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CLIMATIC CHANGES AND GLOBAL MODELING

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September 1982
CP-82-57

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PREFACE

The potential implications of climate variability and change for human activities and welfare have been the subject of considerable interest at IIASA over the past decade. During IIASA's 7-year global energy study, the possible effects of increasing world reliance on fossil fuels on the earth's climate were extensively explored by Drs. J. Jäger, H. Flohn, and other scientists. More recently, IIASA research has focused on the complex interactions between climate and society and on innovative techniques for analyzing them. For example, scientists from IIASA's Resources and Environment Area, including J. Ausubel, J. Robinson, and I. Stahl, have pioneered the application of interactive gaming techniques to the problem of carbon dioxide and climate in an attempt to characterize to some degree the important behavioral aspects of future fossil-fuel consumption and possible climate changes.

IIASA's work on climate issues parallels ongoing research in the Soviet Union, among other countries. In particular, at the All-Union Research Institute for Systems Studies and the Institute of Oceanology of the U.S.S.R. Academy of Sciences in Moscow, development has begun of a linked set of models of the combined "climate and society" system. This set of models will permit detailed exploratory studies of the complex feedbacks between geophysical and environmental processes on the one hand, and socioeconomic developments and responses on the other.

This collaborative paper summarizes preliminary work on a specific subject of mutual interest to IIASA and the Soviet institutions mentioned above. Global models, despite their limitations, provide one of the few available methods for taking into account the many, often subtle interactions between environmental, economic, and social factors that may greatly influence the "net" impacts of climate changes. An earlier working paper by J. Robinson (WP-81-126) highlighted the potential advantages, disadvantages, and caveats associated with the use of global models for climate impact analysis. The approach taken in this paper is to explore a simple link between one global model, WORLD-3 (developed by Meadows *et al.*), and ecological and climatic models under development in the Soviet Union. While other global models could certainly have been selected, WORLD-3 provides a straightforward, transparent, and representative tool for studying potential climate-related impacts.

The analysis presented here is not of course intended to be realistic at this early stage. Nevertheless, it represents an important step towards improved understanding of the likely *integrated* impacts of climate variability and change on society. It is expected that future collaborative research and assessment activities will continue to explore this and other approaches to integrated climate impact assessment.

The work described here was supported in part by the Resources and Environment Area, reflecting IIASA's continuing interest in climate issues and the application of modeling and simulation techniques.

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It is generally accepted that the Earth's climate could be changed by human activities on a global scale and that such climate changes would in turn affect human activities in different ways. Many studies have been carried out which characterize climate as a geophysical system completely independent of mankind's development. On the other hand, much interest exists at the moment concerning socio-economic aspects of the variability of climate, both human-induced and natural. In this study we have tried to incorporate some results of climatic studies into a global model of world development using simplified blocks of a general model now under construction (which we call a "Climate and Society" model from now on). The main objective of this study is to demonstrate an approach to building links and identifying feedbacks on a very prelim-

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inary level of understanding of the interaction in the "Climate and Society" system.

The main possible causes of potential changes in the global climate produced by modern technological society are changes in the gas composition of the atmosphere, the concentration of aerosols in the air, the albedo of the Earth's surface, and other less significant parameters. These changes could result from industrial development, increasing amounts of arable land, deforestation, soil erosion, oil pollution of the sea surface, and so on. At present, most scientists involved in climate studies believe that the main risk of anthropogenic climate changes is the carbon dioxide (CO_2) originating from rising industrial output and associated fossil-fuel combustion. This belief is being constantly reinforced by current observations and numerical modeling.

There has been much work on the subject. For example, the well known Mauna-Loa data (Figure 1) demonstrate that the concentration of CO_2 has increased from 315 ppm in 1958 to 336 ppm in 1979. A thorough survey of the CO_2 issue has been prepared by J. Jäger (forthcoming) and a recent review by the U.S. National Academy of Sciences has appeared this year (Carbon Dioxide Assessment Committee, 1982).

It may be inferred from past studies of the CO_2 problem that difficulties in forecasting CO_2 increases in the air originate from both uncertainties about the carbon cycle as it is now understood and about future fossil-fuel combustion. Nevertheless, some scenarios of the CO_2 problem have been proposed, such as the IIASA Energy Systems Program's scenario (IIASA, 1981).

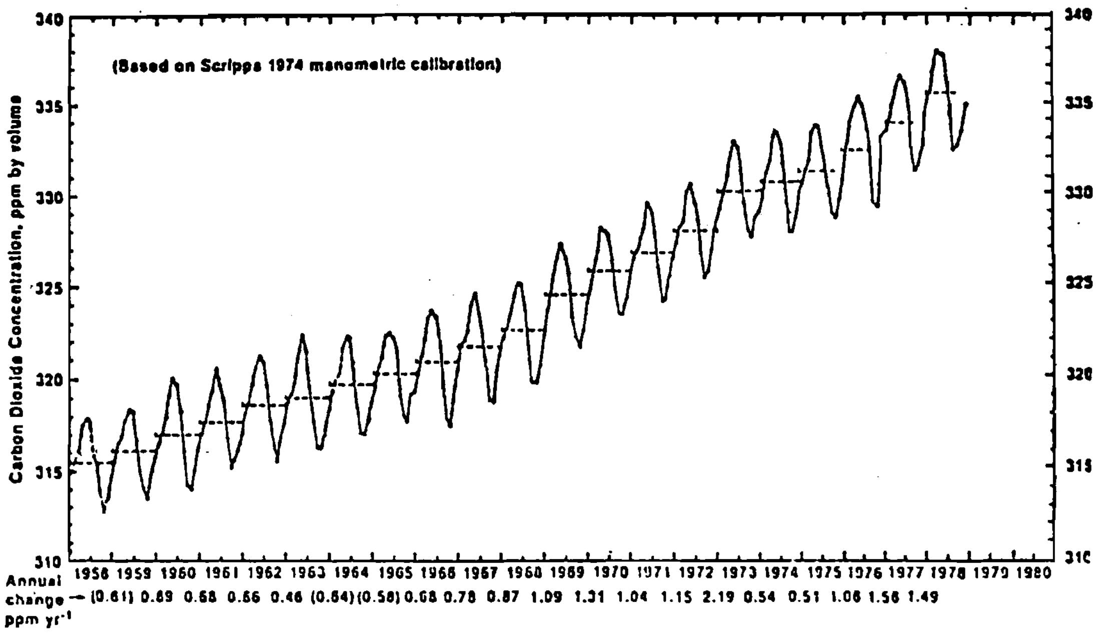

Figure 1. Observations of the CO_2 concentration (in ppm) at Mauna Loa Observatory, Hawaii (after Jäger, forthcoming; see also, Machta, 1979).

Figures 2 and 3 show CO_2 emissions and corresponding temperature changes for two scenarios of high and low energy supply. According to these scenarios there will be between 380 ppm of CO_2 in the air (high scenario) and 365 ppm (low scenario) in 2000 and between 550 ppm and 430 ppm in 2030, respectively. The corresponding temperature changes have been calculated for comparison with these scenarios using a radiative-convective climate model (Augustsson and Ramanathan, 1977).

In 1980, a group of experts, after analysing the results of climate models, concluded that the atmospheric CO_2 concentration will be 380 ppm by the end of the century and will continue to rise, with a "most likely" value of 450 ppm in 2025 (World Climate Programme, 1981). Almost the same result was obtained by Rotty (1977). The basis for these predictions is a comparative analysis of industrial output during the past century and the corresponding rise in the amount of CO_2 in the atmosphere and then a projection of their joint behavior into the future. As determined from other investigations of the problem (Budyko *et al.*, 1981), the probable error of such a prognosis for CO_2 is in the 20% range if the industrial output is accurately specified. However, most scenarios predict doubling of CO_2 content in the air in the coming 100 years. The potential consequences of such a doubling include the catastrophic deterioration of the Earth's climate and thus pose a great challenge to mankind on a global scale.

It should be noted, however, that all of these predictions have been developed assuming *limited* fossil-fuel resources but *unlimited* growth of population and industry. Even if all uncertainties in the evolution of environment and society had been totally ignored, the hypothesis of

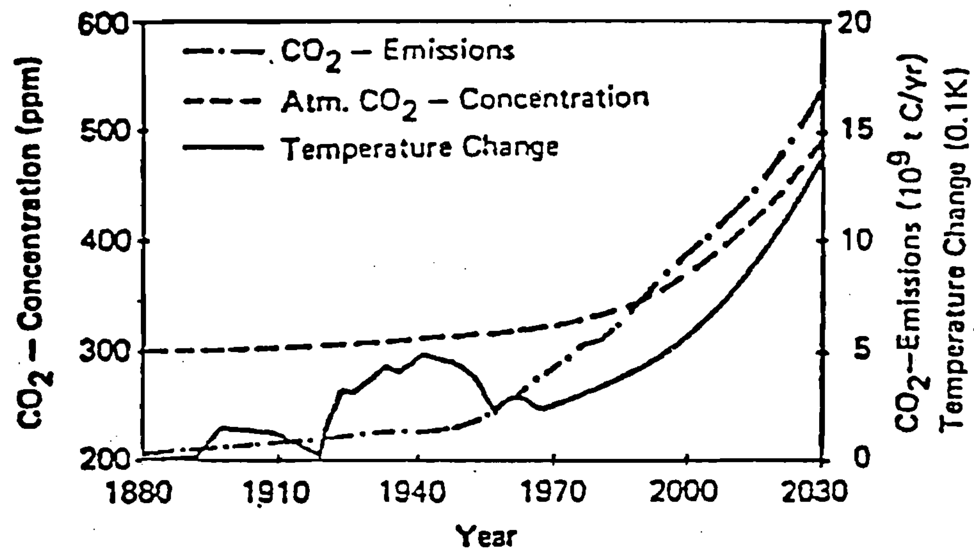

Figure 2. CO_2 emissions, atmospheric CO_2 concentrations, and computed temperature change for the IIASA high energy supply scenario. (IIASA, 1981; after Jäger, forthcoming).

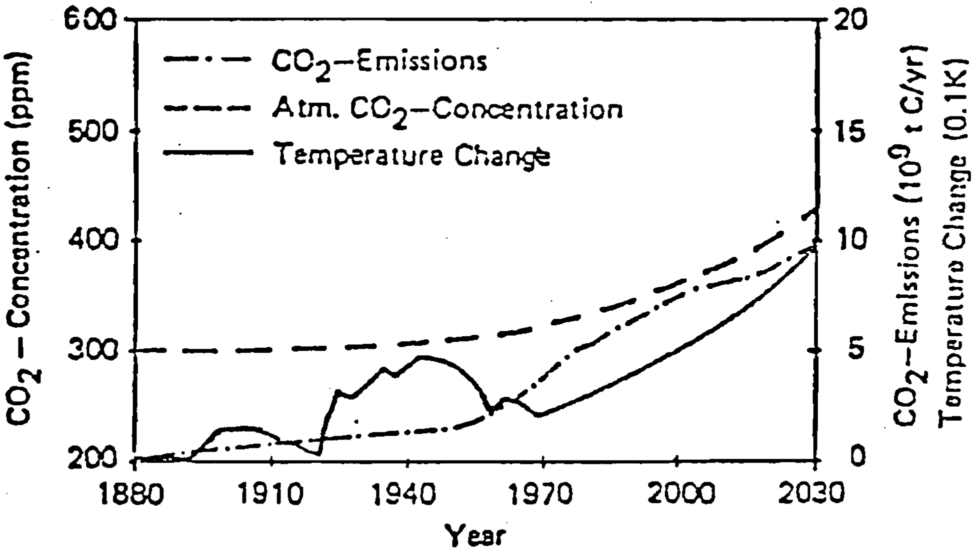

Figure 3. CO_2 emissions, atmospheric CO_2 concentrations, and computed temperature change for the IIASA low energy supply scenario (IIASA, 1981; after Jäger, forthcoming).

unlimited development should not be accepted as the only alternative. In particular, there are studies (e.g., Forrester, 1971, and Meadows *et al.*, 1974) that have proposed certain "limits to growth" in the modern technological world. The studies suggest that there are limits to the rapid development trends that are manifest at the present time. These limits apply to almost all elements of our world--population, food, industrial production, available land, and so on--mainly because the Earth's nonrenewable resources and space are finite.

Let us look at possible changes in the state of the CO_2 problem if we take into account the hypothesis of the existence of certain limits to growth. An aggregate variable suitable for characterizing the stage of industrial development is the industrial output (IO). Supposing CO_2 concentration in the air to be a function of IO, we derive the following equation:

$$n(t) = n(0) + f(\text{IO}), \tag{1}$$

where $n(t)$ is the current CO_2 concentration in the atmosphere, $n(0)$ is the initial CO_2 concentration, and f is some function of industrial output. Let the latter be a linear function:

$$f(\text{IO}) = k \cdot \text{IO}, \tag{2}$$

where IO is given in normalized (non-dimensional) units and k is an empirical coefficient which can be determined by observation.

Observations of the rate of increase in CO_2 concentrations and data on IO for some chosen time period in the past from a global model, WORLD-3 (Meadows *et al.*, 1974), provide the data necessary for this comparative analysis. The coefficient k has been estimated for the 1965-1975 period from Table 1 and is about $35 \cdot 10^{-12}$ ppm.

Table 1. Data on the increase in CO_2 content of the atmosphere and industrial output for the 1965-1975 period (from Meadows *et al.*, 1981).

	PERIOD	
VARIABLE	1965-1970	1970-1975
ΔCO_2 (ppm)	4.73	5.43
$\Delta IO \cdot 10^{-12}$	0.133	0.163

Figure 4 shows the results of calculations using the WORLD-3 model. This is a standard run of WORLD-3 where no alternative policy to prevent the decline of level variables (population, IO, food, etc.) has been introduced into the model. At a certain point in time, the growth of all level variables stops and then the latter begin to drop. Time lags depend on several parameters (e.g., nonrenewable resources and arable land).

If it is assumed that the coefficient k is the same in the future as for the 1965-1975 period, the future CO_2 concentration can be estimated using WORLD-3 model runs. Specifically, the industrial output can be used to derive the CO_2 concentration for different assumptions about the nonrenewable resources available on the Earth.* Numerical experiments have been carried out with nonrenewable resources at presently

*Nonrenewable resources may have been estimated with significant error since large amounts of undiscovered resources may exist.

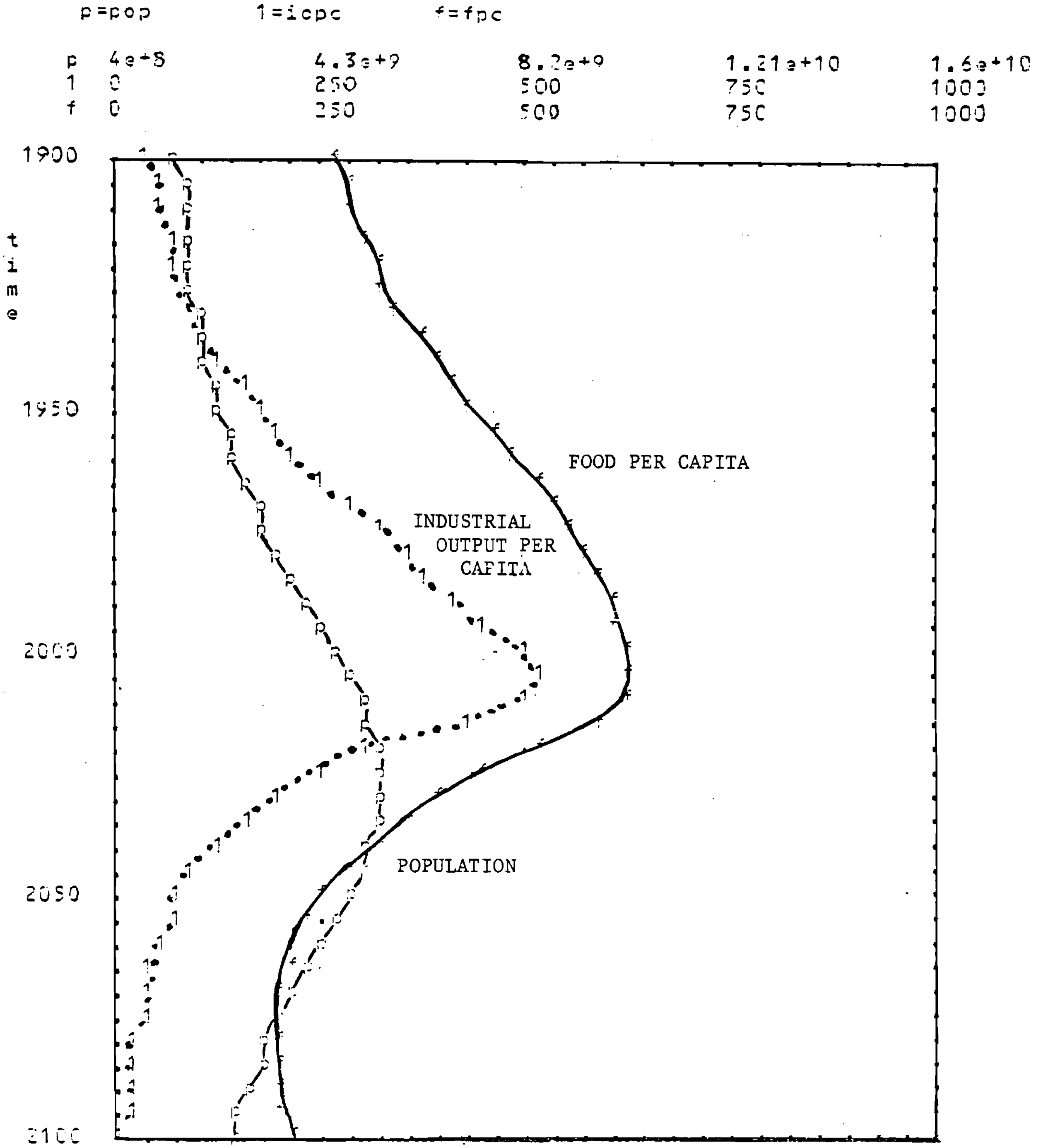

Figure 4. The results of the standard WORLD-3 run with unchanged climate.

estimated levels and with nonrenewable resources at levels twice and three times greater than this. These experiments are presented in Table 2.

Table 2. Predicted CO_2 content in the atmosphere for three different estimates of nonrenewable resources.

NONRENEWABLE RESOURCES (NR)	ATMOSPHERIC CO_2 CONCENTRATION (PPM)			
	YEARS			
	2000	2020	2050	2100
NR=1	373	353	309	297
NR=2	374	428	344	309
NR=3	374	426	428	312

The climatic consequences of increasing CO_2 content in the air have been estimated using a simple climate model (Pitovranov and Seidov, 1982). This zonal climatic model consists of a detailed radiation block constructed so as to consider most of the potential anthropogenic effects on the gas composition and transparency of the atmosphere and on the Earth's surface (CO_2, aerosols, albedo, etc.). The advection of heat by large-scale motion and eddies in the atmosphere has been parameterized in a rather simple manner. The results of this model agree with other two-dimensional climate models. In Table 3, changes in global temperature due to an increasing amount of CO_2 in the atmosphere are shown.

Table 3. Changes in mean annual global temperature for three different estimates of nonrenewable resources due to CO_2 increases.

NONRENEWABLE RESOURCES (NR)	CHANGE IN TEMPERATURE (°C) YEARS			
	2000	2020	2050	2100
NR=1	0.8	0.5	-0.2	-0.3
NR=2	0.8	1.5	0.3	0.1
NR=3	0.8	1.5	1.9	0.0

This zonal climate model is not suitable for computing changes in the humidbity distribution over latitudes since the dynamics of the atmosphere have been highly parameterized. The humidity distribution may instead be evaluated from the results obtained by other researchers who have either analyzed paleoclimatological data (e.g., Vinnikov and Groisman, 1979) or performed a three-dimensional calculation using more sophisticated climate models (e.g., Manabe and Wetherald, 1980). Figure 5 illustrates the qualitative behavior of moisture when the global temperature is 1°C higher than at the present time.

It should be pointed out that independent calculations using different approaches are generally in agreement with each other in predicting the latitudinal distribution of humidity and should therefore be reliable at least for qualitative analyses. It can be seen from Figure 5 that global warming leads to increasing precipitation in low and high latitudes

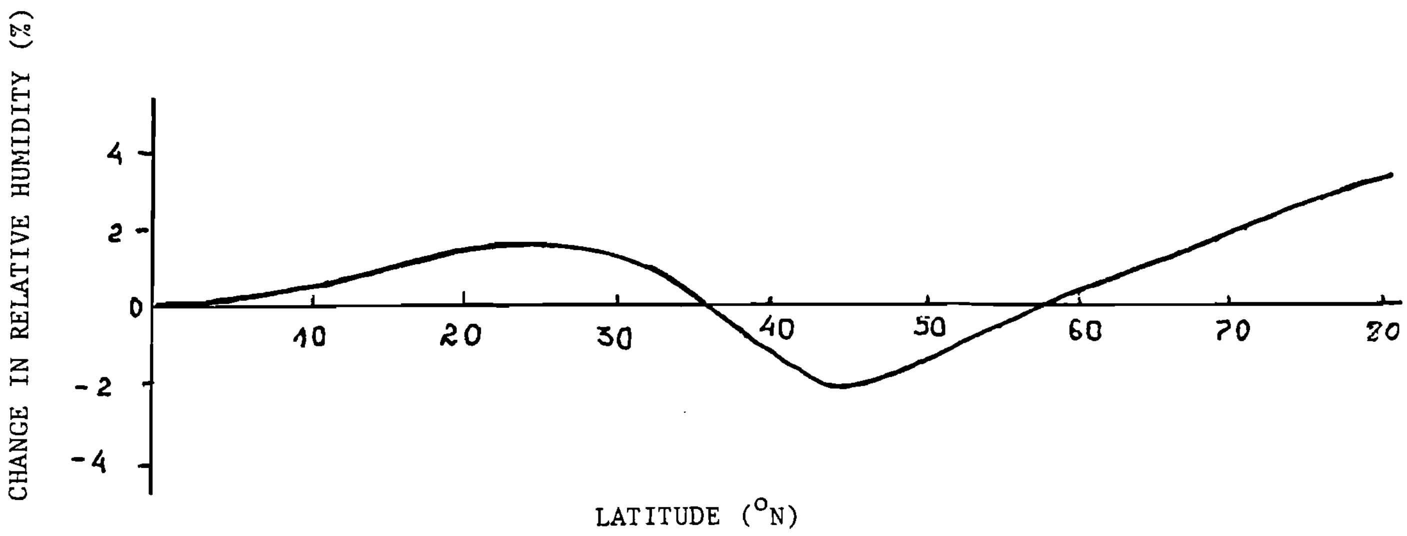

Figure 5. Moisture deviations from the present latitudinal distribution for the case of a 1°C warmer global climate.

but the middle latitudes experience dryness in the 35-50°N belt. Unfortunately, the main grain-producing land is in this belt which may be most affected as the climate becomes warmer.

To estimate changes in the "inherent" land fertility (LFERT), the results of studies conducted at VNIISI were used (Pegov and Rostopchyn, 1981; Volobuev, 1974). From these studies it can be inferred that LFERT for the belt 30-60°N would decline with time due to temperature and moisture changes associated with a warmer climate. Qualitatively, the dependence of the steepness of decline on the temperature deviation from the normal case is shown in Figure 6. Here $LFERT_0$ is the present LFERT assuming an optimum climate now. In addition to these results, it should be mentioned that many scientists believe that a decrease in moisture in the middle latitudes will lead to more frequent droughts in the area (National Defense University, 1978). So, it is likely that the fertility of the crop producing land would decline more steeply than Figure 6 shows.

The variable LFERT in the WORLD-3 model is suitable for experiments to assess the impacts of climatically induced changes on the dynamics of world development. This variable is defined as the average capability of an acre of arable land (AL) to produce crops without the use of any modern agricultural techniques. The assumption is made that the fertility of any land is a complex function of the organic and inorganic content of the soil and the incident solar radiation and climate. The solar radiation and climate have been assumed to be unchanged in the original WORLD-3. The land yield factor, the parameter LYF, is used to adjust the LFERT by simple multiplication in the model and can be used to study the

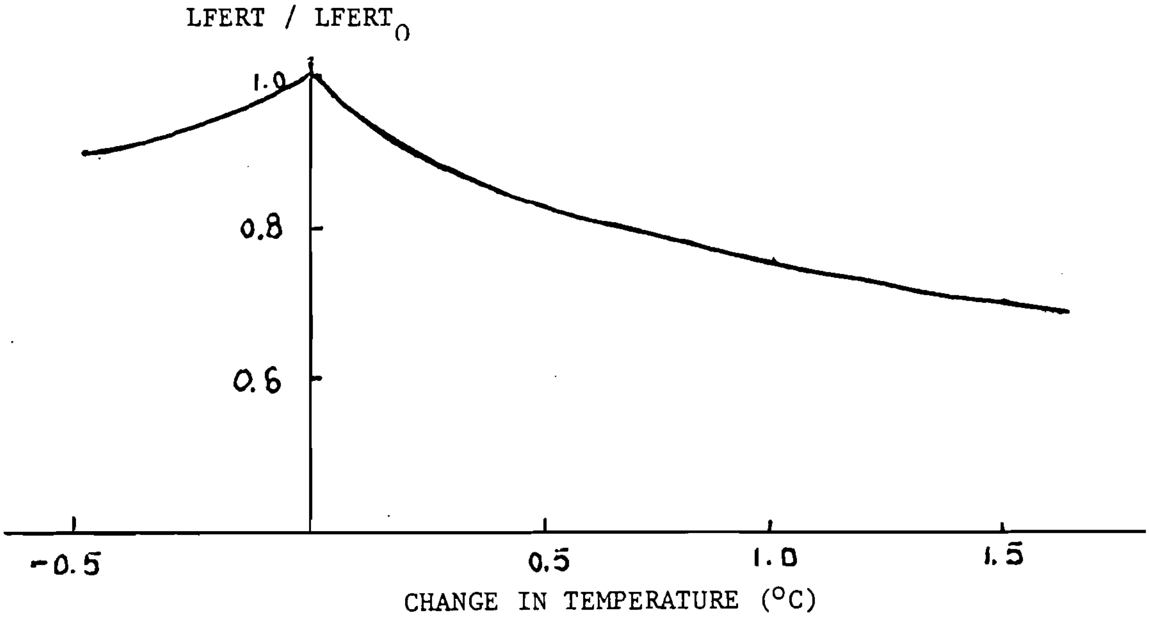

Figure 6. Decrease in LFERT with changing global temperature for the latitude belt 30°-60°N (after Pegov and Rostopchyn, 1981).

climatic impacts in a very primitive way. As a parameter it can be changed abruptly at any chosen time. Exactly this calculation has been made in a series of experiments with WORLD-3.

The first experiment is straightforward. The LYF was set to be 50% smaller than it is now (unity in WORLD-3) beginning in 1990. One might call it a "climatic shock." This experiment shows strong response of all level variables (Figure 7). The population in 2050 is 200 million people less than if LYF had not changed. This is a decrease of almost 16% of the population predicted for the standard case--and food supply for the rest is 41% less than predicted in the standard case in 2050. Thus, the "climatic shock" is a significant deteriorating event and future life on Earth would differ substantially from what WORLD-3 predicts for the "normal climate" case (cf., Figure 4).* We stress here that these kind of experiments have little to do with reality and should be viewed simply as a sensitivity study of the model. On the other hand, one may notice that even under such heavy climatic stress the model demonstrates rather stable behavior.

To present more realistic changes in LFERT in a continuously deteriorating environment, we substituted a "table" function LYFT for the parameter LYF to obtain a smoothly declining LFERT beginning in 1990 for scenarios of weak and strong climatic impacts on the agricultural sector (Table 4). From this table one can infer that even a slow evolution in climate has a noticeable effect on level variables of the global model.

*WORLD-3 does of course predict a global collapse in the standard run. However, for the comparative analysis undertaken here, this should not matter.

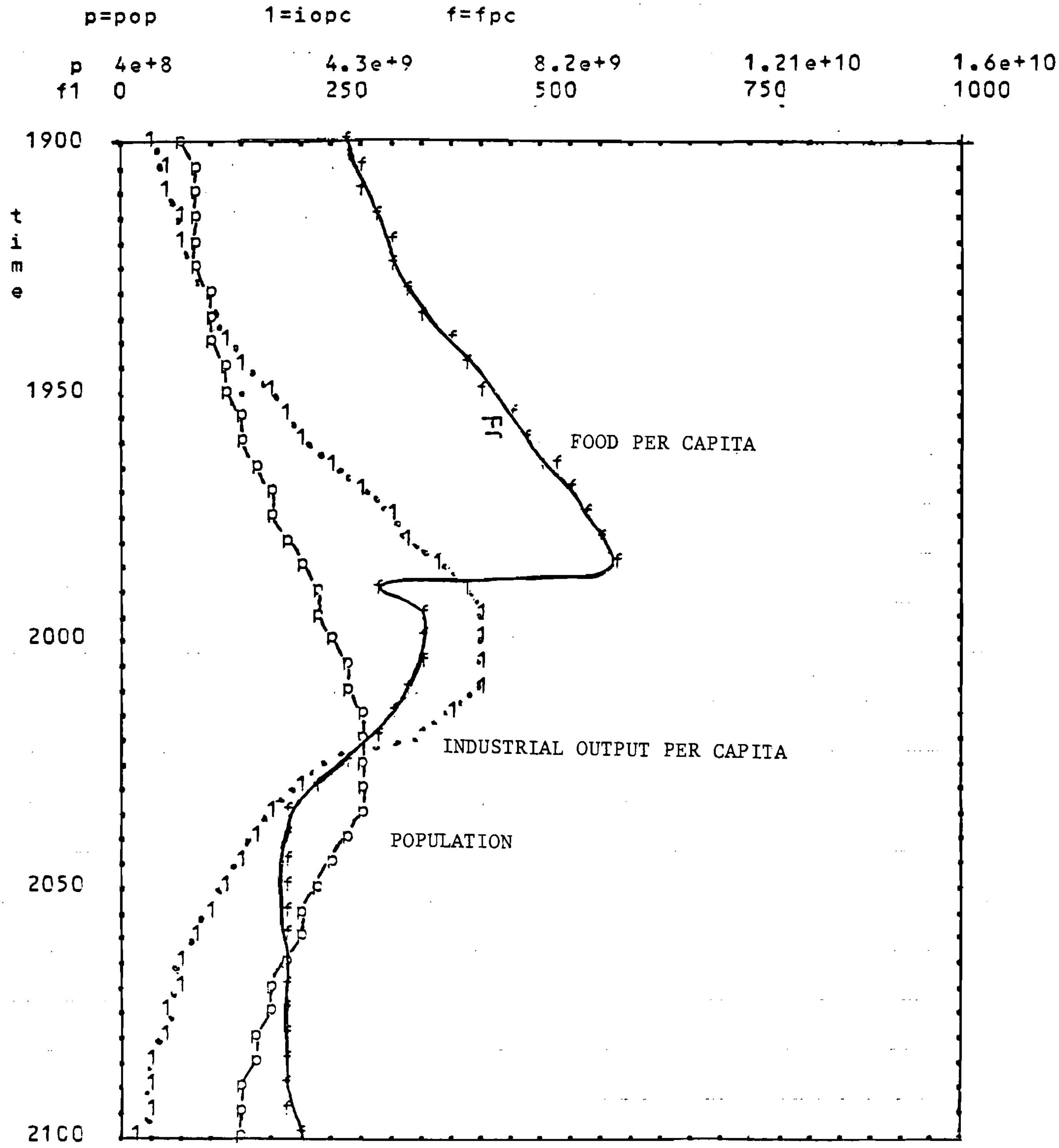

Figure 7. The results of the standard World-3 run with a 50% decrease in LFERT beginning in 1990.

Table 4. Deviations in level variables due to land fertility degradation.

SCENARIOS (Changes of LYFT and associated period)	**MAXIMUM DEVIATION OF LEVEL VARIABLES** (Deviation from standard case and the year when maximum deviation takes place)	
	POPULATION (% and millions of people)	FOOD (%)
1.0 to 0.8 (1990-2000)	3% (143m) year 2020	12% year 2000
1.0 to 0.7 (1990-2020)	4.5% (240m) year 2040	25% year 2020
1.0 to 0.6 (1990-2040)	12% (513m) year 2060	40% year 2040
1.0 to 0.8 with noise (1990-2000)	3.3% year 2020	19% year 2000

An interesting experiment with WORLD-3 is to superimpose a stochastic noise factor (LYFTN) on the continuously but slightly decreasing LFERT. The stochastic noise would be analogous to interannual weather fluctuations such as droughts which induce LFERT fluctuations. The results show that use of LYFTN with a small standard deviation has a weak influence on the general behavior of level variables ($D_P \approx 0.4\%$ for $D_{LYFT} = 0.05$ where D_P is the deviation in population and D_{LYFT} is the deviation in LYFT; see Table 4). This suggests that the model has some inertia that may help to resist short-term fluctuations but does not affect the main path of the global environmental changes.

To review what has been done in this study several significant points may be emphasized:

1) The use of global modeling suggests that the interactions between society and environment need to be considered and that forecasts of the "CO_2 doubling" type may need to be seriously revised.

2) Catastrophic climatic events might be viewed as additional natural "limits to growth" since even a simple and primitive introduction of such an event into the WORLD-3 global model brings about a dramatic deterioration of global conditions.

3) Since the regions most affected by a climatic change are likely to be in middle latitudes and climatic impacts would therefore not be distributed evenly over the globe, it is necessary for more sophisticated modeling to use multi-regional models (with trade flows between them and so on).

It should be pointed out that the preliminary nature of these experiments is due largely to the way in which the climatic impact has been introduced. Only land fertility experienced a climatic shock, even though it is quite clear that other aspects of human activity would be seriously damaged if such a shock were actually to occur. At this stage of "Climate and Society" experimentation, the climatic impact is only a simple correcting loop and is therefore not yet suitable for the study of any really strong interactions. In the future, it will be important to represent climatic and ecological effects more realistically (e.g., as in Figure 8). Such effects cannot be ignored totally since many geophysical scientists predict that they are possible under certain conditions.

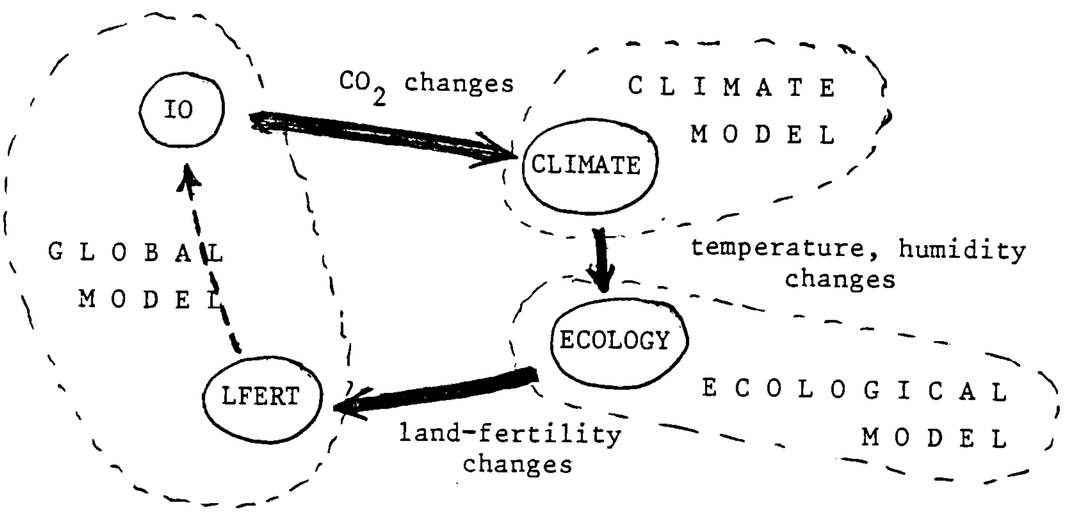

Figure 8. A loop that might be added to WORLD-3 to represent climatic and ecological links to the global model.

One important scientific need in the near term is to improve understanding of how links may be developed between dissimilar models and how new loops can be incorporated into existing global models. The study presented here should be viewed as a preliminary approach to this problem.

ACKNOWLEDGEMENTS

We would like to express our appreciation to Drs. Dennis and Donella Meadows for very fruitful discussions of our results and several suggestions for numerical modeling with WORLD-3 during our visit to IIASA in September 1982. We would also like to acknowledge R. Chen (IIASA) for his contributions to the study. His comments on the results and the draft of the paper were greatly appreciated. Finally, we thank M. Brandl for her able help in preparing the manuscript.

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