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GLOBAL MODELING AND CLIMATE IMPACT ANALYSIS

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PREFACE

Reflecting views in the research community on the inadequacy of knowledge of the relationship of climate with human activities and the environment, the Scientific Committee on Problems of the Environment (SCOPE) has undertaken a project on "Improving the Science of Impact Study: A Review of the Theory, Methodology and Experience of Climate Impact Assessment." The purposes of this project are to review existing methods of climate impact study, develop new concepts and methods, and enlarge the pool of scientific talent engaged in impact study. The project began in mid-1980 and is expected to culminate with the publication of a SCOPE book in late 1982.

A set of about 20 papers has been commissioned for the initial phase of the study. This set includes papers on the basic assumptions of impact study relationships, on major past efforts at climate impact assessment, on our knowledge of the biophysical links between climate and specific sectors, and on societal adjustment to impacts. Techniques of analysis are also being examined. These range from historical studies, to economic approaches, to use of scenarios. Several papers will explore the possible usefulness of integrated, multi-disciplinary modeling and simulation for climate impact analysis. This paper focuses on "global" models. Complementary work will be undertaken on models emphasizing interactions at the regional level.

This paper and the other papers in preparation will be reviewed at an author's meeting scheduled for the autumn of 1981. Subsequently, the papers will be revised and synthesized into a single, coherent volume. For further information on the project, contact either the review coordinator, Prof. Robert Kates (Center for Technology, Environment, and Development, Clark University, Worcester MA 01610, USA), or Dr. F.

Kenneth Hare, chairman of the project's Scientific Advisory Committee (Trinity College, University of Toronto, 6 Hoskin Ave., Toronto, Ontario M5S 1H8, Canada).

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Jesse Ausubel
IIASA, Laxenburg, Austria
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Jennifer Robinson
IIASA, Laxenburg, Austria
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ABSTRACT

A sample of global economic and social system models are examined to ascertain how they might be utilized for climate impact analysis. General values and difficulties of global models as tools for climate impact are discussed. Special note is made of two models whose relatively strong biophysical basises appear to make them particularly compatible with climatological thinking. These and other global models are explored in terms of their time horizon, methods, and substantive focus. Possible contributions toward understanding climate in relation to agriculture, energy, demography, and politics are described. It is concluded that, despite the large number of difficulties with global models, models of some sort are required to investigate quantitative interrelationships of the global system, and that useful results could be extricated from existing models given imagination, critical awareness, and good scientific practice.

CONTENTS

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1. Introduction

In this paper I assume that you, the reader, are in the following situation: you want a global perspective on some aspect of social-climatic interaction; you find global calculations become too complex for the back of an envelope; you think it might be useful to bring in a global modeler and a computer; you do not know what model or models would be most appropriate to your needs, or whether you might do better starting from scratch, or whether you might get as much from reading about models as from having new work commissioned.

In the paper I discuss:

[1] general difficulties with global models as tools for climate impact analysis;

[2] general benefits that may be gotten from global models, especially by studying the literature (that is, without initiating new modeling work);

[3] lesser known global models that may be of particular value for climate impact analysis;

[4] what model might be useful for which climate-related topic, and why.

The bulk of the paper is devoted to the last question--which model for what. The question is treated by examining attributes that affect models' usefulness for climatic analysis, and discussing which models have particularly desirable -- or problematic -- attributes.

I use the term "global models" to refer to models including description of global aspects of human society. In this sense, the term could mean anything from very short term (days and weeks) war games to models of very long term (hundreds of years) models of anthropogenic influences on the earth's biophysical processes.

The paper covers the few dozen models I have become acquainted with in several years of work on global modeling. It is uneven. I do not know all the models equally well; descriptions cover both finished work and work in progress. However, the choice was between covering the small set of models I know well, thereby omitting models with potential high value--or covering the larger set unevenly. In the circumstances, unevenness seemed acceptable. The unfinished models are more problematic. Modelers often make major structural changes (such as deletion of sectors and omission of difficult to parameterize variables) during model construction. However, two models with exceptionally high potential for climatic impact analysis are now under construction and are not well documented. I could not see omitting them. Thus, all statements made about unfinished work must be regarded as tentative.

2. Global Models in General

2.1. Advantages

Formal models could be useful for climate impact analysis both scientifically and in applied terms. Use of models should encourage researchers to make their assertions about the impacts of climatic variability and change more precise and quantitative, and hence, more amenable to testing and improvement. In applied terms, formalization and quantification should help improve understanding of the relative magnitudes of various aspects of climate-related problems, and thus, to assist in developing priorities and identifying workable policies.

Moreover, specific questions pertaining to global climate impacts may be unapproachable without some sort of device for performing computation and organizing data. For example, it is difficult, without some sort of model, study complex patterns of events, such as co-occurence of large scale drought with economic disturbance, oil supply disruption or collapse of a fishery, or of different combinations and sequences of good and bad harvest years in different regions.

2.2. Difficulties

Global models have been constructed for various purposes. A few, such as agricultural buffer stock models, are implicitly related to climate. A few, such as the two models discussed in the next section, are well grounded in physical geography. With such exceptions, climate tends to be remote from the explicit structure of existing global models. Most global models do not include any climate variables or represent human activities as being affected by climate. Unless applied with imagination and judgement, they will be useless for climate impact analysis.

Moreover, in most cases, global model aggregation is inappropriate for looking at climatic questions -- at least from the perspective of a geographer, ecologist or meteorologist. In general, to look at social-climatic interaction, one would want a model that divided the earth into biologically and physically meaningful units. For example, it would be desirable to have a model that distinguished between land, water, and ice, as well as tundra, rain forest, desert, and savanna.

The analytic units of most global models are nations and groups of nations, and in general, model structure follows the availability of social systems data. They thus aggregate very dissimilar ecosystems, while drawing distinctions between regions of similar physical and biological geography, and their implicit coverage of the earth's surface area is extremely uneven. Coverage of planned economies and self-provisioning economies is weak. Coverage of natural systems is even weaker. All but a few percent of the activities which global models describe take place on the few percent of the earth's surface occupied by agricultural land and industrial settlements, while the models all but omit the oceans.

A very different sort of problem is that of testing, validation,* documentation, and, in general, the sociology of global modeling. Most global models are complex. A small one might have in excess of 50 equations, the largest have several thousand. There are no uniform standards for documenting or testing of such models. The extent to which each has been tested and documented has largely been left to the modeler's skill, judgement, and resources. In many cases minimum scientific *desiderata* have not been met, e.g., modeling experiments have been presented without sufficient description of the assumptions used to make the results reproducible, and validation exercises showing the models' ability to reproduce history have been based on the same time periods as those to which the model was parametrically tuned.

Furthermore, global modeling is a young field. Over the 1970's, much of the discussion of global models was polemicized and even acrimonious (see, eg. Oltmans 1974). Thoughtful comparison, evaluation and criticism of global models is not well advanced. The practice of employing different models to gain insight into different aspects of the system, and of testing and/or validating models through comparison with other models--as widely practiced in atmospheric modeling (see, e.g., Schneider and Dickinson 1974)--is rare.** Even works comparing different models' results for key system parameters and explaining the reasons for similarities and disparities, are scarce.*** Few modelers even know whether their models' projections for important variables are higher or lower than those of other models.

*I distinguish between validation and testing as follows: Validation includes all activities undertaken to ascertain a model's value as a representation of the system being modeled. Testing includes all activities undertaken to ascertain (but not necessarily evaluate) model behavior. Thus testing a model's ability to replicate observed behavior is both testing and validation; while sensitivity and structural tests are commonly conducted just to understand model behavior. Likewise, some validation exercises, e.g., description of a model's structural or parametric correspondence with reality, do not involve testing.

** Ethology seems to be on the atmospheric modelers' side here. Atmospheric models, because they all accept certain laws of physical motion, have a lot in common with one another. The features that differentiate one model from the next are clear and fairly easy to specify.

***refer to E.W. Center

The complexity of the models, combined with the low level of documentation, testing, and validation, and the primitive state of model criticism impairs the usefulness of global models. For example, international trade is extremely complex, and models use various simplifications for attempting to describe it (Neunteufel 1977, 1979). In assessing how a change in climate or an extreme climatic event may be transmitted through the international trade system, there is little hard advice to go on as to which trade formulation is most appropriate. Once model results are presented, it may be very difficult to sort out whether the findings are artifacts of the model's simplifying assumptions or attributes of the real system.

2.3. Exceptions

A few models currently under development have a strong biological and/or physical basis and are moving away from some of the difficulties described above. These include the model being constructed by the Laboratory of Mathematical Ecology of the Computing Center of the USSR Academy of Sciences (Alexandrov et al 1981, Krapovin et. al, undated, henceforth called the Soviet model) and the UNFPA/FAO/IIASA work on Land Resources for Populations of the Future in collaboration with IIASA (henceforth, UNFPA/FAO/IIASA).

The Soviet model, at least in its present formulation, has many of the characteristics of the Forrester (1971) and Meadows (1972,1974) models, World2 and World3. (As known from *World Dynamics* and *Limits to Growth.)* However, where Forrester and Meadows used broad generalities about natural systems, the Soviet model attempts to precisely describe specific biogeochemical cycles and energy flows. Moreover, where Forrester and Meadows were highly aggregate, the Soviet model proposes to treat the earth's land surface in great detail. The modelers' aim to parameterize the model for a 500 km^2 grid and to distinguish between major ecological communities. The team is attempting to find resources to back their model with extensive data collection and some field work. If they succeed, they may produce information that will be of use for other climate-related work. For example, model development may entail systematizing and mapping information on biogeography of photosynthesis in combination with information about photosynthetic response to enriched CO_2 atmospheres.

The Soviet model is constructed, deliberately, to be compatible with a zonal atmospheric circulation model. The latter takes into account the dependence of temperature and precipitation on anthropogenic activities and supplies to the carbon cycle model with temperature and precipitation change data. Thus, if satisfactorily developed, the coupled models may be an excellent tool for looking globally at biospheric response to CO_2 induced warming, or other long-term shifts in global climatic patterns.

Social system models are not unified by any common set of behavioral laws, and the differences between them are greater and harder to assess.

It remains to be seen how the social system side of the model will develop. The equations currently in the model follow closely the work of Forrester (1971). How the modelers will link the social system to the 500 km^2 biospheric grid and how the links between disaggregated parts of the social system (e.g., international trade) function have not yet been described.

The UNFPA/FAO/IIASA work (FAO/UNFPA 1979, Shah et al. 1981) is directed toward assessing, in detail, the population support capacities of the earth's surface. It is a major project; to date it has absorbed around 500 man years of labor. The assessment now covers all developing countries except China (which was not in the UN when the project began). The method employed involves detailed climate and soil inventories, which are used to investigate crop and livestock production potential and productivity losses through soil erosion under three levels of technological development. The agro-biological data base assembled in the effort is extremely rich. For example, a section of the study on Africa includes, for 18 food crops, estimates of the range of production for different levels of technological inputs, types and characteristics of soil, lengths of growing season, and temperature and rainfall regimes and soil conservation measures.*

As used by UNFPA/FAO/IIASA, the data base helps specify the cropping pattern most appropriate for various bioclimatic subdivisions of a country under different levels of technological inputs. The data base is highly disaggregated: e.g., the average African country is disaggregated into 660 units. It seems probable that the model could be used to examine climatic change by specifying shifts in land classification implicit in a given climatic change, and looking at the effects on production and cropping pattern. This would provide information on the type of cropping adjustment appropriate for a specified climatic change. As the data on photosynthetic response to CO_2 enhancement relative to water and nutrient status improves, the UNFPA/FAO/IIASA model will also be amenable to looking at the agricultural implications of changes in the chemical composition of the atmosphere. If supplemented with well-designed tests and systematic analysis of model results, the exercise could be extended to look at questions of resilience and vulnerability of cropping patterns altered for climatic change under different levels of technological inputs and soil conservation measures.

2.4. Global Models, Basic Global Trends and Climate Impacts

Climate impact analysis needs to take account of basic global trends that are likely to take place along with climate variation. For example, a credible study of the impacts of doubling atmospheric CO_2 must take into account that, by the mid 21st century, the global picture with respect to population, resources and enviornment will probably be very different from the current situation. Global modeling may help provide

* Maps published on the basis of the UNFPA/FAO/IIASA models are scheduled to be published by FAO by January 1982. These will cover the entire developing world except China. The data and computer programs will probably be attainable through either IIASA or FAO. (Personal communication, Mahendra Shah).

understanding of the human environment within which climatic change might occur within the next 2 to 12 decades. Despite much vocal disagreement about particulars, global modelers have come to broadly similar findings about agriculture, energy, and relationships between rich and poor nations (OTA 1981, Meadows, Richardson and Bruckmann 1981).

In agriculture, all global models that have represented limits to land availability and diminishing returns for agricultural inputs (e.g. fertilizer) have shown increasing stress in the global food system over the coming decades. That is, they show increasing food prices and increasing numbers of people with insufficient food. Likewise, regionally disaggregated models tend to show particularly severe agricultural stress in Southern Asia and non-OPEC Africa. Such forecasts relate to climatic change in two ways: First, presuming climatic change has adverse agricultural consequences, one can expect it to amplify incumbent agricultural stress. Second, stressed agricultural systems tend to be associated with intense exploitation of the unmanaged biosphere and shrinking total biomass. Because biomass is important in moderating microclimates, this implies more severe (desertified) microclimates. Reduced biomass also implies transfer of carbon from living organic matter and soil to other pools – predominantly, the atmosphere and the oceans.

With respect to energy, global models generally show the petroleum economy beginning to give way to other energy systems in the next few decades. There partial convergence of model results about what the energy mosaic of the future will be: use of most every known energy form is expected to expand. But there are fairly large disparities on the relative rates of growth for coal, nuclear, solar and other renewables, and on the growth rates and composition (e.g. liquid vs. solid fuel vs. electricity) of future energy demand. This seems to imply that there are still many options open with respect to what CO_2 loadings humanity puts into the atmosphere in future decades.

Lastly, where global models have been used to explore the development prospects of the poorer nations, model results have generally shown that extreme measures will be required for the poor to keep pace with the rich. Many models show continuation of present trends leading to stagnation or even decline in poorer nations. As the poorer nations are in general tropical, this finding suggests that an equivalent amount of climatic change may be more critical in the tropical regions than in the temperate or boreal regions.

2.5. Data

Lining up an internally consistent and globally comprehensive body of data is a large chore which may be necessary for some sorts of climate impact analysis. For example, to develop first order approximations of various nations susceptibility to climatic influences in agriculture, fisheries, and forestry, one might want to know fractions of GNP coming from agriculture, fisheries and forestry. Such data are not conveniently assembled on a global basis in common statistical sources (e.g., FAO, World Bank or OECD Annual Yearbooks), but have probably been assembled by several global modelers (e.g., Leontief et al. 1977, and Bottomley undated). Similarly, analysis of policy options for reducing CO_2 emissions might have use for data on energy capital infrastructure that has been accrued in consturction of the World Integrated Model or the IIASA energy model (IIASA 1981).

In some cases the data bases assembled in the course of constructing global models may be as or more useful for climate impact analysis than model findings. Some groups, such as the IIASA/FAP modeling group (Sichra 1981) and Bottomley *et. al.* regard making their data bases available as an important part of their work. However, not all model data will be accessible. A combination of poor documentation and organizational problems, and perhaps modelers' proprietary interest in maintaining control of the rewards from data bases that have taken them many years to put together, may make it very difficult to extract data from other models; and furthermore, the models' data bases may be outdated (e.g., energy parameters may come from 1975 and before).

3. Models and Model Attributes

The following section addresses the question of which models may serve what purpose. It is organized around a two-dimensional matrix, listing models and various attributes of the models (for example, time horizon, method, degree of aggregation). The matrix is presented in Tables 1, 2, and 3. In the following text a few categories of model attributes will be discussed at a time. For each attribute, discussion concerns how the attribute relates to climate impact analysis, for example, what time horizons are of interest for different climatic questions. Suggestions are also offered about selection or ruling out of various models for different purposes on the basis of the particular attribute.

3.1. Time Horizon, Method, Focus

Table 1 lists models in order of increasing time horizon, giving for each model a brief description of method and problem focus. From the table one can see that time horizons of existing global models range from 5 to 200 or more years. The character of models, the methods employed, the problems treated, and the model's possible utility for climate work, change with time horizon.

3.1.1. Short to Medium Term

Models in the 1 to 15 year range are typically built by economists and treat such topics as international trade, balance of payment problems, monetary system behavior and intersectoral flows. Such models are the only global models to attempt detailed and precise representation of the global market and monetary systems, and it is logical to look to them for information on the ramifications of climatic events through supply, demand, and price and monetary effects for specific commodities and countries or regions.

In using such models one should be aware of their methodological characteristics. E.g., the variables they contain are generally measured in monetary units. In many cases they do not include physical or biological units. Their logic is generally a combination of causality, extrapolation, and accounting. They tend to be econometric, are often static, and a large portion of their equations tend to involve linear matrix operations.

Table1: General Attributes of Different Global Models

MODEL	AUTHORS	TIME HORIZON (years)	METHOD	FOCUS
Soviet Model	Alexandrov, Krapivin Moiseev, Svirezhev Tarko	hundreds of years	dynamic simulation	society, atmosphere, biogeochemical balances
World2	Forrester	200	system dynamics	population, food, soils, industry, pollution
World3	Meadows et al.	200	system dynamics	population, food, soils, industry, pollution
Latin American World Model	Herrera, Scholnik, et al.	100	dynamic optimization	allocation of labor and capital to meet basic needs
SARUM	Roberts	80	dynamic simulation, input-output, econometric	food and mineral resource adequacy
MOIRA1	Linnemann et al.	45	algorythmic, optimization econometric	hunger, food production, food trade, trade policies
World Integrated Model	Mesarovic, Pestel, Hughes, et at.	25-50	dynamic simulation, input-output	population, capital, energy, food, trade, intersectoral flows
grain buffer stock	Eaton et al.	~25	dynamic stochastic simulation	rules for managing grain buffer stocks
UN World Model	Leontief, Carter, Petri et al.	25	input-output (static)	requirements for, pollution generated by UN development targets
Interactive agricultural model	Enzer, Drobnick and Alter	20	cross impact, interactive projection	global food problem, grain trade
optimal grain reserves	Johnson and Sumner	~20	dynamic stochastic optimization	management of grain reserves
FUGI	Kaya et al.	~15	econometric input-output dynamic	macroeconomic detail energy and resources
USDA Grains Oils and Livestock	Royko and Schwartz	10-20 static	econometric	production, exports, imports, trade of oils, grain, and livestock
input-output	Bottomley	~10	input-output static	international interdependence
FAO price equilbrium		~10	econometric static	world agricultural market prices, trade flows
World Food Economy Model	Takayama and Hashimoto	1-2	econometric quadratic progamming	global agricultural markets and trade
UNFPA/FAO/IIASA		1975,2000	agroecological, analysis,linear programming	population support land resources food production

Table 2: Aggregation of Different Global Models

MODEL	GEOGRAPHICAL AGGREGATION	SECTORAL AGGREGATION	AGGREGATION OF AG. SECTOR
Soviet Model	land by 500km^2 grid, coverage of ocean	agriculture, pollution abatement, mineral, basic capital	unclear
World2	aggregate world	agriculture, industry resource extraction	1
World3	aggregate world	agriculture, industry resource extraction	1
Latin American World Model	5 region; 20 region may exist	agriculture, education, housing, capital, other	livestock, crops
SARUM (1976)	3 regions	10 sectors	4 ag. products, 1 food processing, 3 ag. inputs
MOIRA1	106 nations	agriculture, non-agriculture	1 commodity
World Integrated Model	12 regions (basic) 17 regions (subregional)	7 or more, varies for different regions	5 commodity, 3 land types
grain buffer stock	aggregate world	agriculture only	aggregate grain
UN World Model	16 regions	40 economic sectors	4 agricultural commodities
Interactive agricultural model	10 regions	agriculture only	grain as proxy for all foods
FUGI	14 to 62	15 sectors	4 sector (?)
USDA Grains Oils and Livestock	28 regions	agriculture only	up to 14 commodities
input-output	90 countries	6 economic	one ag., fisheries and forestry
FAO price equilibrium	28 regions	agriculture only	18 commodities
World Food Economy Model	20 regions	agriculture only	8 groups
UNFPA/FAO/IIASA land resources	much of developing world, 10000 ha. units	agriculture only livestock	18 food crops

As commonly employed, such conventions tend to impart the assumption that the biophysical system will remain unchanged, and that most trends observed in the recent past will endure into the future. Linearization inherently assumes either that functional relations are indeed linear, or that system changes will not be so great as to drive system relationships far off a line of linear extrapolation. It may, thus, be inappropriate for describing extreme events. Econometric forecasting gains much of its predictive power from precisely measuring current values and making reasonable estimates of the trajectories on which they are headed (Meadows and Robinson, forthcoming).

Caution must be used if short-term models are to be used for looking at either shocks to the system -- such as extreme climatic events -- or deeper underlying change.* Either temporary shocks or underlying change may violate assumptions of temporal and behavioral continuity often implicit in linearization and econometric modeling. To deduce whether a system handles shocks reasonably, it might be well to examine (or ask the modelers to look at) the behavior of climate sensitive model variables in past years of climatic anomalies to see whether they fit within the model's explanatory power, or merely add to the magnitude of its error terms.

3.1.2. Longer Term

Models with time horizons over 50 years are generally built by interdisciplinary groups (engineers, system analysts, economists, demographers, agronomists, and so forth) and focus on biological and physical processes, such as population dynamics, resource flows, and creation of physical capital stock. These models generally aspire to describe essential trends in system behavior--not to make point predictions.

Such long-term models tend to ignore prices. Whether system behavior can be described without price mechanisms remains an active debate. Most analysts would agree that omission of price mechanisms reduces a model's precision for making short-term predictions. Whether it impairs their long-term descriptive power is a disputed topic. In any case, as stated above, short-term models are probably preferable for investigating the market-related details of climatic variability and extreme climatic events. For example, while long-term models may be useful for studying the evaluation of food scarcity conditions, shorter term models allow one to study the effect of scarcity on prices and on trade and consumption patterns.

Between the short-term and the long-term models are a variety of trade and/or intersectoral flow models with some feedback between economic development and resource depletion, population growth, and other processes. These typically include both price and real variables and are built by a mixture of economists and more physically oriented

* Experience with using large econometric ystems to forecast the consequences of the tripling of oil prices of the early 1970's -- an event analagous, in some ways to climatic disturbances -- suggests that such models are reasonably good at predicting short term market effects, but inadequate to representing long term adjustments. (Personal communication, Bert Hickman.)

scientists.

3.2. Intersectoral Flows

Tracing flows between production sectors and between the household sectors and production sectors is an old preoccupation of economists (dating back, at least, to Walras), and twentieth century economists and statisticians have put great effort into systematically recording flows between sectors.

Intersectoral flows may be important to climate impact analysis for two reasons. Firstly, they are routes by which indirect implications of climatic variations may be felt.* Secondly, intermediate flows (the products that are created in the process of making products rather than meeting end use demand, for example, fuel used in agriculture and industry) account for a very large proportion of all economic activity, and it is difficult to keep track of such activity without a device such as an input-output matrix.

Starting from the UN World model, the prototype of which was described by Wassily Leontief in his Nobel Prize acceptance speech (1977), one branch of global modeling has concentrated on the linkage between intersectoral flows within a country and international trade flows. One might gain information on intersectoral transmission of climate impacts using the UN World Model, the models developed by Bottomley et al., FUGI (Kaya and Onishi), or the World Integrated Model. For greater intersectoral detail, the UN model (Leontief et al.1977) might be preferred. If one simply wants data on intersectoral flows, Bottomley et al. have assembled what is probably the largest collection of input-output models in the world.** The World Integrated Model (Mesarovic and Pestel 1974, Hughes 1980) is sufficiently complex that it might be difficult to distinguish the effects transmitted through intersectoral flows from everything else that is going on in the model. (However, it might be possible to turn this into an opportunity by eliminating intersectoral accounting from the model and seeing if the change in structure significantly affected the system's reaction to some exogenously specified climatic perturbation.)

3.3. Agriculture

The impact of climatic change and variability on agriculture can be observed from many perspectives: management of grain reserves, food and nutrition, trade and balance of payments, or ecological sustainability. Different global models are appropriate for different perspectives.

* Assessment of the magnitude of intersectoral ramifications of variation in production, particularly in agriculture, is needed here. Without such assessment it is difficult to ascertain the importance of intersectoral flows in transmitting climatic impacts. It is not clear, a priori, that intersectoral flows are important. No question, food processing, fertilizer production, and perhaps some textile industries are affected by agricultural variability. What is unclear is the relative importance of these effects to what economists call externalities--e.g. the tendency of drought to accelerate desertification or change patterns of land ownership.

** Moreover, they are very generous about making their data and model available.

The section must commence with a caveat. Global agricultural models' market behavior depends heavily on the formulations used for international trade and for reserve management. Systematic comparisons of the various formulations that have been used and their respective strengths and weaknesses have not been published, and it is beyond the scope of this paper to make them. Thus while this section does comment on the contents of each model, it cannot speak adequately to the essential question of how good the formulations are.

3.3.1. Buffer Stocks and Grain Reserves

Management of grain reserves is an ancient defense against climatic variability. Numerous models have been developed specifically to examine the economics of buffer stock management. Some of these, including the models of Eaton et al. (1976) and Cochrane and Danin (1976) are designed to look at global reserves of all grains, others at specific grain commodities. A good review of buffer stock management models is found in Eaton (1980). In addition, as described in more detail below, disaggregated production and trade models have been used to look at stock management questions. An excellent review on this subject is found in Adams and Klein (1978).

To date, buffer stock modelers have mostly assumed yield variability such as observed in the recent past. Time series employed seldom extend back past 1950. Buffer stock models characterize variability by such parameters as variance around expected production volume, lagged covariance behavior, and form of random behavior (Eaton 1980). The problem of sequential bad years is considered by Eaton, but not by most models.

The extent to which yield variation is caused by weather, the possibility of climatic change, or possible occurrence of extreme climatic events not present in the period from which the model was parameterized are rarely mentioned in the buffer stock model documentation. It would be a simple, and perhaps rewarding task to use existing buffer stock models to look at the implications of climatic variability or extreme climatic events by altering the yield variability parameters used to drive the model.

3.3.2. Production and Trade

Patterns in international agricultural trade originate, in part, from the differences in climate and other endowments among nations. Annual variations in trade flows originate, in part, from weather variability. Thus, in principle, trade can be expected to be sensitive to climate, and climatic perturbations can be expected to be exported through the trade system.

Trade patterns are extremely complex (see, for example, descriptions of grain trade in Morgan 1980 and of commodity markets in Labys 1978) and modeling them necessarily entails simplification. Part of the complexity arises from agricultural production and trade policies, which vary greatly between countries and have significant influence on national and global agricultural markets. Additional complexity is introduced

Table 3: Treatment of Climate and Food Stocks in Different Global Models

MODEL	TREATMENT OF CLIMATE	TREATMENT OF FOOD STOCKS
Soviet Model	includes detailed climate model and mechanisms describing anthropognic climate change	probably excluded
World2	omitted	excluded
World3	omitted	excluded
Latin American World Model	omitted	excluded
SARUM	generally omitted	held in regions
MOIRA1	Production limits = f(photosynthetic potential). Potential estimated from soil maps and climatic maps; past annual harvest variation repeats	stocks assumed to be held at world market level
World Integrated Model	omitted	
grain buffer stock	random perturbation of yields	?
UN World Model	omitted	excluded
Interactive agricultural model	extremes in variation from trend line in past production series ('60-'75) define maximum deviation of random perturbation of yields	
optimal grain reserves	Estimates made of yield as f(rainfall); model driven with synthetic time series with mean, variance, autocorrelation structure of past rainfall data (sample years not specified)	Stocks of commodities determa prices in each region
FUGI	omitted	unclear
USDA Grains Oils and Livestock	"good" and "bad" weather investigated by raising and lowering yields (for Global 2000 runs)	regional stocks fo each commodity; levels policy controlled
input-output	omitted	excluded
FAO price equilbrium	exogenous	unclear
UNFPA/FAO/IIASA land resources	production functions based on climate inventory and assessment of climate responses of different crops	excluded

because different crops and regions vary greatly in the structure and dynamic behavior of agricultural production. For example, coffee flows from mountainous tropical regions to temperate zones. Coffee production is frost sensitive and, largely due to the fact that a coffee tree takes 3-4 years to bear fruit, the coffee market is prone to 7-8 year price and volume fluctuations. Wheat comes largely from temperate, semi-arid countries, is exported to both developed and developing countries, has much shorter production cycles than coffee, and is most affected by drought. Livestock slaughtering and meat prices are sensitive to grain prices; high grain prices induce increased slaughtering and meat supply in the short term, with meat shortage typically following in a matter of months or years (see, for example, Meadows D.L. 1970)

Of the models covered here, SARUM (Roberts et al.1977,SARU 1978), MOIRA1 (Linneman et al. 1979), the WIM, the UN World Model, the Center for Futures Research (CFR) interactive agricultural model (Enzer et al. 1978), the GOL model (O'Brien 1980, Rojko et al 1976, USDA 1978), the FAO price equilibrium model (FAO 1971), and the Takayama-Hashimoto world food economy model all contain mechanisms that account for international agricultural trade. These models' respective abilities for looking at climatic influences depend on what portion of the real system they represent and on the modelers' skill in testing and drawing inference.

In reality, grain reserves, trade and reserve policy, and economic trends all appear to have an important effect on the global agricultural system's response to climatic variability. A bad cropping year following a bumper cropping year has very different consequences than two bad years in a row; a bad harvest year in which the world economy has been strong, and many nations are attempting to increase grain imports (e.g. 1972) will result in much greater market distortion than a bad year in which key nations absorb lesser supply by reducing grain consumption (e.g., reducing grain use for livestock feeding).

Most global models represent agricultural demand as a function of income, and do implicitly reflect the consequences of strong vs. weak economies for agricultural trade. However, changes in income also influence what foods people eat, and agricultural markets are strongly interrelated. (E.g., when people eat more of one thing, they tend to eat less of something else; or, e.g., increased meat production means increased demand for grain.) Thus the fine points of income effects can only be studied with a multi-commodity trade model, such as the GOL, the IIASA/FAP model (Parikh and Rabar 1981, Parikh 1981), or the Takayama-Hashimoto model.

Another area in which models differ is in their handling of reserves. Both the way in which reserve sizes are determined, and the way in which reserves affect prices and other behavior seem important in determining system behavior. The definitive paper comparing models treatments of reserves has yet to be written; here it is possible only to mention some of the ways in which representations of reserves differ. At one extreme, there are models, such as the UN World Model, in which reserves are the residual of supply, demand and trade, and where prices are unaffected by reserves. This representation, obviously, will not show price instability under conditions of short supply. At the other extreme are models, such as the IIASA/FAP model and MOIRA, in which reserves are determined by complex interactions between production and demand responses, trade policies, and (in some cases) reserve policies. Relatively realistic descriptions might be achieved through such representations, but to date, documented validation of the representations is extremely weak. Other models represent reserves as maintained at a policy-specified level through government purchases and sales of grain. In the CFR model, reserves are determined off-line in gaming fashion, by the decision of persons playing the role of political decision makers.

An additional criteria is the model's treatment of the crop or crops of interest. Grain is considered in virtually all global models. In some cases (for example, the CFR model) it is used as a surrogate for all of agriculture. On the other hand, a rather specialized model would be required to explore the consequences of extreme climatic events on the export earnings of large coffee exporters such as Colombia, Kenya, and Brazil. The FAO price-equilibrium model may include coffee, but as coffee cycles are caused by disequilibria, the model is probably incapable of capturing the dynamic behavior of the coffee market.

A few other specialties and climate-relevant aspects of various models are described briefly below. The GOL Model was constructed to study the medium term (~ 10 years) interaction between the global grain, oils, and livestock markets from the perspective of the US as a large grain exporter. This model has been used to study the effects of changes in mean values of climatic parameters as transformed into changes in grain production (NDU forthcoming 1981), although published documentation of the experiment is not very illuminating on the subject of how secondary effects of climate change were transmitted through the livestock and oilseed markets. There are, in published output, no signs that the GOL model has been run stochastically using assumptions of varying weather patterns, and without performing the experiment it is difficult to say how realistically the model would behave if it were.

MOIRA (Linneman et al.1979) was constructed to study the effect of a doubling of population on the world food system. As described below, under demographic behavior, the model is particularly rich in its description of demand; it includes six separate income groups and calculates food consumption (or dietary adequacy) of each as a function of income and price. MOIRA also attempts to model national agricultural trade policy in a more refined fashion than most other global models. However, the behavior of its trade mechanisms is essentially unvalidated.

The IIASA Food and Agriculture Program (FAP) model, when complete, will be a set of mutually compatible national models, interlinked by a trade mechanism (Rabar and Parikh 1981, Parikh 1981). It will feature both multiple commodities (major grains, livestock, and non-food commodities) and detailed description of agricultural policy levers available to different nations. The modelers intend to study the linked system's response to various shifts and disruptions, including climatic shocks. The difficulty with the FAP model is that it is very large, extremely complex, and to date, inadequately tested or documented. Development of the model has taken much longer than anticipated. Modeling work is scheduled for termination in 1984.

3.4. Energy

The impact of energy systems on climate, particularly of fossil fuel through CO_2 generation, has been analyzed using many models (Niehaus and Williams 1979,Jäger 1980) and will not be described here. The tendency of firewood and dung fuel systems to contribute to local climate alteration, soil impoverishment, and desertification has not been, and probably cannot be, included formally in global models due to the fact that several critical variables in the system (for example, firewood usage, forest growth) are not included in global models. However, verbal attempts to describe and quantify such effects were made in both the group of IIASA energy models (IIASA 1981) and the Global 2000 study (Barney 1980,1981).

The main effects of climate on energy systems appear to be through the effect of weather on energy use for heating and air conditioning and on supply of renewable energy sources, such as hydropower, firewood, and so forth (Quirk, 1981). The effect on heating fuel demand is relatively important in developed, temperate regions. The effect on renewables is most important in tropical, less developed regions.

By assuming a relationship between climatic parameters and energy demand and/or supply, one could translate climatic scenarios into scenarios of energy supply and demand, and use these to drive global energy models. As described below, this may not be a very rewarding activity. Using this approach to study effects of climate on supply of renewable energy sources other than hydropower (e.g., wood fuel and solar) is not practical, as treatment of water systems and the unmanaged biosphere is sparse in most global models, and representation of solar energy development remains highly tenuous. One might conceivably use the World Integrated Model (Mesarovic and Pestel, 1974, Hughes 1980) the IIASA energy models (IIASA 1981), the International Energy Evaluation System (IEES) (Barney 1980,1981) or other models containing international energy trade and fuel infrastructure development to study the impact of climate on energy demand, as transmitted through international fuel markets, intersectoral flows, and long-term effects on capital formation and resource depletion. Of the models listed, only IEES contains sufficient detail on energy demand to study the effects of short-term climatic variation. As for long-term climatic change, the long-term effects of a few degree change in average temperature are likely to be sufficiently small in comparison to other system changes such as increased building insulation and increased efficiency of air conditioning (personal communication, William Quirk, LLNL) that the results of this exercise would probably not be very illuminating.

3.5. Demography

Effects on mortality, morbidity, and migration are among the most severe effects of historically observed climatic change. Population growth, being an important and relatively predictable part of social systems development (predictable as, for example, compared to economic growth), is accounted for in virtually all global models. How various global models treat demographic variables is shown in Table 3.

Table 4: Demographic Aspects of Different Global Models

MODEL	DEMOGRAPHY		
	AGGREGATION	STRUCTURE	MIGRATION
Soviet Model	in development	probably none	
World2	no disaggregation	fertility=f(income/cap) mortality=f(food, income)	none
World3	3-5 age	fertility=f(income,services)	none
Latin American World Model	by region rural-urban (n) age cohorts	fertility and mortality are f(basic needs fulfillment); model maximizes life expectancy	rural-urban at rate to maximize life expectancy
SARUM	exogenous	none	
MOIRA1	by nation (106) rural-urban income group (6)	growth exogenous	rural-urban f(income in agri., income outside agri.)
World Integrated Model	by region (12+) age cohort (85)	exogenous	none
grain buffer stock	no disaggregation	exogenous	none
UN World Model	no disaggregation	exogenous	none
Interactive agricultural model	probably none	exogenous	none
optimal grain reserves	probably none; exogenous	none	
FUGI	undisaggregated	exogenous	none
USDA Grains Oils and Livestock	no disaggregation	exogenous	none
input-output		demography excluded, implict in demand projections	
FAO price equilibrium	undisaggregated	exogenous	none
World Food Economy Model	no disaggregation	exogenous	none
UNFPA/FAO/IIASA? land resources		exogenous	none

3.5.1. Migration

To my knowledge, no global model has dealt with migration between nations. Both MOIRA (Linneman et al.1979) and the Latin American World Model describe rural-urban migration. A peculiarity in the optimization routine in the Latin American World Model causes all regions to move toward 100 percent urban at an incredibly rapid speed (OTA 1981, observable in Herrera et al. 1976), and its formulation cannot be taken very seriously.* MOIRA shows rural-urban migration as a function of relative income per capita in and outside of agriculture. In simulation, rates of rural to urban migration follow food price; when prices are high, farmers are better off and migration is less; when prices are low, farmers are poorer and there is more urban migration. It would be an interesting test of the model to see if it would, given severe weather shock in rural areas, replicate the common pattern of massive urban migration in times of famine.

Other than MOIRA and the Latin American World Model, global models can look at migration only by inference, as none explicitly includes migration. One can, however, infer heavy migration as a plausible outcome of food deficits. It is possible to use most global models to look at food availability.

3.5.2. Other Demographic Parameters

Several global models show population growth as interrelated with economic development and food supply (World2 & 3, some versions of WIM, probably the Soviet model), environmental conditions (World2 & 3, the Soviet model), and social welfare (the Latin American World Model and World3).

Models such as these may be pertinent to climatic analyses in three ways. First, where they indicate tight food supplies (a likely result of population growth), one can presume the potential disturbance caused by effects of climatic change and variability on yields will be amplified. Second, where they indicate population pressure, one can infer shrinkage of the unmanaged biosphere and deterioration of soil organic matter (through fire, overgrazing, and so forth), and thus creation of harsher microclimates and increased CO_2 release. Third, if one had reason to believe climatic change would directly affect mortality or fertility, one could rerun the models with the changed parameter to see the consequences in the larger system.

Choice of models for looking at population-environment interaction is a matter of taste. For a moderately high degree of resolution, at the cost of rather difficult to interpret results, the World Integrated Model may be most appropriate. It contains many (12 or more) regions and 85 age groups and can be made to look at the effects of food supply, income, and population control on population dynamics. It also contains international trade linkages and thus could approximate the way in which climatic

* The model maximizes life expectancy at birth. Its functional relationships were developed by statistically relating several variables, including education, fraction of population urban, and others to life expectancy. Because there is a strong correlation between life expectancy and urbanization, the model favors rapid urbanization.

change in one region might be transmitted to affect other regions. For example, say a global warming causes lowered agricultural productivity in the Great Plains, but slight increase in rice yields in most tropical regions. The WIM could be used to investigate whether this will result in more or less hunger and starvation in India, Indonesia, and/or Africa. One could also use MOIRA for this purpose; this would give results that take uneven income distribution into account, but would not permit looking at the feedback to population growth, as population growth in MOIRA is exogenous.

For less detail, but more inclusive structure, World2 or World3 might be recommended. Both see longevity and fertility as affected by food supply, economic resources per capita, and pollution. Neither disaggregates the world into regional populations. World3 normally uses 3 age cohorts, and has, in structural testing, been disaggregated to 5 age cohorts, leading to the finding that model results are not sensitive to the degree of age disaggregation (D.H. Meadows 1974).

The pollution term in World2 or World3 could be adapted to describe effects of anthropogenic climatic change on morbidity and mortality. The part of model structure describing soil deterioration might be expanded or adapted to show shrinking of the biosphere, thus CO_2 generation and desertification.

If it maintains the present tentative model structure, a completed version of the Soviet model might be an authoritative tool for this and other aspects of climatic impact analysis. As mentioned previously, it has a strong geophysical component. Its treatment of population appears to be very similar to that of World3, except that it is disaggregated on a 500 km^2 grid. That is, it describes fertility and mortality as functions of food availability, chemical environment (pollution), and economic well-being, and it represents linkages between the chemical environment and population and economic dynamics.

In contrast, for a model oriented not toward what will happen, but toward what would be best for meeting the basic needs of the world's population, the Latin American World Model is most apposite. Essentially, the model is formulated to find the allocation of labor and capital among various sectors (housing, education, agriculture, capital formation, and other) that maximizes life expectancy at birth. Introducing climatic parameters into the Latin American World Model might not produce meaningful results. Its representations of trade and agricultural production are probably unequal to the problem, and it has some wildly unrealistic tendencies (OTA 1981).

3.6. Political Ramifications

Climatic change is generally expected to benefit some and cost others. The costs of anthropogenic climatic change are apt to be born by groups other than those causing the change. Control of many of the economic and social forces contributing to climatic change (for example, deforestation, CO_2 emission) will in many cases require cooperation. Because these considerations have strong political implications, one might want a formalized model to examine them.

The importance and difficulty of representing political decisions is almost routinely discussed at global modeling conferences (e.g. Meadows, Richardson and Bruckmann 1981) The Wissenschaft Zentrum group in West Berlin, under the directorship of Karl Deutsch, has been working on a politically oriented global model that deals with both domestic stability and international economics and politics. According to recent reports (Bremer 1981, Ward and Cusack 1981), it will employ a five sector aggregation within which it would be very difficult to specify climate impacts (sectors represented are household, government, capital, production and foreign trade). However, extension and adaption of the model might eventually be possible.

The Center for Futures Research (Enzer et al.1978) has constructed an interactive food model, in which persons playing policy makers adjust production targets, reserve targets, import, export, aid and other decisions in each year of simulated time. The model divides the world into 10 regions, each of which is represented by a decision maker. It has introduced stochastic weather effects on yields, and political responses to weather variation on the order of that observed over 1950-1975 have been studied. The model used in conjunction with the "players" decisions about political reactions to changing circumstances might be described as a simple simulation model (it can be simple, as modeling social and political decision making is one of the more difficult aspects of social system model building, and the CFR model's interactive format absolves modelers of the need to be sophisticated in their human behavioral equations), parameterized using Delphi survey techniques.

The Climate Task at the International Institute for Applied Systems Analysis is using a gaming approach to look at strategic and political aspects of CO_2 induced climatic change. There are two games under construction, a computer game and a board game. These consider the strategic and economic aspects of coal extraction and trade and the policy measures available for containing and/or adapting to CO_2 in the context of the evolution of a highly uncertain and unevenly distributed set of costs and benefits arising from climatic change. (Ausubel et al.1980, Robinson and Ausubel 1981). The games might be regarded as initial attempts to build interactive "climate-centered" global models.

4. Concluding Remarks

The preceding text has emphasized the difficulties of using global models for climate impact analysis. The intent was not to dismiss existing models. Any way one approaches global anlaysis of climate impacts will be difficult. If one does not use models, the difficulty of keeping track of information for the global system rapidly becomes prohibitive. Moreover, without formal, quantitative specification of a system of relationships, it is very difficult to test and refine assertions and the inferences that may be drawn from them.

Starting anew, with new, climate-oriented models is not an easy remedy, either. Constructing a new global model can be expected to require many man years of effort, and unless one employs data bases and concepts that have not been employed in previous models, one is likely to end up closely replicating existing models (and reencountering their limitations.)

The problem is not that existing models are unusable, but that they must be employed carefully and critically. A good scientist working with an inadequate model is generally more effective than an inadequate scientist working with a perfected model. Existing models are far from perfected, but with a combination of imagination and good scientific practice, they could be made useful. Essential activities include:

[1] defining the problem one wishes to explore and translating it into terms that are consistent with an existing model or models.

[2] critically examining model method, structure and parameters, perhaps extending the criticism to include structural testing and model validation not produced by the modelers themselves, and comparison of the model with other models. (It is poor science to use global models as black boxes.)

[3] analyzing model output, studying it both mathematically and in terms of real world significance, and comparing it to what is known from other sources.

[4] documenting one's findings in a fashion that makes them accessible to critical review and examination by others.

If one prefers to contract research with an existing global modeling group, much of the work in the points above can be conducted by the modelers themselves. However, it must be realized that global modeling has not generally adhered to (or been rewarded for adhering to) rigorous scientific standards. Unless one is willing to insist on--and pay for---upgrading standards of practice, one is likely to end up with results that will not withstand critical review.

APPENDIX: SOURCES OF INFORMATION ON GLOBAL MODELS

There is no one central collection point for global models, but several persons and institutions are attempting to coordinate and organize information on the subject. Below are listed points of reference.

1. Conferences on global modeling have been held annually for the last eight years at the

International Institute for Applied Systems Analysis
A-2361 Laxenburg, Austria.

These have facilitated communication between some, but not all, segments of the global modeling community, and are a source of documents on many models. The IIASA library also has a good collection of global model documents, and IIASA itself has housed the development of two global models. At present, however, IIASA has only a small manpower commitment to global modeling. Gerhardt Bruckmann, who is in charge of IIASA's work on the subject, works 1/5th time, and is unable to do much more than coordinate conferences and edit proceedings.

2. Gerald O. Barney is working on a catalog of global models. In this he will attempt to describe subjects of interest to potential model users (terms of availability, computer requirements, documentation, etc.). This should be available sometime in late 1982. For information contact:

Gerald O. Barney and Associates
1730 North Lynne Street, Suite 400
Arlington, Virginia 22209
USA

3. The Systems Research Institute, Poona, India, in cooperation with the International Development Research Centre, Ottawa,Canada, is establishing a Documentation Centre on Global Modelling, with special attention to the use of modelling by developing countries. For further information contact:

Prof. J.G. Krishnayya
Documentation Centre on Global Modelling
Systems Research Institute
17-A Gultekdi
Poona -- 411037
INDIA

4. The Global Models in the Policy Process (G-MAPP) project of the East West Center has done considerable work comparing models, and are presently working with FUGI, a revised verion of SARUM (AREAM) and the World Bank Model (not covered in this paper). They may prove a useful source of up to date model documentation for the models on which they are working, and on comparisons of global models in general. For more information contact:

Dr. Don MacRae
Coordinator, G-MAPP Project
East-West Center
1777 East-West Road

Honolulu, Hawaii 96948
USA

5. I will be willing to supply further information on most any subject herein--if you can reach me.

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The following designations are used to assist readers in locating documents appropriate to their needs.

T = primary texts describing one model
E = technical model description, including equation listing
O = overview, summary text describing one model
W = working document: unfinished work
S = survey text, describing many models

For working papers and similar documents, I have tried to attach addresses from which they might be acquired. A fuller list of addresses is available in Meadows, Richardson and Bruckmann (1981) below. If one is interested in working seriously with any model, it is advised that one contact the modelers directly, as bibliographies such as this are almost always incomplete and out-of-date.

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