hadley cell* in which warm air ascends in equatorial latitudes and decends at 30°N (Northern Hemisphere Hadley cell) or at 30°S (Southern Hemisphere Hadley cell). This circulation *(Hadley circulation)* is important in maintaining the angular momentum balance of the earth-atmosphere system, the trade winds of the tropics, and the heat transport from low latitudes.

Heliostat comes from the Greek "helios" or sun. It is a mirror that tracks the motion of the sun, and is used in solar thermal electric power plants to concentrate sunlight on an absorbing unit to produce steam or heated gases.

Horizontal stress components the fluid moving over a level surface exerts a horizontal force on the surface in the direction of motion of the fluid. This force can be expressed per unit surface areas as a stress. Generally, the horizontal components considered are the east-west and north-south. This stress represents a flux of momentum from the fluid to the surface.

Hydrology is the study of water as a substance in the earth-atmosphere system. *Surface hydrology* refers to the balance among precipitation, evaporation, soil moisture storage, runoff, snowmelt or accumulation, at a given surface location.

Intertropical Convergence Zone (ITCZ) is the zone where the trade winds of the two hemispheres converge. The rising branches of the Hadley cells are in the intertropical convergence zone.

Lapse rate is the rate of change of temperature with height in the atmosphere.

Meridional temperature gradient is the rate of change of temperature with respect to distance in a north-south (meridional) direction.

Mesoscale refers to atmospheric systems with a spatial scale on the order of 20 to 500 km, and a time scale on the order of 1 to 100 hr.

Microscale refers to a spatial scale on the order of 0.1 to 1 km and a time scale of 1 hr. or less.

Photovoltaic means the direct conversion of light to electricity by solid state means specifically in devices called solar cells.

Planetary albedo is the total reflecting power of the earth, including the atmosphere. It is defined as the fraction of incoming solar radiation returned to space by scattering and reflection in the atmosphere, and reflection from clouds and the earth's surface.

Radiative balance is the difference between the net longwave radiation at the surface and the amount of incoming solar radiation absorbed at the surface.

Rankine cycle is defined as the thermodynamic cycle of modern steam turbines.

Roughness length is a hydrodynamic parameter which is a measure of the "roughness" or structure of a surface, and is distinct from roughness concepts arising from visual or tactile impressions of a surface. A lucid discussion of the physical significance of this parameter is beyond the scope of this Glossary (see McIntosh and Thom, 1969).

Synoptic refers to atmospheric events on the scale of cyclones and anticyclones, typically 1000 km and more, on the order of several days.

Turbidity refers to the atmospheric absorption due to the presence of aerosols (e.g. dust).

Appendix 2: About the Participants

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