NOT FOR QUOTATION
WITHOUT PERMISSION
OF THE AUTHOR

PREDICTING CHANGES IN CROP YIELD DUE TO CO_2-INDUCED CLIMATIC CHANGE -- SOME CAUTIONARY COMMENTS

Robert G. Watts

March 1984

WP-84-15

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
2361 Laxenburg, Austria

PREFACE

For several years researchers at IIASA have been investigating that most crucial of interactions between man and the biosphere -- the interaction between climate and society.

In 1978, for example, a meeting was held on "Carbon Dioxide, Climate and Society". This meeting brought together experts from around the world to assess the state of knowledge on the prospects of climatic change resulting from increasing atmospheric injections of carbon dioxide and in particular to review work on this subject in the IIASA Energy Systems Program. In the same year, IIASA hosted the International Workshop on Climate Issues organized by the Climate Research Board of the US National Academy of Sciences and a preparatory meeting for the World Climate Conference organized primarily by the World Meteorological Organization (WMO) of the United Nations. In 1980, a Task Force meeting on the Nature of Climate and Society Research was convened to advance our knowledge of the relationship of climate to specific aspects of physical and social systems. More recently, in 1982, an international workshop on "Resource and Environmental Applications of Scenario Analysis" was organized. This workshop focused on innovative approaches for dealing with issues like climatic change which involve considerable uncertainty and require multidisciplinary analysis. Now, a major 2-year project is being implemented with the support of the UN Environmental Programme. This project is investigating the impacts of short-term climatic variations and the likely long-term effects of CO_2-induced climatic changes on agricultural output at the sensitive margins of food grains and livestock production.[1]

[1]For a description of the methodology behind this project, see Parry and Carter, 1983, Assessing impacts of climatic change in marginal areas: the search for an appropriate methodology, IIASA Working Paper, WP-83-77.

One of the first tasks of the project is to evaluate some of the impact models now available. This paper sets a high standard by examining closely both a particular model and also more general issues relating to model development. IIASA acknowledges the support given to this work by the U.N. Environment Programme and the Government of Austria.

Martin Parry
Leader
Climate Impacts Project

ACKNOWLEDGMENTS

This research was done while the author was a visiting scholar at the International Institute for Applied Systems Analysis in Laxenburg, Austria. I express here my appreciation to Dr. Martin L. Parry and Mr. Tim Carter, and to many other scientists at IIASA for making my stay there both pleasant and productive. I also thank Marilyn Brandl for typing the manuscript. The research was partly funded by a grant to the IIASA Climate Project from the Austrian Government.

CONTENTS

PREDICTING CHANGES IN CROP YIELD DUE TO CO_2-INDUCED CLIMATIC CHANGE -- SOME CAUTIONARY COMMENTS

Robert G. Watts

1. Introduction

Prediction that the atmospheric carbon dioxide content will reach twice the preindustrial value by the middle of the next century, and that this will lead to significant changes in the earth's climate, have led to renewed interest in the effect of climatic change on world food production.

CO_2 is a "greenhouse" gas. Its presence in the atmosphere produces a warming of the lower atmosphere because it is largely transparent to incoming solar radiation, but largely opaque to longer wavelength infrared radiation leaving the earth. Climate models indicate that a doubling of atmospheric CO_2 will probably cause the globally averaged temperature of the atmosphere near the ground to increase by 1.5° C to 4.5° C (National Academy of Sciences, 1983). Accompanying this increase will, of course, be changes in other climatic variables: precipitation, seasonality, winds, etc. Both recent numerical model experiments (Manabe, Wetherald, and Stouffer; 1981) and empirical estimates (Vinnikov and Groisman, 1979) indicate that the accompanying climatic change will depend strongly on both season and location. While climatologists can say with confidence that CO_2-induced climatic change will be spatially and temporally nonuniform, there is considerably less confidence in quantitative predictions of the variations. Generally, however, it appears that temperature increases will be largest at high latitudes during winter (decreasing seasonality) and that the difference between precipitation and evaporation will decrease in many mid-latitude continental regions (decreasing soil moisture). The latter, especially, is cause for concern because of the possible effects on agricultural productivity (Manabe, Wetherald, and Stouffer, 1981).

The effect of weather and climate on crop production is at least as complex and difficult to predict as is the climate itself. The rate of growth of a particular crop plant depends on local values of wind speed, humidity, CO_2 concentration, solar flux, and a host of other climatic variables as well as on the availability of nutrients from the soil. The yield of a crop is typically dependent upon the details of climate patterns over the growing season. Thus, rather short time scales are probably necessary in order to relate annual yield to weather and climate. It must also be kept in mind, however, that soil characteristics can change with soil moisture availability and other climatic variables, and that these changes might occur on time scales of many years. Thus, the range of time scales necessary for the proper treatment of climate and of agricultural systems seems to be somewhat similar.

A number of models of varying complexity have been developed for studying the effects on agricultural yield of changes in a variety of external (climatic) variables. These models fall generally into two broad classes (although some resist such categorization): simulation models and empirical-statistical models. Simulation models generally treat the dynamics of plant or crop growth over a single season by computing basic plant processes such as photosynthesis, respiration, transpiration and the like (see, e.g., Monteith, 1981). In some cases certain elements of soil physics and chemistry are also included (Shawcroft et al., 1974). Excellent summaries of some of these models can be found in Baier (1977). A very complex and comprehensive environmental model that contains both crop growth and soil components is the VNIISI model (Kroutko et al, 1982). The crop model uses only annually averaged climate data (i.e., seasonal variations are not accounted for) but it has the advantage of allowing other variables, such as soil characteristics, to evolve over very long times.

Empirical-statistical models use year to year variations in yield together with variations in selected climatic variables to devise yield-climate correlations through multiple regression analysis. The results are essentially always site and crop specific, and by their nature cannot account for long-term changes in soil characteristics due to climatic change. (Long-term trends are normally lumped together under the heading of "technological change".) Empirical-statistical models have been reviewed by Baier (1977). Models of this type have been used by Palutikof et al. (1983) and others to assess the possible influence of CO_2-induced climatic change on crop yields.

In the next section a simple formulation of yield sensitivity to climatic change is presented as a device for demonstrating that factors operating on separate time scales can lead to a certain amount of confusion in interpreting sensitivity obtained from short-term experiments with crop yield models or from empirical-statistical models. Long-term and short-term sensitivities of a given crop to changes in climatic variables can be quite different.

In Section 3, the results of some sensitivity studies using the VNIISI model are presented. While making no claim on the quantitative accuracy of these results, I note that the differences between long- and short-term sensitivities of wheat yield to precipitation are perhaps cause for a re-examination of the way yield sensitivity is defined and measured. This is briefly discussed in the last section.

2. Sensitivity

The yield of a particular crop depends upon many climatic variables, such as rainfall, temperature, sunlight, and their seasonal variations. Even the diurnal cycle can be important, as in the cases of tomatoes and potatoes, for example, which apparently grow best when there is a pronounced diurnal temperature cycle (Oliver, 1973). In addition to climate, yield depends upon a variety of chemical and physical properties of the soil; for example, its permeability, acidity, and available nutrients. These properties can change in response, for example, to precipitation changes, with time constants of many years.

Obviously, no model can hope to account for all the *variables* that affect crop yield. To keep matters simple, and for the sake of the following argument, let us suppose that yield (Y) depends upon a set of temperatures (T_i), a set of precipitation values (P_j) and a soil index (S) which somehow contains all of the appropriate soil properties.

$$Y = Y(T_i, P_j, S) \tag{1}$$

For any given year, or over a few consecutive years, the soil index will remain sensibly constant. Thus, the change in yield accompanying changes in the variables T_i and P_j can be expressed as

$$\Delta Y = \sum_i \frac{\delta Y}{\delta T_i} \Delta T_i + \sum_j \frac{\delta Y}{\delta P_j} \Delta P_j \tag{2}$$

The quantities $\left[\frac{\delta Y}{\delta T_i}\right]$ and $\left[\frac{\delta Y}{\delta P_j}\right]$ are the sensitivities of yield to short term variations in T_i and P_j, respectively. One might reasonably hope to obtain sensitivities of this sort by the kind of multiple regression schemes used in the empirical-statistical models.

If a change in climate persists over a very long time (some tens of years, say) then ultimately the soil index will change. This change will be reflected in the yield.

$$\Delta Y = \sum \frac{\delta Y}{\delta T_i}\Delta T_i + \sum \frac{\delta Y}{\delta P_j}\Delta P_j + \frac{\delta Y}{\delta S}\Delta S \tag{3}$$

Assuming that the climate changes from one statistical steady state to another, and that (to continue our simplistic view) soil index is a function of long-term averaged climatic conditions such as local time average temperature (T) and precipitation (P), then

$$S = S(T,P), \tag{4}$$

and

$$\Delta S = \frac{\delta S}{\delta T}\Delta T + \frac{\delta S}{\delta P}\Delta P \tag{5}$$

Substitution into (3) gives

$$\Delta Y = \sum \frac{\delta Y}{\delta T_i}\Delta T_i + \sum \frac{\delta Y}{\delta P_j}\Delta P_j + \left[\frac{\delta Y}{\delta S}\right]\left[\frac{\delta S}{\delta T}\right]\Delta T + \left[\frac{\delta Y}{\delta S}\right]\left[\frac{\delta S}{\delta P}\right]\Delta P \tag{6}$$

The last two terms in (6) represent long-term sensitivities of yield to temperature and precipitation changes acting through the mechanism of changes in soil characteristics.

3. Long- and Short-Term Sensitivities

The VNIISI model is unique in that it can be used to predict the response of wheat yield to both interannual and long term changes in precipitation and temperature. It can therefore be used to explore the relative importance of the short-term and long-term sensitivity terms in (6). It should be stated at the outset that I make no claim on to the quantitative accuracy of the results to be described below. I am not making predictions about sensitivity. My conclusions will be stated in the most general way. At this stage I am more interested in seeking what questions should be asked to guide future research in crop-climate interaction than in finding definitive answers.

I examined the sensitivity of the model to temperature and precipitation changes in the following way. First the soil and geography of the model were fixed to represent approximately the Great Plains of the United States (plains, loamy sand). Nitrogen fertilizer application was fixed at 0.05 tonnes per hectare and phosphorus at 0.01 tonnes per hectare (similar to current fertilizer use on wheat in Kansas) for one set of runs (Figure 2), and at 0.07 tonnes nitrogen per hectare and 0.05 tonnes of phosphorus per hectare for another (Figure 1). The model allows for local temperature to be changed as an input. Long-term average precipitation values can also be specified, but the model itself imposes a stochastic variation of precipitation about the average value. I chose various temperature and precipitation values and ran the model until a statistical steady state was reached. Average yield and the variations of precipitation and yield about the average were recorded. The experiment was then repeated for another set of average temperatures and precipitations.

The results are shown in Figure 1 and 2. I did many runs for various soil types, fertilizer application rates, and geographic regions, and the results were all qualitatively similar to those shown. The solid lines in each figure show the steady state variations of yield with (average) precipitation for various temperatures. The slopes of these lines represent the long-term sensitivities of yield to precipitation changes at various temperatures. The dashed lines represent variations of yield caused by the year to year variation of precipitation. The two are clearly not the same. In fact, for the cases of $T = 9^{\circ}$ C, and $T = 7^{\circ}$ C with P = 670 mm/yr, the *signs* of the sensitivities are different.

4. Some Tentative Conclusions

What can be concluded from this? I emphasize once more that I do not present the data in Figures 1 and 2 as quantitatively accurate sensitivity data for use in

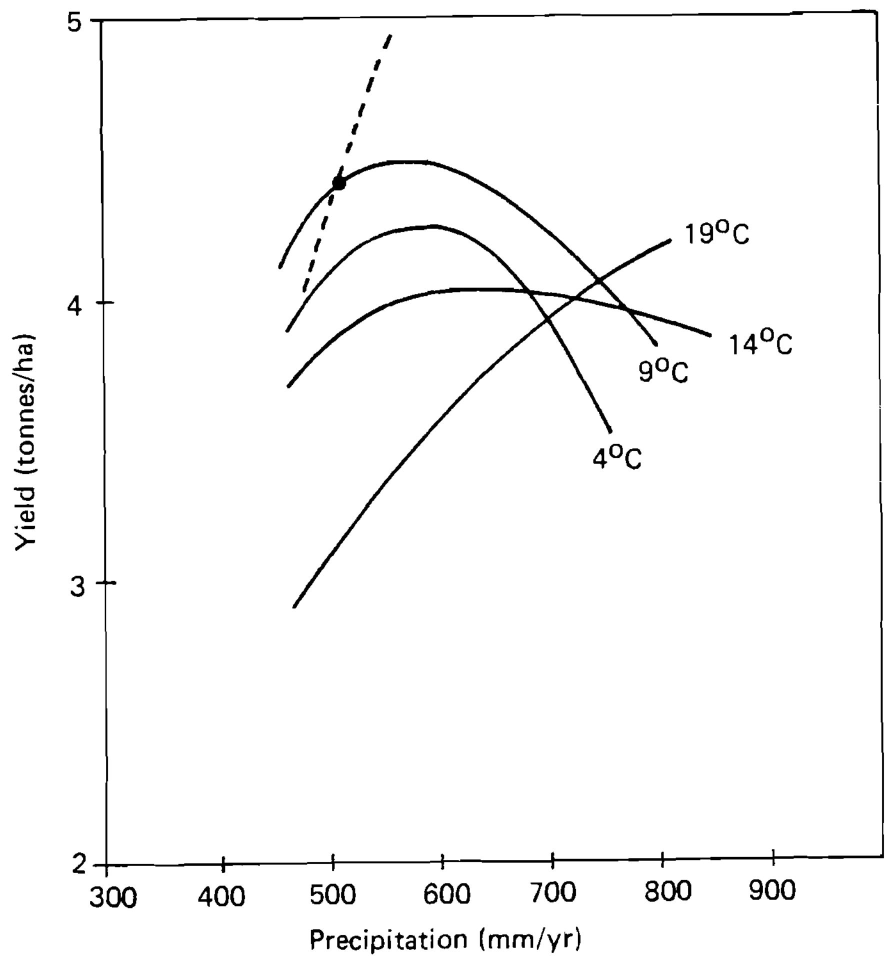

Figure 1. Long- and short-term sensitivities for wheat (nitrogen fertilizer, 0.07 tonnes/ha; phosphorus fertilizer, 0.05 tonnes/ha).

devising scenarios of crop yield following CO_2-induced or other climatic change. I merely wish to point out that short- and long-term sensitivities may not be the same, that empirical-statistical crop yield models measure only the first two sensitivity terms in (6), while in analyzing crop yield changes due to long-term climatic change *both* are important.

This last comment is perhaps in need of some elaboration. Long-term changes in climate, in temperature and precipitation, say, quite obviously might affect average crop yields. It appears from the present results that the sensitivity to short-term climatic variations, i.e., the short-term sensitivities, also change when long-

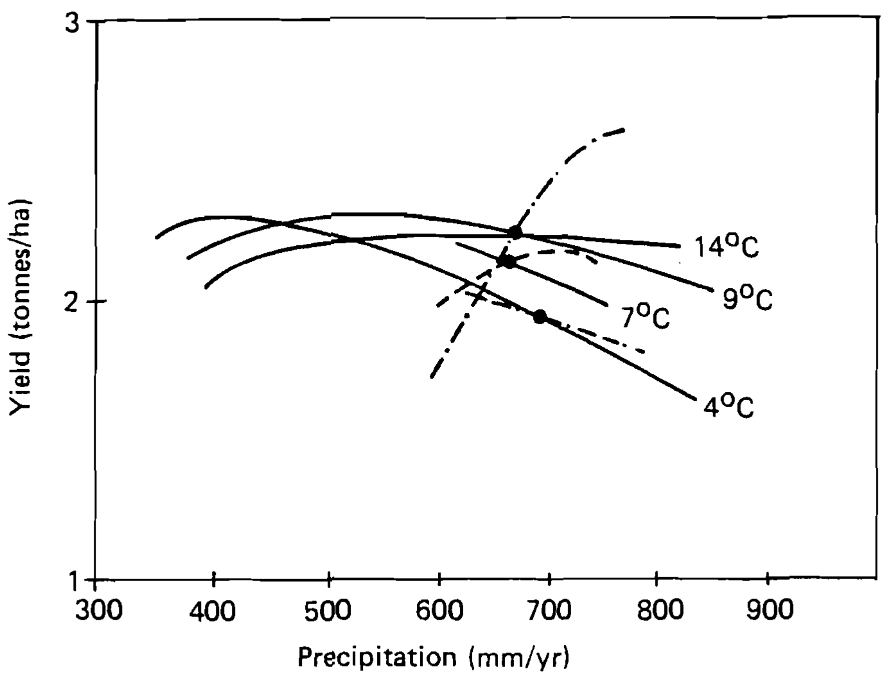

Figure 2. Long- and short-term sensitivities for wheat (nitrogen fertilizer, 0.05 tonnes/ha; phosphorus fertilizer, 0.01 tonnes/ha).

term climatic change occurs. Variability of interannual temperature and precipitation is also expected to change in response to long-term climatic change. If a given climate change caused both these variabilities and the associated short-term sensitivities to decrease, the variability of crop yields could decrease substantially, and this could be very important for regions of marginal agriculture (Parry, 1976). On the other hand, increases in both variabilities and short-term sensitivities could prove disastrous to marginal agriculture, even if long-term average yields increased.

What does this suggest about future research in the effect of long-term climatic change on agriculture and food production? I believe that it points towards the need for intensified efforts to *understand* the climate-crop-soil system in a holistic sense. This is, of course, an enormously difficult job. For one thing, large scale computational approaches like that used in the VNIISI model tend to hide the physics. Computational exercises such as the one reported here cannot often lead to the same kind of physical understanding that can be gained from simpler models that are described by sets of equations that can be manipulated by hand. Moreover, the VNIISI model does not really include enough (!) in its computation of crop yield, since yield responds only to annually averaged climate. However, I do not want to imply that I believe that *only* large scale models should be studied. In the field of climatology, much understanding has resulted from the study of the whole span of models, from simple energy balance models to general circulation models. The same is true of models of the climate-crop-soil system. Real understanding of the system will come when each of its components is understood. There is an urgent need for this.

REFERENCES

Baier, W. 1977. Crop-weather models and their use in yield assessments. World Meteorological Organization Technical Note No. 151. Geneva, WMO.

Kroutko, V.N., S.A. Pegov, and B.M. Khomyakov. 1982. A dynamic model of environmental development. Preprint. The All-Union Institute for Systems Studies (VNIISI). Moscow.

Manabe, S., R.T. Wetherald, and R.J. Stouffer. 1981. Summer dryness due to an increase of atmospheric CO_2 concentration. *Climatic Change* 3:347-386.

Monteith, J.L. 1981. Climatic variation and the growth of crops. *Q. Journal of the Royal Meteorological Society* 107:749-774.

Oliver, J.E. 1973. *Climate and Man's Environment: An Introduction to Applied Climatology.* John Wiley and Sons, Inc., New York.

Palutikof, J.P., T.M.L. Wigley, and G. Farmer. 1983. The impact of CO_2-induced climatic change on crop-yields in England and Wales. *Int.J. of Biomet.* (in press).

Parry, M.L. 1976. The significance of variability of summer warmth in upland Britain. *Weather* 31:212-217.

Shawcroft, R.W., E.R. Lemon, L.H. Allen, D.W. Stewart, and S.E. Jensen. 1974. The soil-plant-atmosphere model and some of its predictions. *Agricultural Meteorology* 14:287-307.

Vinnikov, K.Ya., and P.Ya. Groisman. 1979. Empirical model of modern climatic changes. *Meteorologiya i Gidrologiya* 3:25-36. (Translated from Russian by Allerton Press.)