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CROP YIELDS AND CLIMATE CHANGE TO THE YEAR 2000. VOLUME I. REPO--ETC(U)
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CROP YIELDS AND CLIMATE CHANGE TO THE YEAR 2000

VOLUME I

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CROP YIELDS AND CLIMATE CHANGE TO THE YEAR 2000,

VOLUME I.

REPORT ON THE SECOND PHASE OF A CLIMATE IMPACT ASSESSMENT.

CONDUCTED BY THE

RESEARCH DIRECTORATE
OF THE
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// 1980

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FOREWORD

Economic issues are becoming more important in the relationships between the United States and other countries. This second National Defense University (NDU) report on climate and crops addresses one element in the complicated calculus of economic strengths and vulnerabilities.

The authors conclude that, to the year 2000 at least, climate will probably be a much weaker determinant of crop yields than agricultural technology. Nevertheless, they found interesting country-to-country differences among the responses of crop yields to possible climate changes.

The study was conceived against a backdrop of concern about the effects of climatic change on shrinking world food reserves. Although some of that concern evaporated after five years of high worldwide grain production, the initial research question has assumed a new relevance following the recent spate of poor harvests and President Carter's partial embargoes on the export of grain and technology to the Soviet Union. It should be noted, however, that the research project was originally undertaken with only the general idea that U.S. agriculture is an important national security asset. It seemed useful to future policymaking for NDU to help estimate how various climate changes might affect the global agricultural economy.

A secondary goal of this interdisciplinary effort was to advance the art of making climate impact assessments; the research team devised a prototype climate-response model. In addition, the team combined futuristic and probabilistic techniques with expert judgments to surmount two major obstacles: data voids and the relative uncertainty surrounding future climate and technology.

We at the National Defense University extend our deep appreciation to the cosponsoring agencies for their support and to the many individuals whose professional contributions made this study possible.

R. G. GARD, JR.
Lieutenant General, U.S. Army
President

ABSTRACT

As previously reported, a broad spectrum of subjective probabilities was distilled into five scenarios which describe possible global climate changes to the year 2000. Reported herein are estimates of how crop yields would respond to these climate changes if there were no changes in agricultural technology. The most likely climate change, a slight global warming with a "probability" of 0.30, was found to have negligible effects on 15 "key" crops. The more appreciable effects of the other climate changes differed from crop to crop in direction and magnitude; Canadian and Soviet wheat yields registered the largest responses. The potential crop-yield effects of technological change are judged to be severalfold larger than the effects of the posited climate changes.

* * * * * * *

In the second phase of this study, a simple climate-response model was used to project frequency distributions of annual yields, absent technological change. The inputs for a particular crop and assumed climate change were (1) a joint distribution of annual temperature and precipitation, and (2) an expression for annual yield as a function of the same variables. The first input was derived from the climatological records of the crop region, the second from estimates made by an Agriculture Panel.

The panelists also projected yield trends to 2000 AD in consideration of perceived changes in technology, but no change in climate. When aggregated, their projections imply yield increases of about 10% for Australian wheat and 50% for Argentine corn; the remainder of the expected technology-induced increases lie between 20% and 40%.

The primary purpose of the second phase, however, was to isolate and quantify the effects of plausible climate changes. Aside from the slight global warming, the climate scenarios delineated a large cooling ("probability" 0.10), a moderate cooling (0.25), a moderate warming (0.25), and a large warming (0.10).

1. In order of sensitivity, Canadian wheat, Soviet spring wheat and Soviet winter wheat were the key crops most affected, partly because global temperature changes are amplified at higher latitudes. Average yields were depressed 4.3% to 3.4% by moderate cooling and 8.5% to 6.2% by large cooling. The moderate and large warmings enhanced yields by somewhat smaller percentages; the slight warming enhanced them by fractions of a percent.

2. Next most sensitive were Australian wheat, Argentine wheat, Argentine corn and Indian wheat, all of whose yields were stimulated in the two cooling scenarios and inhibited in the three warming scenarios.

3. Less sensitive still were U.S. corn, soybeans and winter wheat, which had positive responses to cooling, as well as U.S. spring wheat and Chinese winter wheat, which had negative responses. Moderate and large warming elicited opposite yield responses.

4. The average yields of three subtropical crops—Indian rice, Chinese rice and Brazilian soybeans—were depressed slightly in all the climate scenarios.

These technology-neutral conclusions are subject to considerable uncertainty regarding the expected zonal changes in precipitation, the more important of the two weather/climate variables.

The influence of a climate change on the interannual variability of yields is more problematic than its consequences for average yields. Relative variability generally decreased in the cooling scenarios and increased in the warming scenarios; Soviet winter wheat was a signal exception to this pattern. For most crops, climate-induced yield trends would be masked by both the year-to-year fluctuation of yields and the enhancement of yields due to technological factors. Nevertheless, the yield projections for 2000 suggest that, on the margin and with low probability, climatic change could have substantial effects (directly or indirectly) on the agricultural economies of several countries, if not on total world food production. Such effects and their policy implications are examined in the final phase of the National Defense University's climate impact assessment.

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PREFACE

The buildup of carbon dioxide will lead to global warming! The earth is entering another ice age! Public concern about such pronouncements is being translated into support for a coordinated attack on fundamental climatic questions.

At the international level, the World Meteorological Organization and other U.N. agencies sponsored a World Climate Conference in February 1979. The conferees declared that "an interdisciplinary effort of unprecedented scope" is needed if climate is ever to be predicted in a meaningful way. A few months later, a congress of the WMO resolved to implement a comprehensive World Climate Program aimed at a better understanding of the causes and effects of climatic change, past and future. Responsibilities for the four main facets of the program—climate data, climate applications, climate research, and climate impact studies—will be shared variously among the WMO, the International Council of Scientific Unions, the United Nations Environment Program, the U.N. Food and Agricultural Organization, and several other entities.

Earlier, in September 1978, President Carter had committed the United States to parallel goals when he signed the National Climate Program Act (Public Law 95-367). Two years prior to that milestone, the National Defense University undertook a pilot climate impact assessment, presuming to quantify what will remain unknowable for some time.

The policy-oriented NDU project addressed two questions. How much is climate likely to change by the year 2000? To what extent will possible climatic changes affect economic and military activities? With respect to the first question, we queried climatologists for probabilistic answers that would be of some use to policymakers in lieu of reliable, scientifically based predictions. The second question proved too ambitious, so we settled for a case study of agriculture. However, our climate-response methodology can be transferred to other subject areas by replacing its objective functions (annual crop yields) with, say, functions pertinent to heating-fuel requirements or water resources.

The focal point of the endeavor was a small, interdisciplinary staff drawn from several branches of the Government. Assisted by the Institute for the Future, the resident staff conducted a brokerage operation, planning the study around futuristic techniques for the solicitation and analysis of nonexistent information, and orchestrating advice, "data" and insights from a host of volunteers.

The study was broken into the tasks described at the beginning of the summary chapter. In Task I, after surveying a panel of climatologists, the staff developed and published five global climate scenarios for the year 2000. Task II, the main subject of the present report, dealt with the implications of the climate scenarios for the yields of selected crops, in the absence of technological change. The implementation of Task II resembled that of Task I, i.e., the staff processed and analyzed contributed data. Roles were reversed for Task III, the results of which are being published separately. In this instance the staff furnished data (climate-crop scenarios) for a policy analysis by an invited group of agricultural economists.

The climate-response model used in Task II has several virtues, one being the capacity to handle arbitrary climate changes. (We take no sides in the debate between "warmers" and "coolers.") Another is its potential for generalization beyond agriculture. And not least is the model's transparency: crop yields were related to temperature and precipitation by means of a natural, first-principles logic without resort to "fitting." The independent weather/climate variables and the dependent crop-yield variables were treated as incremental departures from the averages of the recent past, making it easier to compare inputs and outputs between crops and climate scenarios. One might criticize the failure of the model to account for all the complications of real life. Additional crop-weather variables could indeed be accommodated, at a price. Despite its simplicity, the present model generates quantitative answers in considerable detail; by projecting *distributions* of annual yields, it reflects the impact of a climate change on the year-to-year variability of yields, as well as the impact on average yields.

Had there been a choice, we would have employed "hard" data throughout Task II. But we hold that an assessment founded on expert judgments is preferable to none. Nothing ventured, nothing gained. The inputs to the climate-response model are (1) an expression for yield as a function of annual temperature and precipitation, (2) an assumed climate change, and (3) a joint distribution of annual temperature and precipitation corresponding to the climate change. The annual-yield functions were aggregated from estimates made by members of our Agriculture Panel. Since the climate of 2000 AD cannot be predicted, we used the global climate scenarios that were formulated in Task I. The joint distributions of annual temperature and precipitation are "hard" data insofar as they are based on climatological records of the recent past. All three input components are of interest quite apart from what the climate-response model does with them.

On the output side of the ledger, the reader will find five mutually exclusive (but not necessarily exhaustive) global climate-crop scenarios. The scenarios are not predictions. Rather they are plausible, coherent pictures of climate and crop yields around the year 2000; they are incomplete in that only the "pure" effects of climate change have been quantified. The scenarios are assigned subjective probabilities of occurrence, a novel feature intended to increase their utility for policymakers. Also, we went beyond the specific climate scenarios of Task I and compiled an atlas of yield responses for a continuum of climate changes. With this atlas the reader can construct climate-crop scenarios *ad lib*. To complement the technology-neutral scenarios, we present the Agriculture Panel's perceptions of how technological changes might affect yields if there were no climate change. The technology projections cast some light on the relative importance of technology and climate for the remainder of the 20th century. However, the uncertainty manifested in the technology projections bespeaks a need for additional research on ways to extrapolate technology trends and analyze the interactions between technology and climate.

At the outset, the study seemed to be well worthwhile if it could place in perspective some of the conflicting and dire assertions about climate change that were then in circulation. We are reasonably sure now that from a global standpoint climate change is unlikely to be a critical determinant of crop yields during the next two or three decades. We cannot, of course, rule out greater climatic effects in the more distant future.

In drafting this report we envisioned an inhomogeneous audience of meteorologists, climatologists, agronomists, economists, futurists, model builders, and policymakers, to name a few. The Summary is designed to meet part of everyone's needs. Beyond that, the subject matter is divided between methodology and inputs, on the one hand, and results on the other. Chapter I is devoted to methodology. The basic results appear in Chapter II (the effects of technological change on crop yields) and Chapter III (the climate-crop scenarios). Chapter IV contains comparative analyses of the basic results, as well as an examination of the expertise represented in the crop-yield data bases. In the second volume we elaborate on the climate-response model, present inputs and outputs of general interest, and discuss questions of sensitivity and uncertainty (Chapters V and VI). Material deemed to be of narrower interest was consigned to appendixes.

Some caveats are in order for a demonstration project of this sort. We recognize that refinements and extensions of Tasks I and II are desirable. Anyone using the results of this report should appreciate not only our assumptions and methodologies, but also the uncertainties that arise from the substitution of expert judgment for "hard" data. Finally, the reader should note that there is no attempt to project the *combined* effects of changes in technology and climate.

ACKNOWLEDGMENTS

The Research Directorate of the National Defense University (NDU) was merely a catalyst and logistical facilitator of this climate project. The credit for the present report on Task II belongs to scores of people whom I am pleased to acknowledge on behalf of my predecessors.

Mr. Joseph W. Willett, recently retired from the U.S. Department of Agriculture, proposed the study in 1976 when he was a Senior Research Fellow at The National War College, and he remained in close touch with it. Lieutenant General Robert G. Gard, Jr., U.S. Army, President of the NDU, like his predecessor Vice Admiral M. G. Bayne, U.S. Navy (Retired), supported the research as a matter touching on the broad security interests of the United States.

Colonel Andrew J. Dougherty, U.S. Air Force (Retired), the university's first research director, was the prime mover of the project. But for his persistence and powers of persuasion, the enterprise would have been stillborn. After winning the support of several government agencies, he assembled a small staff of full-time Senior Research Fellows and part-time investigators, and simultaneously recruited a standing Advisory Group representative of the public and private sectors. His successor, Captain John J. McIntyre, U.S. Navy (Retired), supervised the later stages of the project.

The Defense Advanced Research Projects Agency contributed funding through its Cybernetics Technology Office, which was directed at the time by Dr. Robert A. Young. Dr. Young's encouragement was an intangible asset, while a DARPA contract secured the collaboration of the Institute for the Future, Menlo Park, California. Thanks to the DARPA computer network, Dr. Roy Amara, president of the Institute, and Dr. Hubert Lipinski became staff members at a distance. They suggested appropriate methodologies and furnished computer programming and other technical assistance in the analytical phases of the first two tasks.

Without the Climate Panel there would have been no *Climate Change to the Year 2000*, the initial report on the project. So again we recognize the highly respected climatologists who provided the substance for the climate scenarios, the first building block of Task II. Equally indispensable were the distinguished members of the Agriculture Panel whose crop-yield estimates formed the second building block.

ACKNOWLEDGMENTS

Major Russell A. Ambroziak, U.S. Air Force Reserve, an analyst with the Central Intelligence Agency, played a unique role. In his capacity as Adjunct Research Fellow at the NDU, he conceived and developed the climate-response model which was the mortar of Task II. Furthermore, he researched the third building block, the joint distributions of annual temperature and precipitation.

For completeness, we must also acknowledge the members of the Policy Panel who used the Department of Agriculture's world food economic model to analyze the policy implications of this report. Their analysis, which is informed by their expertise in agricultural economics, will be published later as a Task III report.

The dispersion of the advisers and panelists was a handicap, but there was enough interaction to spawn an abundance of serendipity and synergism. The Advisory Group was our principal safety net, a necessity because NDU was out of its normal element. The advisers helped fill in the details of the study plan, critiqued the methodology, and reviewed the results. We are doubly indebted to those advisers who also performed yeoman service as panelists. And we are happy to note that one adviser was a 1979 Nobel Laureate in economics.

Colonel Theodore H. M. Crampton drafted this report with numerous contributions and suggestions from Major Russell A. Ambroziak, Dr. Hubert Lipinski and sometime staff colleagues Dr. Paul C. Dalrymple, Mr. William R. Gasser and Colonel Vernon M. Malahy, Jr. Many able NDU employees—editors, research assistants, secretaries, artists and illustrators—worked on the text, graphics and design. Mrs. Deloris A. Midgette, U.S. Department of Agriculture, did an outstanding job on the word processing for about half the text.

The National Defense University is very grateful to those mentioned above, to all those listed below, and to the cooperating agencies whose personnel manned the project staff.

FRANKLIN D. MARGIOTTA
Colonel, U.S. Air Force
Director of Research
National Defense University

RESIDENT STAFF

The full-time Senior Research Fellows, with the dates they returned to their parent organizations, were:

Mr. William R. Gasser, U.S. Department of Agriculture (USDA), May 1978
Colonel Vernon M. Malahy, Jr., U.S. Air Force, June 1978
Dr. Paul C. Dalrymple, U.S. Army Engineer Topographic Laboratories, December 1978
Colonel Theodore H. M. Crampton, U.S. Army

Mr. Gasser, who retired in early 1980, is an agricultural economist. The specialties of the other fellows are respectively meteorology, geography and mathematics. Two part-time investigators rendered valuable assistance:

Dr. Richard E. Felch, agricultural climatologist, USDA
Mr. Douglas M. LeComte, meteorologist, National Oceanic and Atmospheric Administration (NOAA)

In addition, the historical data presented in the crop-yield questionnaire (Appendix A-1) were provided by:

Mr. Richard C. McArdle, agricultural economist, USDA
Lieutenant Colonel David S. Lydon, meteorologist, U.S. Air Force

ACKNOWLEDGMENTS

ADVISORY GROUP

The composition of the Advisory Group changed over time. Dr. J. Murray Mitchell, Jr., was the senior scientific adviser for Task I. During Task II this role was filled by the troika of Drs. James E. Newman, Louis M. Thompson, and Eric G. Walther. The Advisory Group was convened at Fort McNair in December 1976, June and December 1977, and September 1978. Subgroups of advisers met for special purposes in July, August and November 1977, and March 1978. Members who attended at least one meeting are listed below; the affiliations were effective as of the meeting dates.

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DR. GEORGE ALLEN, Oxford University
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From Foundations and Research Institutions

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DR. EDWARD DEAGLE, Rockefeller Foundation
DR. MALCOLM GRAY, Aspen Institute for Humanistic Studies
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DR. WALTER O. ROBERTS, Aspen Institute for Humanistic Studies
DR. FRED H. SANDERSON, Brookings Institution
DR. ERIC G. WALTHER, Charles F. Kettering Foundation (initially) and John Muir Institute
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ACKNOWLEDGMENTS

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The following individuals responded to the crop-yield questionnaire (Appendix A-1); affiliations were effective as of late 1977:

DR. GERALD F. ARKIN, Texas A&M University
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DR. LOUIS M. THOMPSON, Iowa State University
DR. ERIC G. WALTHER, Charles F. Kettering Foundation
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CLIMATE PANEL

Listed below are the scientists who responded to the climate questionnaire in Task I; affiliations were effective as of spring 1977.

DR. HIDETOSHI ARAKAWA, Tokai University, Japan
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POLICY PANEL

Dr. D. Gale Johnson was the principal investigator for Task III and drafted the forthcoming report. Mr. Patrick M. O'Brien did the computational work using the USDA Grain-Oilseeds-Livestock model. The other panelists helped plan Task III, reviewed intermediate results, and commented on the draft report.

DR. GEORGE ALLEN, Oxford University
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DR. ERIC G. WALTHER, John Muir Institute

SUMMARY

TED CRAMPTON

SUMMARY

S-1 INTRODUCTION

Some scientists foresee a cooler world climate by the turn of the century, others a warmer one. In 1976, the Research Directorate of the National Defense University organized a cooperative study to quantify such judgments and assess the impact of the perceived climate changes on agriculture. The study was divided into four tasks:

- Task I: To define and estimate the likelihood of changes in climate during the next 25 years, and to construct climate scenarios for the year 2000.

- Task II: To estimate the likely effects of possible climatic changes on selected crops in specific countries, and to develop a methodology for combining crop responses and climate probabilities into climate-crop scenarios for the year 2000.

- Task III: To evaluate the domestic and international policy implications of the climate-crop scenarios, and *to identify the climatic variables that are of key importance* in the choice of policy options.

- Task IV: To transfer the climate-crop research results and a generalized climate-response methodology to individuals and organizations concerned with the consequences of climatic changes in fields other than agriculture, and *to identify areas of research which might refine or extend the findings of the first three tasks.*

The results of Task I were published in *Climate Change to the Year 2000, A Survey of Expert Opinion*, National Defense University, February 1978. The present report is concerned with Task II and the italicized portions of Tasks III and IV.

Task II was accomplished by means of a simple, discrete climate-response model of apparently broad applicability. To project the effects of an assumed climate change on a particular crop, the model combines two matrices; one matrix expresses relative annual yield as a function of mean temperature and precipitation, and the other describes the joint distribution of annual temperature and precipitation. The primary output of the model is a frequency distribution of relative annual yields which reflects the year-to-year variability of temperature and precipitation in the assumed climate state. The annual-yield matrix is based on estimates solicited from a panel of agricultural scientists, and the crop-weather matrix is based on climatological records.

The model isolates the climate component of crop yields by assuming a constant agricultural technology. To help the panelists put aside the dynamics of technology before they addressed weather-yield relationships for a crop, we asked them to project separately the effects of technology on yield trends assuming no change in climate between 1976 and 2000. Although technology was a secondary issue in the context of Task II, the technology component of crop yields is a subject of great importance. Indeed, one of our principal conclusions is that technology, rather than climate, is likely to be the chief determinant of most crop yields in the last quarter of the 20th century.

S-2 METHODOLOGY: THE CLIMATE COMPONENT OF CROP YIELDS

The climate-response model projects frequency distributions of annual crop yields for arbitrary climate states, which are referred to the climate of the recent past (the "Base Period"). In calculating these distributions we assumed no change from the indigenous technologies in 1976. The inputs and outputs of the model are illustrated in Chapter I.

The model was applied to the 15 "key" country-crop combinations in Table S-1. Peculiar to each combination is a matrix whose elements express relative annual yield Y as a function of ΔT and ΔP, where

ΔT = the departure of a year's mean heading-period temperature from the long-term average prevailing in the Base Period, and

ΔP = the percentage departure of the same year's mean crop-year precipitation from the long-term average prevailing in the Base Period.

To be more precise, the annual crop-weather points (ΔT, ΔP) are midpoints of rectangular regions in the temperature-precipitation plane. The same yield value Y(ΔT, ΔP) is ascribed to all joint weather events that lie in the rectangle centered on the point (ΔT, ΔP). All three variables are considered to be spatial averages for the crop region of interest. The annual-yield matrix is itself an expertise-weighted average of individual matrices submitted by members of the Agriculture Panel. Graphs of the aggregated annual-yield functions are presented in Section 5-5.

Associated with each annual-yield function Y(ΔT, ΔP) is a climatological probability density function. The latter is a bivariate normal distribution (BND) which approximates the joint distribution of ΔT and ΔP observed in the Base Period. The duration of the Base Period varies from crop to crop according to the length of the available climate records from which were extracted the parameters of the BND—the standard deviations of ΔT and ΔP, and their correlation coefficient. The bivariate normal distribution is treated as a matrix indexed by ΔT and ΔP; each matrix element BND(ΔT, ΔP) gives the probability that a joint departure of temperature and precipitation will fall in a rectangular region of fixed dimensions centered on the crop-weather point (ΔT, ΔP).

To calculate the probability that an annual yield will lie within a particular interval of yields, one sums the probabilities BND(ΔT, ΔP) such that the corresponding yields Y(ΔT, ΔP) lie in the interval. Doing this for a sequence of adjacent yield intervals, one constructs the frequency distribution of annual yields induced by the joint distribution of ΔT and ΔP in the Base Period. With some obvious liberty, we interpret the Base-Period BND for each country-crop combination as a description of "present" climate, or the state of "no climate change." However, the Base-Period yield distributions have no direct historical analogs because they are "frozen" in 1976 technology.

In our model, a climate change is a joint occurrence of ΔT and ΔP, where

ΔT = change in the long-term average of annual mean heading-period temperature, and

ΔP = percentage change in the long-term average of mean crop-year precipitation,

both changes being referred to the Base Period. Unlike ΔT and ΔP, the long-term shifts in temperature and precipitation are not restricted to discrete values.

In order to project a distribution of annual yields after a given climate change, we assumed that the pattern of interannual fluctuations of temperature and precipitation about their new averages would be the same as in the Base Period. This assumption is equivalent to making linear transformations of the random variables in the Base-Period bivariate normal distribution. Hence, it is a simple matter to calculate for the given climate change a new crop-weather matrix BND(ΔT, ΔP) whose rows and columns are compatible with the annual-yield matrix. Then, summing the probabilities BND(ΔT, ΔP) over a sequence of yield intervals, one computes the frequency distribution of annual yields that corresponds to the new climate state. All such frequency distributions employ a uniform scale of "normalized" relative yields on which 100 represents the calculated average yield of a crop in the Base Period.

Yield distributions were projected for 49 assumed climate changes. We summarized all the distributions for each key crop by plotting their ex-

Table S.1

THE EXPECTED CLIMATE CHANGES ASSUMED TO AFFECT THE KEY CROPS IN THE FIVE GLOBAL CLIMATE SCENARIOS

		KEY CROPS					CLIMATE SCENARIOS: EXPECTED CHANGES IN ZONAL TEMPERATURE (ΔT °C) AND PRECIPITATION (ΔP %)									
							LARGE COOLING (LC)		MODERATE COOLING (MC)		SAME AS THE LAST 30 YEARS		MODERATE WARMING (MW)		LARGE WARMING (LW)	
Zone of Latitude	Hemisphere	CORN	RICE	SOYBEANS (SYBN)	SPRING WHEAT (SPWT)	WINTER WHEAT (WNWT)	ΔT	ΔP	ΔT	ΔP	ΔT	ΔP	ΔT	ΔP	ΔT	ΔP
HIGHER MIDDLE 45 - 65	N				CANADA U.S. USSR	USSR	-1.05	-2.0	-0.50	+2.0	+0.25	0.0	+0.65	+2.0	+1.40	+6.0
LOWER MIDDLE 30 - 45	N	U.S.		U.S.		PRC U.S.	-0.85	+2.0	0.35	0.0	+0.25	0.0	+0.45	0.0	+1.00	+2.0
	S	ARG*				ARG* AUS*	0.95	+2.0	-0.20	0.0	+0.15	0.0	+0.45	0.0	+1.00	+2.0
SUB-TROPICAL 10 - 30	N		INDIA PRC			INDIA	0.50	2.0	0.30	2.0	+0.20	0.0	+0.40	0.0	+0.75	+2.0
	S			BRAZIL			-0.50	-2.0	0.20	2.0	+0.15	0.0	+0.40	0.0	+0.75	+2.0

*NOTE ARG = Argentina, AUS = Australia.

pected values and standard deviations as smooth functions of ΔT and ΔP (see Section 6-4). These plots provide a synoptic view of the crops' responses to a wide range of climate changes. The likelihood of climate change is a separate consideration.

S-3 THE CLIMATE-CROP SCENARIOS

In Task I, after surveying a panel of climatologists, we compiled five global climate scenarios for the year 2000. The climatologists estimated changes in a number of climatic parameters. The individual estimates most relevant to Task II took the form of subjective probability distributions for the global value of ΔT and the values of ΔT and ΔP in certain zones of latitude. Various schemes involving expertise weights were used to aggregate the individual distributions and to derive for each scenario a "probability" of occurrence and a set of "expected" zonal climate changes.

Table S-1 contains the names of the global climate scenarios, the expected zonal climate changes, and the latitude zones of the key crops. The "probabilities" of the scenarios are 0.10 for large cooling and large warming, 0.25 for moderate cooling and warming, and 0.30 for the Same as the Last 30 Years Scenario (a slight global warming). Roughly speaking, these "probabilities" measure the Climate Panel's collective credence in the *global* temperature change associated with each scenario.

Using the data in Table S-1, we calculated frequency distributions of annual yields for each climate scenario. The resulting climate-crop scenarios are discussed below (see also Chapters III and IV).

S-4 METHODOLOGY: THE TECHNOLOGY COMPONENT OF CROP YIELDS

In addition to estimating weather-yield relationships, the Agriculture Panel projected average yields to the year 2000 assuming no change from present climate patterns, but taking into account the likely rate of adoption of new or existing agricultural technology.

A panelist's projection for a single crop consisted of three paths representing the 10th, 50th and 90th percentiles of yield trends. The triplets of percentiles for 2000 AD were converted to probability density functions which in turn were weighted according to self-ratings of expertise and then averaged to produce an aggregated frequency distribution of yield estimates. The expected values of these distributions are examined in the next section; Chapter II deals with the technology projections in greater detail.

Table S.2

PROJECTED EFFECTS OF CLIMATE AND TECHNOLOGY ON CROP YIELDS BY THE YEAR 2000

Zone of Latitude	Hemisphere	Crop and Country	CLIMATE SCENARIOS: EFFECT ON EXPECTED YIELDS — LC p 0.10	MC p 0.25	MW p 0.25	LW p 0.10	NO CLIMATE CHANGE: EFFECT OF TECHNOLOGY ON EXPECTED YIELDS	CLIMATE SCENARIOS: [illegible] — LC p 0.10	MC p 0.25	[illegible]	[illegible]
HIGHER MIDDLE	N	SPWT: *Canada*	- - -	- -	++	+++	24	-	-	+	++
		U.S.	-	-	+		26	- -	-	+	+
		USSR	- - -	- -	++	+++	25	-	-	+	-
		WNWT: *USSR*	- - -	- -	++	+++	23	+++	++	- -	- - - -
LOWER MIDDLE	N	CORN: *U.S.*	+	+	-	-	32	- - -	-	++	++
		SYBN: *U.S.*	+	+	-	-	22	- - -	-	++	++
		WNWT: *U.S.*	+	+	-	-	25	- -	-	+	+
		PRC	-	-	+	+	39	- -	-	+	++
	S	CORN: *Arg*	++	+	-	- -	51	- -	-	+	+
		WNWT: *Arg*	++	+	-	- -	32	- -	-	+	+
		Aus	++	+	-	- -	11	- -	-	+	+
SUB-TROPICAL	N	RICE: *India*	-	-	-	-	34	+	+	+	-
		PRC	-	-	-	-	27	-	-	+	+
		WNWT: *India*	+	+	-	- -	29	-	-	+	+
	S	SYBN: *Brazil*	-	-	-	-	40	+	+	+	+

Increase (+) or decrease (-) in the expected (average) annual yield compared to the Base Period, assuming no change in technology.

CHANGE	SYMBOL	APPROX RANGE
"SMALL"	•	0 3
"MODERATE"	••	3 6
"LARGE"	•••	6 9

Percent increase in the expected (average) yield over 1972-76 assuming no change in climate.

[illegible]

CHANGE	SYMBOL	[illegible]
SMALL	•	[illegible]
MODERATE	••	[illegible]
LARGE	•••	[illegible]
VERY LARGE	••••	[illegible]

S-5 RESULTS: AVERAGE YIELDS AROUND THE YEAR 2000

Salient elements of the climate-crop scenarios and the technology projections are summarized in Table S-2. The left-hand portion of the table pertains to the projected average effects of the Task I climate scenarios, assuming no change in technology. (The "Same" scenario, the most likely of the five, is omitted because its effects on crop yields are negligible.) The middle column pertains to the "expected" effects of technological change, assuming no change in climate.

As for the climate component of yields, one notes that the impact of a particular climate scenario, relative to the Base Period, differs from crop to crop. Some yields are enhanced (+) by the climate change, others are depressed (−). Among the nine wheat crops, for example, there are five "losers" and four "gainers" in the cooling scenarios. Most crop entries are antisymmetrical, i.e., a cooling scenario and the corresponding warming scenario have opposite and approximately equal effects. "Small" yield changes are in the majority, even in the two extreme scenarios, which have the most-pronounced effects.

- The climate changes have the greatest impact in the northern higher middle latitudes where global temperature changes are amplified. The Canadian and Soviet wheat crops suffer "large" or "moderate" losses in the cooling scenarios and enjoy similar gains in the warming scenarios. U.S. spring wheat responds in the same directions, but its yield changes are "small."

- Next most sensitive after Canadian and Soviet wheat are the key crops of the southern lower middle latitudes, but the directions of their yield responses are contrary to those in the northern higher middle latitudes.

- Yield changes for key crops of the northern lower middle latitudes are "small" in all cases. Changes are in the same directions as in the southern zone, except for Chinese winter wheat, which responds like the more northerly wheat crops.

- In the subtropical latitudes, most yield changes are "small" and negative. Indian wheat has a pattern similar to U.S. winter wheat.

The "exact" changes in expected yields are graphed in Section 4-3.

Table S-2 also deals with what we regard as the Agriculture Panel's "best" point estimates of the potential effects of technology, namely, the expected values of the aggregated yield distributions projected for the year 2000. Individually and collectively, the panelists' technology estimates reflect substantial—and understandable—uncertainty about the future adoption of technology for most of the key crops. Therefore, the expected values of the technology projections should be seen as very "fuzzy" numbers (for more on this uncertainty, see Chapters II and IV). The expected technology enhancements are expressed as percentage increases over the average yields of 1972–1976 in order to make them commensurable with the expected yield changes attributable solely to climate change. The climate-neutral technology projections, however, are valid only for the "Same" scenario.

Setting aside Australian wheat for the moment, we note the following:

- The relative technology increments, ranging from 22% to 51%, are severalfold larger than the magnitudes of the respective climate-induced changes.
- U.S. corn excepted, the key crops of Canada, the U.S. and USSR have rather modest technology gains of 26% or less.
- All but one of the technology gains ranging upward from 27% are registered by the countries which currently have low technology bases—Argentina, Brazil, India and the PRC.

Returning to Australian wheat, we remark that the panelists projected a conspicuously small increase in the technology component of its yields, and that they did so with a relatively high degree of certainty. Their projections manifest a rare consensus: current Australian growing conditions discourage investment in technology inputs. Therefore, one might infer that the panelists would have projected larger technology gains for Australian wheat had they been asked to assume the more benign climates of the cooling scenarios. Climate can affect the rate at which technology is adopted, and technology can modify the response of crops to climate change. Clearly, the interaction of technology and climate merits further study. Section 4-5 contains a more detailed comparison of the *independent* effects of technology and climate on crop yields.

S-6 RESULTS: THE VARIABILITY OF CROP YIELDS AROUND THE YEAR 2000

The right-hand portion of Table S-2 pertains to the projected fluctuations of annual yields as measured by the coefficient of variability (the ratio of the standard deviation to the expected value of a distribution). Different approaches to the variability of yields are taken in Chapter III (the projected incidence of "crop shortfalls") and Section 4-4 (the projected frequencies of "low," "normal" and "high" yields). A concise, graphical summary of the projected yield distributions is presented in Section 4-2.

The variability of yields is determined by the interplay between the annual yield matrix and the BND matrix, which describes the year-to-year fluctuations of temperature and precipitation. The integration process involved in the calculation of average yields tends to smooth out any errors in the two matrices. Most measures of variability, however, are sensitive to errors in both matrices.

In the subtropical latitudes there is a mixed pattern of uniformly "small" relative increases (+) and decreases (−) in the coefficients of variability (CVs). Such responses are to be expected in latitudes where the climate changes and their impacts are small.

In the higher and lower middle latitudes, by contrast, changes in the CVs tend to be greater in magnitude and more regular in direction. About 40% of the changes range from "moderate" to "very large," and, with two exceptions, variability decreases or increases as global temperature decreases or increases. The more notable exception is Soviet winter wheat. Qualitatively, its yields become more variable in the cooling scenarios and less variable in the warming scenarios. Quantitatively, in each climate scenario it has the largest relative change in variability.

There are two kinds of correlation between the changes in expected yields and the changes in variability. For Chinese winter wheat and the three spring wheat crops, the correlation is positive, i.e., relative increases or decreases in the average yields of these crops are generally accompanied by like changes in the CVs. For the remaining crops, the correlation is predominantly negative.

In view of the assumed single pattern of crop-weather fluctuations for all climate states, it is noteworthy that the model still projects changes in the variability of annual yields. These changes can be quite striking (see Appendix E-1).

S-7 POSSIBLE IMPLICATIONS OF THE YIELD PROJECTIONS

A *quantitative* assessment of climatic effects must be based on agricultural production, which is only partially determined by yield. However, one can draw conditional and *qualitative* inferences from the foregoing yield projections. For example, both Soviet wheat crops are twice-favored by the Large Warming Scenario: not only are the average yields enhanced, but the annual yields become more "dependable." At the same time, all but one of the other key crops have less dependable annual yields, and all but three have lower average yields than in the Base Period. To a similar degree, the Soviet wheat crops are disadvantaged in the Large Cooling Scenario.

Table S-2 suggests that the effects of an extreme climate change on wheat yields in the USSR might alter the Soviets' role in the international grain market and thus indirectly affect their behavior in the political arena as well. The first consideration is whether their average yields would support adequate production for domestic needs, but this is likely to depend more on technological developments than on climatic change. If average yields were high enough, the Soviet Union could become a net exporter of grain. If average yields were low enough, the country could become a more consistent and heavier buyer of grain. In either case, the variability of its wheat yields would be a secondary matter.

On the evidence of Task II one can say only that average yields would be considerably higher in large warming than in large cooling, other things being equal. It is remotely possible, of course, that technological shortfalls would negate the favorable effects of large warming on Soviet wheat. Also, in the Large Cooling Scenario, technological improvements could enable the Soviets to achieve self-sufficiency in wheat despite the climate handicap.

The variability of yields, which is determined primarily by climate rather than technology, becomes a critical issue when average yields are just adequate or slightly less than adequate. If this were the case, the Soviets would again be better off, economically and politically, in the Large Warming Scenario than in the Large Cooling Scenario.

These speculations can be extended to second parties. For instance, the Soviets are least likely to be grain buyers in the Large Warming Scenario, hence the competition between Canada and the U.S. for other markets could become acute, given the climatic enhancement projected for Canadian wheat yields. On the other hand, large cooling might leave Canada in a poorer position than Argentina, Australia and the U.S. to capitalize on potential Soviet wheat requirements.

S-8 A PROBLEM OF DETECTION

The results of Task II indicate that by 2000 AD climate-induced changes in average yields are likely to be masked by the larger effects of technological improvements. Hence, one may ask whether changes in the climate component of yields will be discernible at the turn of the century.

Year-to-year fluctuations of yields will also tend to mask any changes in average yields caused by a climate shift. One index of this second masking effect is the ratio of the projected standard deviation of relative annual yields to the distance between the average yield projected by the climate-response model and the average yield calculated for the Base Period. The ratio is greater than 3.0 for 68 of the 75 scenario-crop combinations, greater than 6.0 for 53 cases, and greater than 12.0 for 37 cases. The remaining seven cases, all of which involve the sensitive Canadian and Soviet wheat crops, have smaller ratios lying between 1.2 and 2.7; they offer the best chances for discriminating climate-induced changes in average yields.

Thus, recognition of the effects of climatic change will hinge on filtering out the effects of technology and the "noise" of interannual yield fluctuations. It is apparent that climatic change may have some important agricultural consequences—for individual countries if not for total world food production—but assessment of causes will probably be difficult in the event (see Section 4-8).

S-9 SENSITIVITIES OF THE CLIMATE-RESPONSE MODEL

Of the two weather/climate variables, precipitation emerges as the more important. It is the primary determinant of the variability of annual yields in the Base Period, and is likely to remain so in any of the climate scenarios (Section 5-7). Moreover, the projected average yields in the climate-crop scenarios are sensitive to the assumed long-term changes in precipitation. For every country-crop combination, a 10% decrease in average precipitation (with no change in average temperature) depresses the expected yield to a greater degree than the most detrimental climate scenario. And, except for Canadian wheat, a 10% increase in average precipitation stimulates the expected yield more than the most beneficial climate scenario.

We found that *average* yields are not sensitive to 25% changes in the standard deviations of ΔT and ΔP (Section 5-10). For a given small climate change, we conclude that the average yield (i.e., the expected normalized relative yield) depends primarily on the "shape" of the annual-yield function and not on the BND. Hence, if the annual-yield functions are not biased, the average yields in a climate-crop scenario ought to be quite accurate—provided, of course, that the expected zonal precipitation changes are consistent with the assumed global temperature change.

Absolute measures of yield variability are strongly affected by the standard deviation of ΔP but not the standard deviation of ΔT (Section 5-10). However, the "normalized relative" coefficient of variability (NRCV)—the ratio of the CV after a climate change to the CV in the Base Period—is rather insensitive to the standard deviations of ΔT and ΔP. This *relative* measure of variability is determined by the relationships among the particular climate change, the annual yield function, and the correlation coefficient used in the BND (see Section 5-11 and Appendix D-4). We have more confidence in the projected NRCVs, the bases of Table S-2, than we do in the ordinary coefficients of variability.

S-10 CAVEATS

The preceding discussion concerns not fact but the output and behavior of a climate-response model. Our findings are affected by the simplicity of the model, which has only two highly aggregated weather/climate variables, and by a number of assumptions. The results are also subject to uncertainties about the annual-yield functions (Section 5-4) and the expected zonal climate changes in the climate scenarios, especially the considerable uncertainties about the expected precipitation changes (Sections 6-6 through 6-8). The uncertainties affecting the technology projections are obvious (Section 4-7).

Even if they were "correct" in every respect, the two types of yield projections would have to be interpreted with care. In the first place, we have not accounted for the *combined* effects of climatic change and technological change on crop yields. Secondly, one must heed the distinction between absolute yields and relative yields (Sections 4–6 and 5–9). The former are the currency of the technology projections, the latter of the climate-response model.

The "validity" of the model is an intricate question because the effects of technology, economics and agricultural policy must be removed from recorded yields before one can compare them with the yield distributions calculated for the Base Period. Such factors have a marked effect on the variability of historical yields, but they are absent from the uncalibrated model. Thus, real-life complications may thwart a straightforward validation test based on an absolute measure of variability like the CV (Appendix D-5). Nevertheless, the projected normalized relative CVs could be fairly accurate if technology *et al* remained constant.

Our confidence in the climate-response model rests mainly on its cogency, its lack of sensitivity to certain parameters, and the consistency of its output. As for the "soft" inputs to the model—the annual-yield functions and the five climate scenarios—the case rests partly on the expertise of the panelists (Section 4-9) and partly on the techniques used to aggregate their estimates. If the reader takes exception to our particular climate scenarios, he can invent his own and assess their consequences with the materials provided in this report. Ideas for improving the study are set forth in Section 2-7 and Appendix E-4.

S-11 THE SEQUEL

Early in 1979, a group of agricultural economists headed by D. Gale Johnson undertook the policy-oriented third task using a world food economic model developed by the U.S. Department of Agriculture. Their analysis has been completed, and the publication thereof will conclude the substantive portion of the National Defense University's climate impact assessment.

CHAPTER ONE

TED CRAMPTON

CHAPTER ONE
METHODOLOGY

1-1 INTRODUCTION

In Task I of the climate research project, five global climate scenarios were developed for the year 2000, each with a "probability" of occurrence.[1] In Task II, the subject of this report, we devised a general climate-response model and used it to estimate the effects of the Task I climate scenarios on the yields of selected crops. The primary outputs of the model are frequency distributions of annual yields corresponding to a given climate state. Thus, the model projects not only the average effects of a global climate change on annual yields, but also its effects on the year-to-year variability of yields.

In the present chapter we first indicate how we isolated the effects of changes in technology from the effects of changes in climate. We then describe the logic, inputs and outputs of the climate-response model using U.S. corn as an example. Fourteen other country-crop combinations were treated in the same fashion.

Chapters V and VI contain additional details about the model, along with certain inputs and outputs for all the country-crop combinations. The basic findings of Task II are presented and analyzed in the next three chapters.

1-2 THE RESEARCH APPROACH TO TASK II

To meet a requirement for particular crop-yield data, we sent a structured questionnaire to a panel of volunteer experts. The questionnaire dealt with the 15 "key" country-crop combinations indicated in Table I-1.

Potential participants in the crop-yield survey were identified by the research staff with assistance from the project Advisory Group. The American and foreign scientists invited to contribute to Task II were selected for both their competence in agronomy and their specialized knowledge of particular country-crop combinations. The preponderance of the data returns, however, came from U.S. experts. The members of the Agriculture Panel, i.e., the group of actual respondents, are listed in the acknowledgments. The questionnaire, "Crop Yields and Climate," was circulated in late 1977. Representative portions of it are contained in Appendix A-1.

[1]See *Climate Change to the Year 2000: A Survey of Expert Opinion*, National Defense University, Washington, D.C., February 1978.

Table I-1

COUNTRY-CROP COMBINATIONS STUDIED IN TASK II

COUNTRIES	CROPS: CORN	RICE	SOYBEANS	SPRING WHEAT	WINTER WHEAT
ARGENTINA	X				X
AUSTRALIA					X
BRAZIL			X		
CANADA				X	
INDIA		X			X
PRC (CHINA)		X			X
UNITED STATES	X		X	X	X
USSR				X	X

The wheat crops of Argentina, Australia and India, which have little or no dormancy, were placed in the winter wheat group on the basis of the seasons in which they are planted and harvested.

For each key crop, two quantitative estimates were requested of the panelists: the first was a probabilistic projection of the influence of technology on yields to the year 2000, and the second was an estimate of yield as a function of annual temperature and precipitation. One feature of the questionnaire, important for aggregating the panelists' individual estimates, was the requirement that respondents rate their own expertise relative to each part of the questionnaire. In addition, the panelists were encouraged to give the rationale for their estimates and to make any comments they deemed relevant.

Technology and climate are both prime determinants of crop yields, but the principal aim of the study was to assess the impact of climate change on agriculture.[2] To help the panelists mentally separate the effects of technology from climatic effects, we asked them at the outset for their perceptions of how technology might affect yields if there were no change in climate.

While the technology projections are interesting in themselves, they are incidental to our primary purpose. The core question was: How do crop yields respond to certain *annual* growing conditions, assuming current technology? Hence, the panelists were asked to estimate the effects of "weather" on crop yields, but not the effects of climate change.

[2]Economics in general and national agricultural policies in particular also affect crop yields. Implicitly, we subsume nonclimatic influences on yields under the rubric of "technology."

The climate-response model provides the link between yield-as-a-function-of-weather and long-term climate change. For an assumed climate change, the model projects a frequency distribution of annual yields by combining an annual-yield function with a distribution of annual growing conditions.

1-3 THE ROLE OF THE EXPERTISE RATINGS

In both parts of a country-crop question, each panelist was asked to rate his own expertise on an arithmetic scale of 4-3-2-1. The categories of expertise—Expert, Quite Familiar, Familiar and Unfamiliar—were defined in the questionnaire. In addition, panelists were asked to provide (for the weather part only) the names of persons whom they considered "Expert" or "Quite Familiar." Besides identifying authorities whom we had overlooked, this information served as a partial check on the self-assigned expertise ratings.

In the aggregation of individual numerical estimates, the panelists' responses were weighted according to their self-determined expertise. The particular geometric weighting scale is shown in Table I-2. The weighting scheme reflects the largely empirical and intuitive notion that the

Table I-2

CONVERSION OF EXPERTISE RATINGS TO WEIGHTS

Category of Expertise	Expertise Rating	Expertise Weight
EXPERT	4	4
QUITE FAMILIAR	3	2
FAMILIAR	2	1

opinion of an "Expert" is worth about twice as much as the opinion of someone who is "Quite Familiar," whose opinion, in turn, is worth twice that of an individual who is only "Familiar" with the subject. Responses with expertise levels of "Unfamiliar" (expertise = 1) were given weights of zero, i.e., they were omitted from the data bases.

1-4 PROCESSING THE TECHNOLOGY RESPONSES

In the first part of each twofold country-crop question, the panelists were asked to make low, median and high projections of yield trends, taking into account the adoption of new or existing technology, but assuming no change from present climate patterns. The three estimates were recorded by extrapolating a graph of historical yields. The first estimate was to be a trend path drawn to the year 2000 such that the panelist perceived only one chance in ten of the actual yield trend being lower; the second was to be a path with a perceived even chance that actual yields would be either lower or higher; and the third was to be a path for which there was only one chance in ten that the actual yield trend would be higher. The three paths were to begin at a point representing the average yield for the period 1972-76. A sample response for U.S. corn is shown in Figure I-1.

The responses for a given crop were processed by the same method that was used for the pivotal global temperature question in Task I.[3] The three trend paths drawn by the panelists correspond to the 10th, 50th and 90th percentiles of yield. For each of the years 1980, 1985, 1990 and 2000, a single respondent's three yield data were converted first to a cumulative probability function and then to a probability density function of projected average yields. The individual probability density functions were aggregated as follows:

- Each density function was multiplied by the panelist's expertise weight.
- The weighted density functions were summed for all the respondents.
- The summed function was divided by the total of the expertise weights to normalize the group response.

From the aggregated probability density functions we calculated the 10th, 50th, 90th and intermediate percentiles for the selected years and plotted them as extensions of the historical yield series. The result is a graphical summary of the panel's estimates for the crop in question. The aggregated projections for U.S. corn are displayed in Figure I-2.

Another way to depict the technology projections is to show the aggregated probability density functions (or frequency distributions) for a sequence of years. The frequency distributions applicable to 2000 AD are presented in Appendix B-2 and summarized in Chapter II. For U.S. corn, the turn-of-the-century distribution of projected yields is the probability density function corresponding to the cumulative probability function that one gets from slicing Figure I-2 at the year 2000.

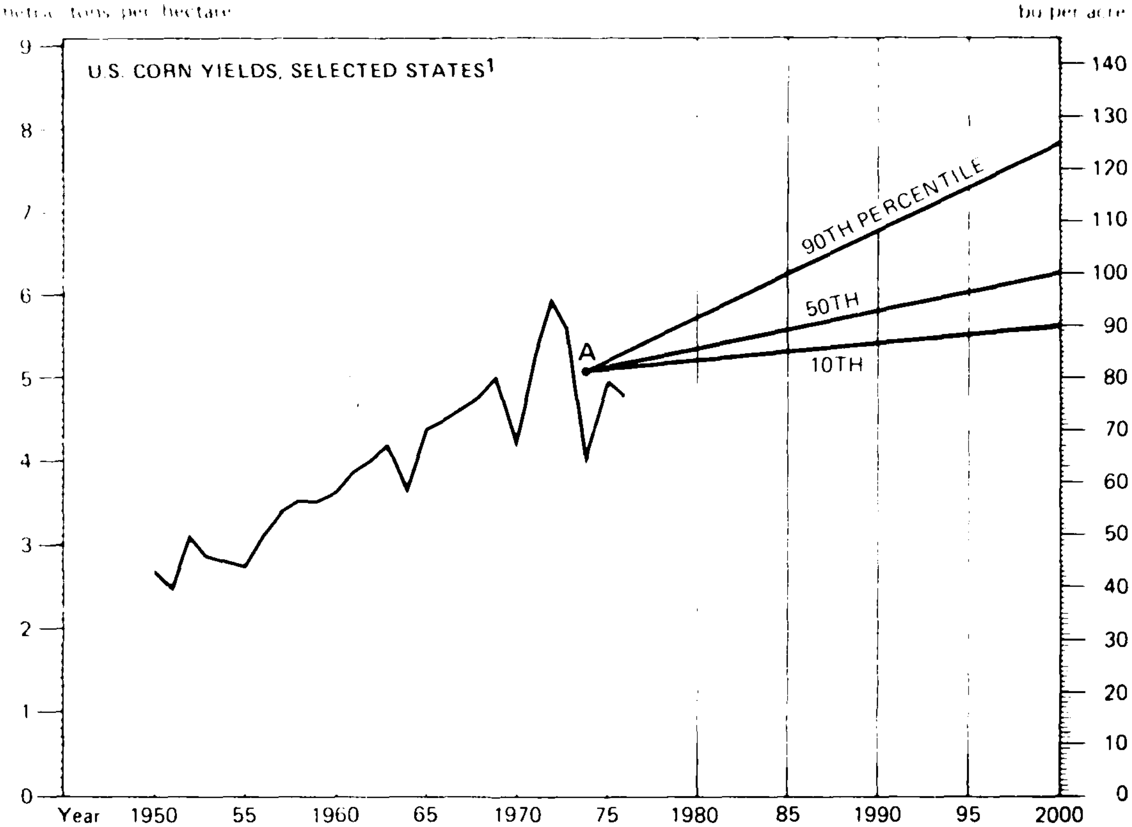
The remainder of this chapter is devoted to the climate-response model, which projects the effects of climatic change on crop yields in the absence of technological change.

[3]A full description of the method is given in *Climate Change to the Year 2000*, pages 4-11

Figure 1.1

PROJECTED EFFECTS OF TECHNOLOGY ON U.S. CORN YIELDS (SAMPLE RESPONSE)

A sample estimate of yield trends based on consideration of potential changes in technology, but assuming no change from current climate. (High, median, and low trends expressed as percentiles of yield.)



Point A 1972-76 Average = 81.4 bu/a = 5.11 tons/ha

Note: Yield calculated on area harvested

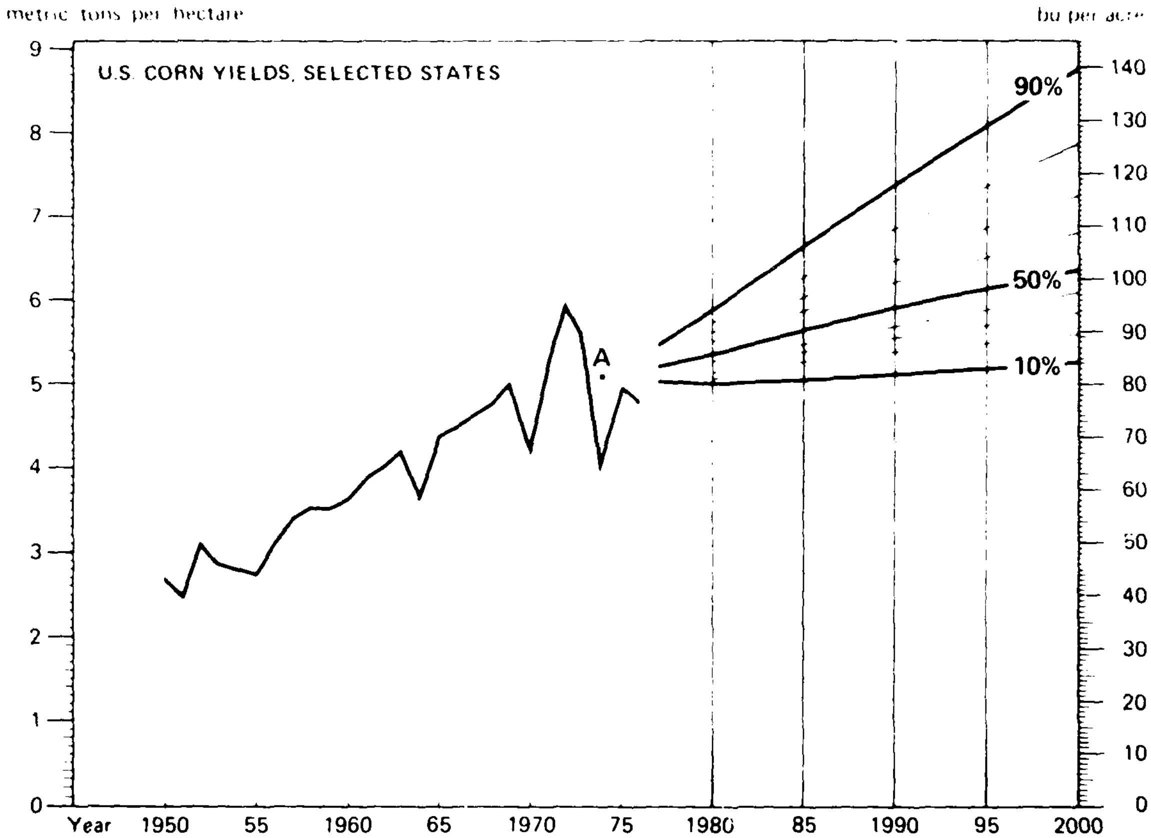
[1] Nine states - Ohio, Indiana, Illinois, Minnesota, Iowa, Missouri, Nebraska, South Dakota, and Wisconsin - account for about 80 percent of corn production.

	Year	tons/ha	bu/a	Year	tons/ha	bu/a	Year	tons/ha	bu/a
	1950	2.74	43.62	**1960**	3.67	58.32	**1970**	4.32	68.72
U.S. CORN YIELDS	1951	2.55	40.48	1961	3.92	62.35	1971	5.34	84.98
	1952	3.17	50.44	1962	4.04	64.22	1972	6.03	95.92
	1953	2.91	46.29	1963	4.23	67.21	1973	5.64	89.72
	1954	2.84	45.13	1964	3.74	59.44	1974	4.09	64.97
	1955	2.77	44.17	**1965**	4.43	70.42	**1975**	4.96	79.13
	1956	3.17	50.40	1966	4.55	72.29	1976	4.85	77.38
	1957	3.42	54.38	1967	4.67	74.32			
	1958	3.58	56.89	1968	4.82	76.71			
	1959	3.54	56.32	1969	5.06	80.41			

Figure I 2

PROJECTED EFFECTS OF TECHNOLOGY ON U.S. CORN YIELDS (GROUP RESPONSE)

Aggregation of 22 panelists' estimates of yield trends based on consideration of potential changes in technology, but assuming no change from current climate. (Trends expressed as percentiles of yield.)



Point A = 1972-76 Average = 81.4 bu/a = 5.11 tons/ha

Note: Yield calculated on area harvested

The aggregated yield projection implies respective means of 87.1, 97.7 and 107.3 bushels per acre for 1980, 1990 and 2000.

1-5 DEVELOPING THE ANNUAL-YIELD FUNCTIONS

In the second part of each country-crop question the panelists were asked to fill out a set of grids with estimates of likely crop yields for specified annual growing conditions, assuming no change from the technology then in use. These estimates were aggregated into matrices that express annual yield as a function of "annual crop weather" in the crop region.

In this study, "annual crop weather" connotes a temporal-spatial mean of temperature and a spatial mean of precipitation. More precisely, we give a differential definition of annual crop weather as a joint occurrence of ΔT and ΔP, where

ΔT = the departure of a year's mean heading-period temperature from the long-term average prevailing in the Base Period (expressed in degrees Celsius), and

ΔP = the departure of the same year's mean crop-year precipitation from the long-term average prevailing in the Base Period (expressed in percent).

The meaning of "the Base Period" will be clarified in the next section; for the moment it will suffice to think of it as the recent past. As used here and elsewhere in this chapter, "Δ" may be regarded as a difference operator (see Appendix A-2 for details).

Since they represent annual departures from prevailing averages, the differential crop-weather variables ΔT and ΔP themselves average to zero over the Base Period. For the sake of brevity we call ΔT "annual temperature" and ΔP "annual precipitation." In Section 5-2 we give the rationale behind the choice of temperature during the period of heading and precipitation during the crop year (the 12 months ending with harvest).

Subsequent computations are carried out with discrete variables. Thus, we deal with a lattice of representative "annual crop-weather points" (ΔT, ΔP) which are midpoints of rectangular regions in the temperature-precipitation plane. The same annual yield $Y(\Delta T, \Delta P)$ is ascribed to all weather points that lie in the rectangle centered on the point (ΔT, ΔP).

The panelists' estimates of annual yield as a function of ΔT and ΔP were supposed to represent spatial averages over the crop region.[4] For each

[4] In some cases the crop regions were indicated by maps that accompanied the questionnaire. For three U.S. crops—corn, spring wheat and winter wheat—the crop region was specified in terms of selected states. The definition of "yield"—the ratio of total production to sown or harvested area—varied according to usage in the individual countries. The yield definitions and the "selected" states are annotated on the figures in Appendix B-1.

specification of the annual crop-weather variables, the panelists were to assume a "normal" temporal distribution of temperature and precipitation in the course of the crop year.

Three crop-yield grids were provided in the questionnaire. In the first two grids, the panelists recorded numerical estimates of the yields expected from given values of ΔT and ΔP. These estimates were expressed as percentages of the 1972–76 average crop yield. The center cell in each grid, corresponding to "average" crop weather ($\Delta T = 0$, $\Delta P = 0$), was assigned the reference value of 100. Therefore, from the beginning, the climate-response model deals with yields in relative rather than absolute terms. In the third grid, the panelists were to draw a curve within which they expected at least some yield and to indicate the point of maximum yield. A sample response is shown in Appendix A-1.

Not all panelists completed Grid 3, so only the first two grids were used in the analysis. In addition, several respondents did not complete Grids 1 and 2. If a panelist had made estimates for the four corners of a grid, the research staff interpolated missing values that were consistent with his entries. If a pair of grids could not be completed by interpolation, both were discarded.

To aggregate the individual estimates for a given grid cell, we weighted each of them by the appropriate expertise weight (Table I-2), added the weighted values, and then divided by the sum of the weights. The weighted mean, the coefficient of variability[5] and the skewness[5] of the distribution of responses for each grid cell were then assembled into Master Yield Grids. The Master Yield Grids for U.S. corn are shown in Table I-3. They constitute the Agriculture Panel's collective estimate of relative annual yield as a function of annual crop weather.

[5]The ratio of the standard deviation to the mean of the distribution As an intrinsic measure of dispersion, it facilitates cell-to-cell comparisons of the panelists' collective uncertainty about yields

[6]The third moment of the distribution divided by the cube of the standard deviation

Table I 3

MASTER YIELD GRIDS -- U.S. CORN (1976 TECHNOLOGY)

Summary of 23 panelists' aggregated estimates of relative yield for specified values of the crop weather variables ΔT and ΔP (100 = yield for average crop weather in the Base Period.)

ΔT Departure of mean heading period temperature from the average value prevailing in the Base Period

ΔP Departure of mean crop year precipitation from the average value prevailing in the Base Period

WEIGHTED MEAN YIELD (UNNORMALIZED)
COEFFICIENT OF VARIABILITY
SKEWNESS

GRID 1

ΔT (°C)	ΔP (%) −20	−10	0	10	20
	73.5	82.3	90.0	95.3	98.9
2	0.152	0.133	0.142	0.135	0.157
	−1.22	−1.07	0.28	2.07	2.69
	78.1	86.9	95.4	102.1	102.9
1	0.128	0.082	0.066	0.077	0.132
	−1.16	−1.47	0.16	1.93	2.56
	82.7	92.3	100.0	106.6	107.2
0	0.133	0.070	0.000	0.076	0.102
	−0.59	−1.50	0.00	1.97	1.27
	84.7	93.9	102.9	108.0	108.8
−1	0.139	0.088	0.069	0.118	0.122
	−0.18	−0.78	0.66	1.97	0.45
	83.7	93.0	100.7	105.1	107.0
−2	0.175	0.128	0.114	0.134	0.188
	0.56	0.50	0.72	0.94	0.75

GRID 1

GRID 2

ΔT (°C)	ΔP (%) −80	−40	0	40	80
	13.8	31.8	64.1	74.1	75.8
6	1.361	0.733	0.505	0.410	0.436
	1.00	0.43	0.07	0.37	0.57
	19.7	47.2	83.6	95.6	92.[illegible]
3	1.059	0.446	0.256	0.172	0.304
	0.82	−0.15	−0.11	0.25	0.21
	25.0	60.3	100.0	108.5	98.4
0	0.920	0.333	0.000	0.188	0.292
	0.55	−0.88	0.00	1.30	0.18
	30.3	63.7	95.6	102.3	91.6
−3	0.897	0.362	0.216	0.232	0.350
	0.38	−0.30	0.94	2.14	0.64
	31.2	54.5	73.6	79.2	73.2
−6	0.998	0.539	0.423	0.416	0.491
	0.62	0.27	0.26	0.52	0.43

GRID 2

From the Master Yield Grids we constructed the *annual yield matrix*, a table of relative annual yields for values of ΔT between −6 C and +6 C and for values of ΔP between −100 and +80. The temperature interval was 0.25 C and the precipitation interval was 5. Matrix elements for ΔP = −100 (i.e., no annual precipitation) were set equal to zero. The entries in the matrix for which there were no corresponding grid values were obtained by linear interpolation. The annual-yield matrix for U.S. corn is shown in Table I-4. Because of space limitations in the computer printout, yields are rounded to the nearest integer, and tabulated only for ΔT in multiples of 0.5 C and ΔP in multiples of 10.

Table I-4

ANNUAL - YIELD MATRIX - - U.S. CORN (1976 TECHNOLOGY)

Annual yield as a function of the annual crop-weather variables ΔT and ΔP [illegible] *unnormalized* [illegible] annual yields in Table I-3 (100 = yield for average crop weather in the Base Period).

ΔT Departure of mean heading-period temperature from the average value prevailing in the Base Period.

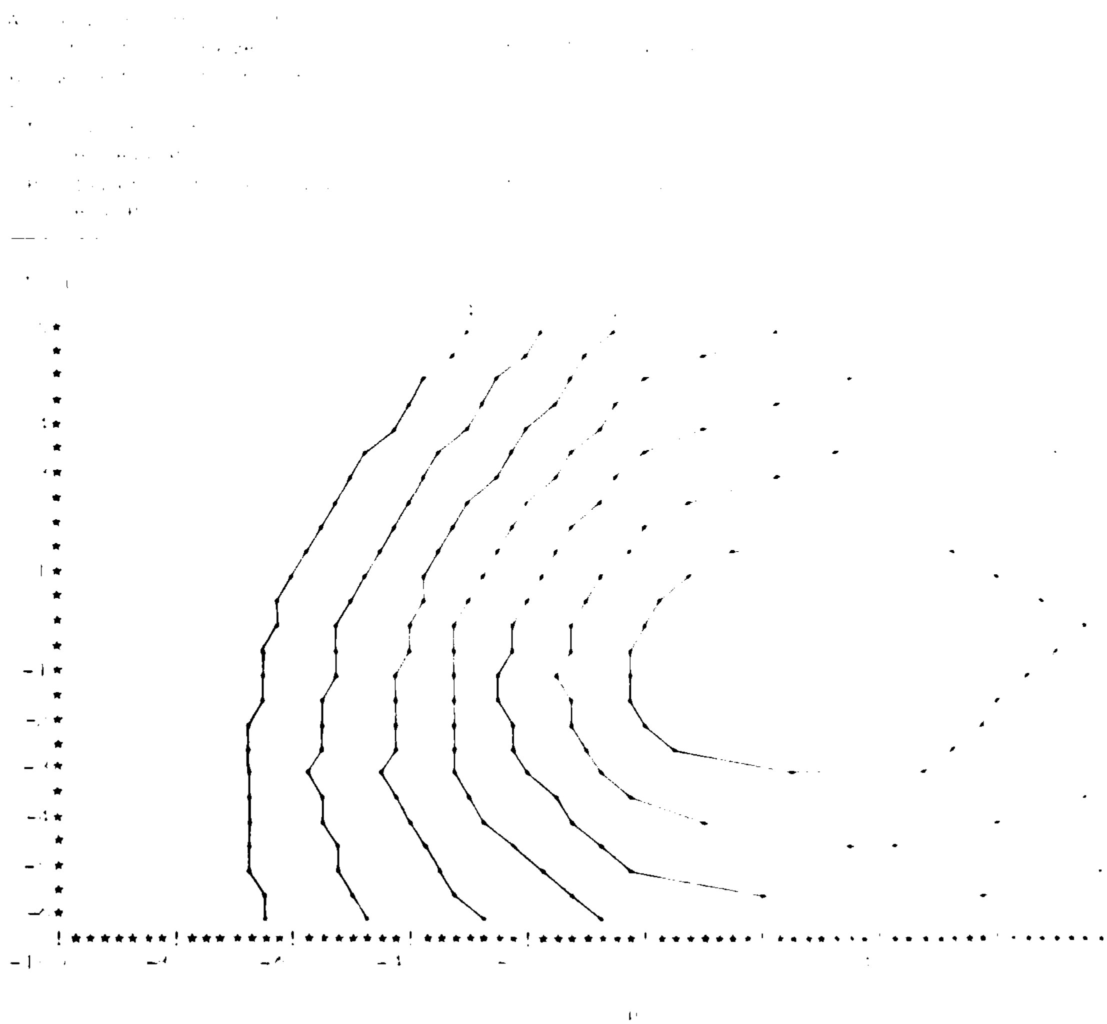
ΔP Departure of mean crop-year precipitation from the average value prevailing in the Base Period.

ΔP (%)

ΔT (C)	−100	−90	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80
6★	0	7	14	18	23	27	32	40	48	56	64	67	[illegible]	[illegible]	74	75	[illegible]	[illegible]	[illegible]
★	0	7	15	20	25	29	34	43	51	59	67	71	73	76	78	78	[illegible]	78	78
5★	0	8	16	21	26	32	37	45	54	62	71	73	76	79	81	81	81	81	81
★	0	8	17	22	28	34	39	48	57	65	74	77	79	82	85	85	84	84	84
4★	0	9	18	24	30	36	42	51	60	68	77	80	83	85	88	88	88	87	[illegible]
★	0	9	19	26	32	38	45	54	62	71	80	83	85	89	92	91	91	[illegible]	89
3★	0	10	20	27	33	40	47	55	65	75	84	87	90	93	96	95	94	93	[illegible]
★	0	10	21	28	35	42	49	59	69	78	87	91	94	96	98	97	96	94	93
2★	0	11	21	29	37	44	52	63	74	82	90	95	99	99	[illegible]	98	97	96	94
★	0	11	22	30	38	46	54	65	76	85	93	99	101	101	102	100	[illegible]	97	96
1★	0	12	23	31	40	48	56	67	78	87	95	102	103	104	104	102	100	98	96
★	0	12	24	33	41	50	58	69	80	90	98	104	105	106	106	104	102	100	97
0★	0	12	25	34	43	51	60	71	83	92	100	107	107	108	109	106	103	101	98
★	0	13	26	35	43	52	61	72	84	93	101	107	108	108	107	105	102	100	97
−1★	0	13	27	35	44	53	61	73	85	94	103	108	109	108	106	104	101	[illegible]	96
★	0	14	28	36	45	53	62	73	84	93	102	107	108	107	105	103	100	98	95
−2★	0	14	29	37	46	54	63	73	84	93	101	105	107	106	104	102	99	97	94
★	0	15	29	38	46	55	63	72	82	90	98	101	103	103	103	101	98	95	93
−3★	0	15	30	39	47	55	64	72	80	88	96	97	99	101	102	100	97	94	92
★	0	15	30	38	46	54	62	70	77	85	92	94	95	97	98	96	94	91	89
−4★	0	15	31	38	46	53	61	68	74	81	88	90	91	93	95	92	90	88	85
★	0	15	31	38	45	52	59	65	72	78	85	86	88	89	91	89	87	85	82
−5★	0	15	31	38	44	51	58	63	69	75	81	82	84	85	87	85	83	81	79
★	0	16	31	37	44	50	55	61	67	72	77	79	80	82	83	81	80	78	75
−6★	0	15	31	37	43	49	55	59	64	69	74	75	76	78	79	78	76	75	73

Perhaps a more meaningful way to depict the annual yield function is to graph it as a response surface using contours of equal values of constant yield. The *annual yield response surface* for U.S. corn is presented in Figure I.3. Although relative yields below 40 were not plotted, they were available for subsequent calculations.

ANNUAL YIELD RESPONSE SURFACE U.S. CORN 1976 TECHNOLOGY



1-6 THE BASE PERIOD THE HISTORICAL PATTERN OF ANNUAL CROP WEATHER

[illegible] matrix [illegible] read Y(ΔT, ΔP) the expected relative [illegible] given values of ΔT and ΔP. In order to model the fluc- [illegible] the year to year variation of ΔT and ΔP one [illegible] how joint [illegible] of ΔT and ΔP are dis- [illegible] different [illegible] states.

[illegible] of the variation in annual crop weather is based on clima- [illegible] data [illegible] the world into [illegible] areas we calculated certain [illegible] observed frequency distributions of ΔT and ΔP for the years [illegible] weather stations were providing data [illegible] the period of time covered by the climatological records as [illegible] which necessarily differs from crop to crop. The statistics [illegible] were then spatially averaged to get statistics for the [illegible] interest. We found that the observed frequency [illegible] approximated quite well by bivariate normal distribu- [illegible] we assumed bivariate normal dis- [illegible] ΔT and ΔP [illegible] Base Period.

[illegible] the functional form of the bivariate normal [illegible] ΔT and ΔP [illegible] by

[illegible]

[illegible]

[illegible] ΔT and ΔP are the random variables that [illegible] crop weather. If graphed as a surface [illegible] has the shape of a distorted bell. Verti- [illegible] normal probability curves. Horizontal sections are ellipses, the eccentricity and orientation of which are determined by the climatological parameters

s_T = standard deviation of ΔT in the Base Period,

s_P = standard deviation of ΔP in the Base Period,

r = correlation coefficient for ΔT and ΔP in the Base Period

Using the climatological records of each growing region, we calculated the BND parameters—s_T, s_P, r—that characterize the year-to-year variability of crop weather in the Base Period.[*] For U.S. corn the standard deviation of ΔT during the Base Period was 1.23 °C, the standard deviation of ΔP was 12.0%, and the correlation coefficient was −0.41.

The historical frequency distribution of annual temperature and precipitation (as approximated by the BND) is tabulated in the same format as the matrix of relative annual yields. That is, the rows of the Base-Period BND matrix are identified by ΔT (in multiples of 0.25 °C) and the columns are identified by ΔP (in multiples of 5%). For a given pair of values of ΔT and ΔP, the BND matrix element is the probability that a joint occurrence of annual temperature and precipitation will fall in the rectangle of dimensions 0.25 °C and 5% centered on the point (ΔT, ΔP). Table I-5 contains the printout of the *coarse BND matrix* for U.S. corn which corresponds to the coarse annual-yield matrix in Table I-4.

Having adopted the increments ΔT and ΔP as random crop-weather variables, we can ignore the absolute values of the long-term historical averages of temperature and precipitation in the various crop regions. The annual-yield matrices, the BND matrices and the variables which characterize climate change are all expressed in terms of *differences* from the historical averages. The underlying *absolute* crop-weather variables and their bivariate normal distributions are discussed in Appendix A-2.

[illegible] Research Paper [illegible] National Foreign Assessment Center [illegible] Agency, [illegible]

BND MATRIX FOR THE BASE PERIOD — U.S. CORN BELT

1-7 FREQUENCY DISTRIBUTIONS OF ANNUAL YIELDS IN THE BASE PERIOD

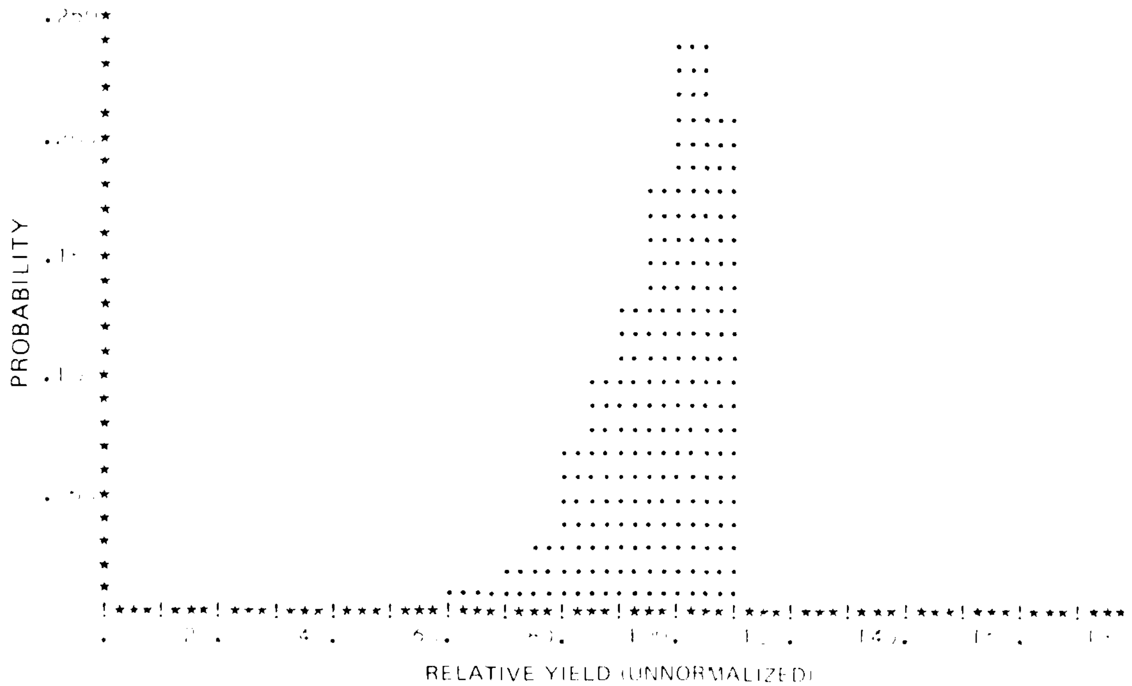
The distributions of relative annual yields for the Base Period are calculated in a straightforward manner. We interpret these Base-Period distributions as quasi-historical distributions in which yields have been restated to reflect current technology (circa 1976).

First, the BND matrix is superimposed on the annual-yield matrix. (The rows and columns of the "stacked" matrices are thus indexed by common values of ΔT and ΔP.) We then identify all the entries in the annual-yield matrix whose values lie between 0 and 5 and sum the BND probabilities which overlie these entries. This sum is the probability of having a relative yield between 0 and 5. Next, for all annual-yield matrix values between 5 and 10, we sum the corresponding BND values to determine the probability of having a relative yield between 5 and 10. This procedure is continued until the maximum yield value is reached. The resulting frequency distribution for U.S. corn is shown in Figure I-4. Because current technology was assumed

Figure I-4

FREQUENCY DISTRIBUTION OF ANNUAL YIELDS IN THE BASE PERIOD -- U.S. CORN (1976 TECHNOLOGY)

Histogram of calculated *unnormalized* relative yields reflecting the pattern of annual crop weather shown in Table I-5 (100 = yield for average weather in the Base Period)



CUMULATIVE PROBABILITY AND RELATED STATISTICS

PROB	VAL	PROB	VAL	PROB	VAL	PROB	VAL
[illegible]	44.7	[illegible]	[illegible]	10	82.3	15	[illegible]
20	[illegible]	25	[illegible]	30	92.6	35	93.8
40	[illegible]	45	97.1	50	98.1	55	[illegible]
60	101.1	65	[illegible]	70	103.2	75	104.3
80	105.1	85	106.5	90	107.2	95	107.8
100	[illegible]						

EXPECTED VALUE = [illegible]
STANDARD DEVIATION = [illegible]
COEFFICIENT OF VARIABILITY = [illegible]
SKEWNESS = [illegible]

in the calculation, the distribution cannot be compared directly with historical yields. The problem of validating a Base-Period yield distribution is addressed in Appendix D-5.

The expected, or average, relative yield Y in the Base Period is obtained by the formula

$$Y = \Sigma f Y,$$

where f is the probability of having yield Y. For U.S. corn, the expected yield is 96.20. One notes that it is less than 100, in agreement with the well-known tenet that average yield is less than the yield at average weather. The two yields differ because of the convexity of the annual-yield response surface in Figure I-3: yield decreases more rapidly for "bad" weather than it increases for "good" weather.

In Chapter V we examine the sensitivity of the Base-Period yield distributions to the values of the BND parameters.

1-8 NORMALIZING THE RELATIVE ANNUAL YIELDS

The expected value of annual yields was calculated for each of the 15 country-crop combinations. Since a different expected yield was obtained in each case, each crop-yield data base was normalized so as to make the expected yield for the Base Period equal to 100. For example, all the yield entries in the Master Yield Grids for U.S. corn were divided by the normalization factor 96.20 and multiplied by 100.** The processing steps described in Section 1-5 were then repeated. That is, starting with the *normalized* Master Yield Grids (Appendix D-1), we interpolated new *normalized* annual-yield matrices and plotted new *normalized* annual-yield response surfaces (Chapter V). All the *normalized* Base-Period yield distributions that now result from applying the BND matrices to the respective normalized annual-yield matrices have expected values of 100.

Henceforth, with one exception in Section 4-4, the discussion of climate effects is limited to *normalized* relative yields. The normalized relative yields facilitate comparisons between crops and across scenarios because they share a common interpretation: whatever the key crop or climate state, a normalized relative yield is expressed as a percentage of the calculated average annual yield of the recent past (the Base Period). All such yields are contingent on 1976 technology.

** The dimensionless coefficient of variability and skewness are unaffected by this normalization of the Master Yield Grids.

1-9 CHARACTERIZING CLIMATE CHANGE

Climate may be regarded as weather averaged over area and time. In this report the temporal cutoff between weather and climate is 12 months. The simplified "annual crop weather," affecting one year's planting of a given crop, is specified by ΔT (annual temperature) and ΔP (annual precipitation); it contains all the spatial and temporal variance not attributed to climate change. Essentially, we define a "climate change" as a change in average annual crop weather.

In a broad sense, climate is described by the set of all statistics computed from weather observations. Paralleling the approach to annual crop weather, we chose temperature and precipitation as the most important climate variables for our purpose. That is, we describe climatic states solely in terms of the long-term averages of temperatures and precipitation, interpreting "long-term" as more than 10 years. In particular, a change from the Base-Period climate of a crop region is characterized by a point (ΔT, ΔP), where

ΔT = long-term average (or expected value) of ΔT *in the new* climate state, and

ΔP = long-term average (or expected value) of ΔP in the new climate state.

It should be noted that, although they are used in the definition of *potential* climate states, the annual crop-weather variables ΔT and ΔP are increments measured from Base-Period norms, i.e., they are referred to *recent* climate.

Since the long-term Base-Period averages of ΔT and ΔP are both zero, one can say that ΔT and ΔP are *changes* in the long-term averages of annual temperature and precipitation referred to the Base Period. In Appendix A-2 it is shown that these differential definitions may also be expressed, somewhat more awkwardly, in terms of absolute measures:

ΔT = change in the long-term average of annual mean *absolute* heading-period temperature referred to the Base Period, and

ΔP = percentage change in the long-term average of mean *absolute* crop-year precipitation referred to the Base Period.

For brevity we call ΔT and ΔP "expected changes" in annual temperature and precipitation. On occasion we shall want to talk about an "assumed" climate change (ΔT, ΔP) without any implication of prognostication. On the other hand, if ΔT and ΔP refer to expected changes that are part of a

Task I global climate scenario, then we shall speak of (ΔT, ΔP) as "the expected climate change" affecting a specific crop in that scenario

The climate state specified by $\Delta T = 0$ and $\Delta P = 0$ is the Base Period, for ΔT and ΔP have expected values of zero in the Base Period. This is semantically appropriate: the Base Period represents both "present" (i.e., recent) climate and "zero" climate change. All climate changes and yield projections are therefore referenced to the Base Period.

1-10 THE PATTERN OF ANNUAL CROP WEATHER AFTER A CLIMATE CHANGE

In a new climate state there will be year-to-year oscillations of temperature and precipitation about their new long-term averages. As in the Base Period, we want to account for the effect of such natural fluctuations on annual yields. This necessitates an assumption about the temporal distribution of temperature and precipitation in the new regime. Little is known about how this distribution might differ from the Base-Period distribution of ΔT and ΔP. Consequently, we made the critical assumption that the pattern of fluctuations in annual crop weather will be almost identical to the pattern observed in the Base Period.

We say "almost" identical because one might expect the standard deviation of precipitation to change proportionately with a change in the long-term average of precipitation. Therefore, we assume that the *ratio* of the standard deviation of absolute crop-year precipitation to the long-term average of absolute crop-year precipitation is not affected by climate change. In other words, the coefficient of variability (CV) of mean absolute crop-year precipitation is assumed to be invariant. This assumption implies that the CV of the differential variable ΔP is also invariant. In regard to the other two parameters of the bivariate normal distribution, we simply assume that the standard deviation of temperature and the correlation coefficient are the same in all climate states.

The incremental crop-weather variables in the annual-yield function $Y(\Delta T, \Delta P)$ are measured from Base-Period averages. The distribution of ΔT and ΔP in the Base Period is given by equation (1) of Section 1-6, but to project the spectrum of annual yields after an assumed climate change (ΔT, ΔP) one needs to know their distribution in the new climate state. Let $BND(\Delta T, \Delta P)$ denote the required distribution. As demonstrated in Appendix A-2, it follows from our assumptions that $BND(\Delta T, \Delta P)$ is functionally related to $BND(\Delta T, \Delta P)$, the Base-Period distribution of ΔT and ΔP, by

(2) $$BND(\Delta T, \Delta P) = BND([\Delta T - \Delta T], k[\Delta P - \Delta P]),$$

where

$$k = 100/(100 + \Delta P).$$

This is our mathematical model of annual crop weather after the climate change (ΔT, ΔP). Equation (2) states that the distribution of ΔT and ΔP after a climate change is expressible in terms of the climate-change variables and the Base-Period BND given by equation (1). The scaling factor k reflects the assumption about the invariance of the CV of precipitation.

With the annual-yield function $Y(\Delta T, \Delta P)$ and the distribution $BND(\Delta T, \Delta P)$ in hand, one can calculate the frequency distribution of annual yields after a climate change. The probability that an annual yield will fall in a given interval is the sum of all the probabilities $BND(\Delta T, \Delta P)$ such that the corresponding yields $Y(\Delta T, \Delta P)$ lie in the interval.

The assumption about the patterns of annual crop weather is not essential. The climate-response model can handle any preconceived distributions of temperature and precipitation. The assumption leads to simpler calculations and makes the basic logic of the climate-response model quite transparent, although it was not made solely for these reasons.

1-11 MAPPING THE EFFECTS OF CLIMATE CHANGES ON CROP YIELDS

We now give a matrix interpretation to the assumption about patterns of annual crop weather as it relates to our primary objective—projecting the distribution of annual yields after an assumed climate change (ΔT, ΔP). Conceptually, the desired yield distribution is obtained as follows:

- Shift the Base-Period BND matrix on the annual-yield matrix until it is centered over the yield entry $Y(\Delta T, \Delta P)$ for which $\Delta T = \Delta T$ and $\Delta P = \Delta P$.

- Recalculate the BND matrix using equation (1), but replacing ΔP by $k \cdot \Delta P$, where $k = 100/(100 + \Delta P)$.[12]

- Calculate the frequency distribution of annual yields by the summing procedure described in Section 1-7.

[12] This step adjusts the precipitation dimension of the translated BND matrix in accordance with the assumption about the variability of ΔP. It could also be performed before the shift.

Table 16

EXPECTED-YIELD SUMMARY TABLE -- U.S. CORN (1976 TECHNOLOGY)

Summary of normalized relative yield statistics calculated for assumed climate changes (ΔT, ΔP) (100 = expected value of annual yield in the Base Period.)

ΔT Change in the long term average of annual mean heading period temperature referred to the Base Period.

ΔP Change in the long term average of mean crop year precipitation referred to the Base Period.

EXPECTED RELATIVE ANNUAL YIELD (NORMALIZED)
STANDARD DEVIATION
SKEWNESS
TOTAL PROBABILITY

ΔT (C)		ΔP (%) -30	-20	-10	0	10	20	30
3	Expected relative annual yield	59.2	68.7	77.4	84.5	89.4	92.5	94.5
	Standard deviation	12.5	13.8	14.1	13.3	11.9	10.6	9.3
	Skewness	0.24	0.06	-0.14	-0.34	-0.46	-0.54	-0.67
	Total probability	0.995	0.995	0.995	0.995	0.995	0.995	0.994
2	Expected relative annual yield	64.5	74.5	83.5	90.8	95.8	98.7	100.3
	Standard deviation	12.6	13.8	14.0	13.1	11.5	9.8	8.4
	Skewness	0.09	-0.12	-0.32	-0.58	-0.81	-0.99	-1.14
	Total probability	1.000	1.000	1.000	1.000	1.000	1.000	0.999
1	Expected relative annual yield	69.2	79.6	88.9	95.3	101.2	103.9	105.0
	Standard deviation	12.1	13.1	13.1	12.0	10.2	8.3	6.7
	Skewness	-0.05	-0.29	-0.51	-0.83	-1.23	-1.57	-1.74
	Total probability	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0	Expected relative annual yield	72.6	83.3	92.6	100.0	104.8	107.2	107.9
	Standard deviation	11.1	11.9	11.7	10.5	8.4	6.4	5.0
	Skewness	-0.17	-0.43	-0.68	-1.09	-1.67	-2.25	-2.38
	Total probability	1.000	1.000	1.000	1.000	1.000	1.000	1.000
-1	Expected relative annual yield	74.2	84.7	94.0	101.1	105.8	108.0	108.5
	Standard deviation	9.8	10.4	10.1	8.9	7.1	5.3	4.4
	Skewness	-0.22	-0.46	-0.74	-1.14	-1.71	-2.25	-2.15
	Total probability	1.000	1.000	1.000	1.000	1.000	1.000	1.000
-2	Expected relative annual yield	74.1	83.8	92.6	99.3	103.6	105.9	106.5
	Standard deviation	8.3	9.1	9.0	8.1	7.0	6.0	5.6
	Skewness	-0.15	-0.31	-0.52	-0.75	-1.0[illegible]	-1.26	-1.38
	Total probability	1.000	1.000	1.000	1.000	1.000	1.000	0.999
-3	Expected relative annual yield	72.3	80.9	88.8	94.8	98.8	101.1	102.1
	Standard deviation	7.1	8.1	8.4	8.1	7.7	7.4	7.3
	Skewness	0.02	-0.02	-0.17	-0.30	-0.37	-0.51	-0.60
	Total probability	0.995	0.995	0.995	0.995	0.995	0.995	0.994

To explore the effects of climate changes on a given crop, a regular lattice of 49 points was established in the ΔT, ΔP-plane; on this lattice, ΔT ranges from $-3°C$ to $+3°C$ and ΔP ranges from -30% to $+30\%$. At each lattice point the expected value, the standard deviation and skewness of the yield distribution were calculated and then assembled into an Expected-Yield Summary Table. The summary table for U.S. corn is reproduced in Table I-6.[13] At nine of the 49 lattice points the three-step process was used to calculate the complete yield distributions (see Appendix E-1).

The Expected-Yield Summary Tables are analogous to the Master Yield Grids: just as the master grids contain essentially all our information about *annual* yield Y as a function of crop weather (ΔT, ΔP), so do the summary tables contain all our information about average, or *expected*, yield Y as a function of climate change (ΔT, ΔP). Table I-6, for example, defines an expected-yield function $Y(\Delta T, \Delta P)$ for U.S. corn.

[13] The TOTAL PROBABILITY [illegible]

Interpolating between the entries in Table I-6, we calculated an *expected-yield matrix* for ΔT in multiples of 0.5°C and ΔP in multiples of 5% (Table I-7). Finally, we graphed Y(ΔT, ΔP) as a continuous function, using the convention of contour curves. The *expected-yield response surface* for U.S. corn, displayed in Figure I-5, is analogous to the (unnormalized) annual-yield response surface in Figure I-3.

Table I-7

EXPECTED - YIELD MATRIX - - U.S. CORN (1976 TECHNOLOGY)

Expected value of normalized relative annual yield as a function of climate change (ΔT, ΔP). (Interpolations between the expected-yield entries in Table I-6; 100 = expected value of annual yield in the Base Period.)

ΔT Change in the long term average of annual mean heading period temperature referred to the Base Period.

ΔP Change in the long term average of mean crop year precipitation referred to the Base Period.

ΔP (%)

ΔT (°C)	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30
3★	59	64	69	73	77	81	85	87	89	91	93	94	95
★	62	67	72	76	80	84	88	90	93	94	96	97	97
2★	65	70	75	79	84	87	91	93	96	97	99	99	100
★	67	72	77	82	86	90	94	96	98	100	101	102	103
1★	69	74	80	84	89	93	96	99	101	103	104	104	105
★	71	76	81	86	91	94	98	101	103	104	106	106	106
0★	73	78	83	88	93	96	100	102	105	106	107	108	108
★	73	79	84	89	93	97	101	103	105	106	108	108	108
-1★	74	79	85	89	94	98	101	103	106	107	108	108	108
★	74	79	84	89	93	97	100	102	105	106	107	107	107
-2★	74	79	84	88	93	96	99	101	104	105	106	106	107
★	73	78	82	87	91	94	97	99	101	102	104	104	104
-3★	72	77	81	85	89	92	95	97	99	100	101	102	102

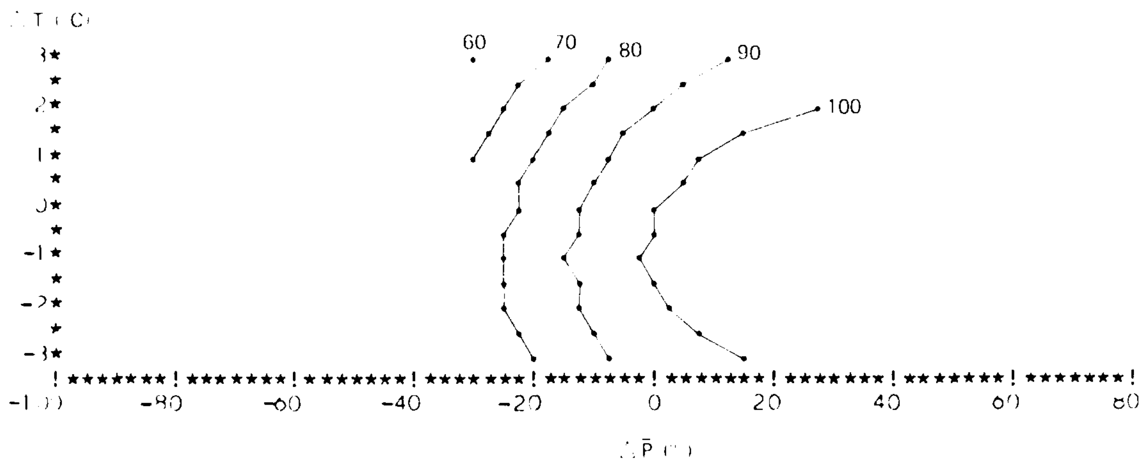
Figure I.5

EXPECTED-YIELD RESPONSE SURFACE--U.S. CORN (1976 TECHNOLOGY)

Expected value of the annual yield plotted as a function of climate change ($\Delta\bar{T}$, $\Delta\bar{P}$) (Isopleths of normalized relative yield derived from Table I.7; 100 = expected annual yield in the Base Period.)

$\Delta\bar{T}$ change in the long term average of annual mean heading period temperature referred to the Base Period.

$\Delta\bar{P}$ change in the long term average of mean crop year precipitation referred to the Base Period.



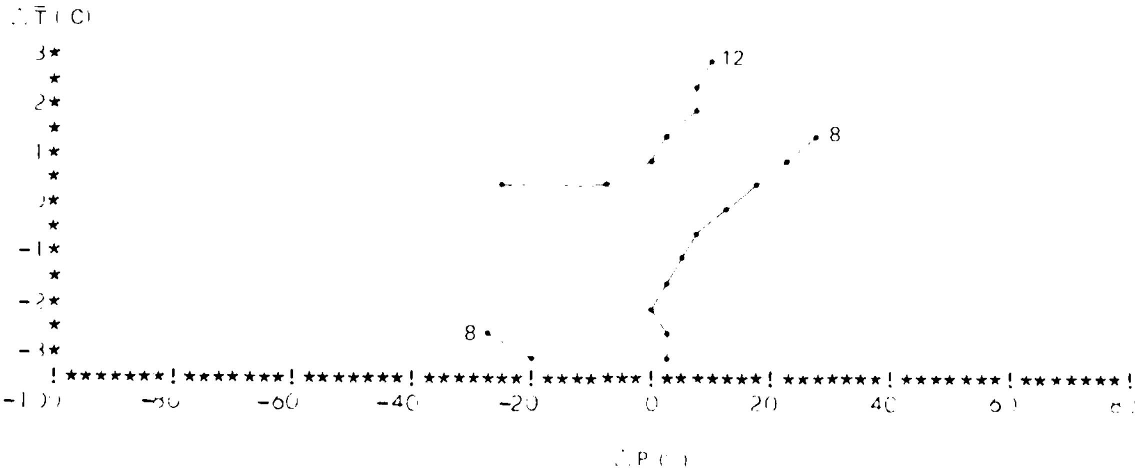
To provide an overall view of how climate changes might affect the year-to-year variability of yields, we also plotted the projected standard deviation of annual yields as a function of climate change. The *standard-deviation response surface* for U.S. corn is shown in Figure I-6. We refer to Figures I-5 and I-6 collectively as *climate response surfaces*.

Figure I-6

STANDARD-DEVIATION RESPONSE SURFACE--U.S. CORN (1976 TECHNOLOGY)

Standard deviation of annual yields plotted as a function of climate change (ΔT, ΔP). (Isopleths of normalized relative yield derived from Table I-6; 100 = expected value of annual yield in the Base Period.)

ΔT change in the long-term average of annual mean heading-period temperature referred to the Base Period.
ΔP change in the long-term average of mean crop-year precipitation referred to the Base Period.



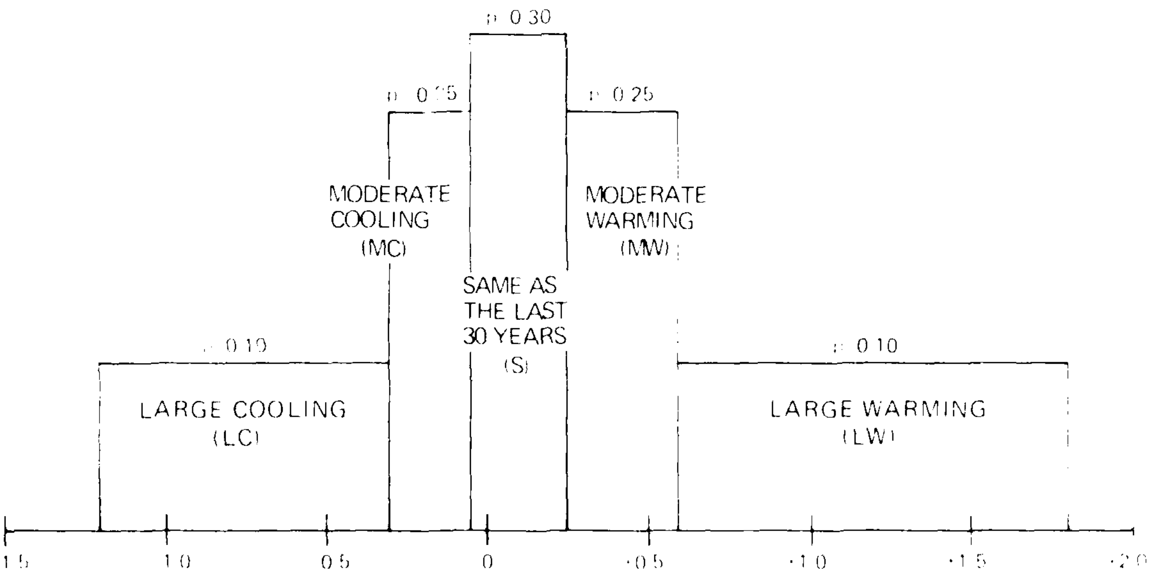
1-12 ASSESSING THE EFFECTS OF THE FIVE GLOBAL CLIMATE SCENARIOS

The general climate-response model was employed to assess the effects of the Task I global climate scenarios on the 15 key crops. The resulting "climate-crop" scenarios, which isolate climate effects from technology effects, appear in Chapter III.

Each climate scenario was defined by a range of possible changes in mean global temperature to the year 2000, and each was assigned a "probability" of occurrence.[1] The names and abbreviations of the scenarios, their temperature boundaries and their "probabilities" are shown in Figure 1-7. Despite its name, the Same as the Last 30 Years Scenario is actually a slight global warming. For two reasons the temperature boundaries are not symmetric with respect to temperature: (1) the aggregated distribution of estimated global temperature changes was somewhat biased and skewed toward warming, and (2) the distribution was partitioned so as to make the global scenarios symmetric with respect to probability.

Figure 1-7

TEMPERATURE BOUNDARIES AND "PROBABILITIES" OF THE FIVE GLOBAL CLIMATE SCENARIOS



Change in Mean Annual Temperature of the Northern Hemisphere From 1969 to 2000 (Degrees Celsius)

[1] The probabilities of the scenarios may be likened to tallies of weighted votes cast by the climate experts polled for Task I. For a fuller explanation see pages 15-16 of *Climate Change to the Year 2000*.

[illegible]

[illegible] we evaluated the effects of [illegible] about zonal climate change [illegible] global climate scenario, we took the expected climate changes ΔT, ΔP for the various latitude zones, where ΔT and ΔP are the expected (average) values of the climatologists' aggregated distributions. The expected zonal climate changes for each global climate scenario are shown in Table S-1 of the Summary. The table also indicates the latitude zone to which the key crops were assigned.

Strictly speaking, one should use the expected climate change for a specific crop region rather than the expected climate change for the entire latitude zone in which the crop region lies. Over a period of, say, ten years, a zonal climate change need not be reflected in like changes of temperature and precipitation in all regions comprising the zone. However, we based our regional yield projections on the expected zonal values of ΔT and ΔP because we could not anticipate the shifting long-wave patterns that would cause shorter term differences among regions. Furthermore, we have some evidence that the distinction between regional and zonal climate changes is of relatively little importance over the longer term. Using the historical Base-Period data, which extend over episodes of slight warming and cooling, we computed temperature and precipitation means for each latitude zone and for the regions therein. The zonal and regional changes were found to be remarkably similar.

With the data in Table S-1, the canonical frequency distribution of annual yields can be calculated for each key crop in each global climate scenario by the procedures already described. Conceptually, this involves shifting the appropriate Base-Period BND matrix (modified in the precipitation dimension) until its center lies over the element of the annual-yield matrix

[illegible]

which corresponds to the values of ΔT and ΔP in the expected climate change. In the general case this is impossible because ΔT and ΔP do not coincide exactly with any combination of ΔT and ΔP in the annual yield matrix. (The problem did not occur in the preceding section because the climate changes assumed there meshed exactly with the rows and columns of the annual yield matrices.) This difficulty was circumvented by using equation (2) of Section I.10 to compute a new scenario-specific BND that has the appropriate displacement.

For example, the expected climate change affecting U.S. corn in the Large Warming Scenario has $\Delta T = +1.0$ C and $\Delta P = +2.0$. These values do not correspond to any element in the annual-yield matrix. The BND matrix computed especially for large warming is shown in Table I-8. Its lack of symmetry about the center of the matrix reflects a "built-in" shift. The recomputed BND matrix was then superimposed directly on the annual-yield

Table I-8

BND MATRIX FOR THE LARGE WARMING SCENARIO -- U.S. CORN BELT

[illegible]

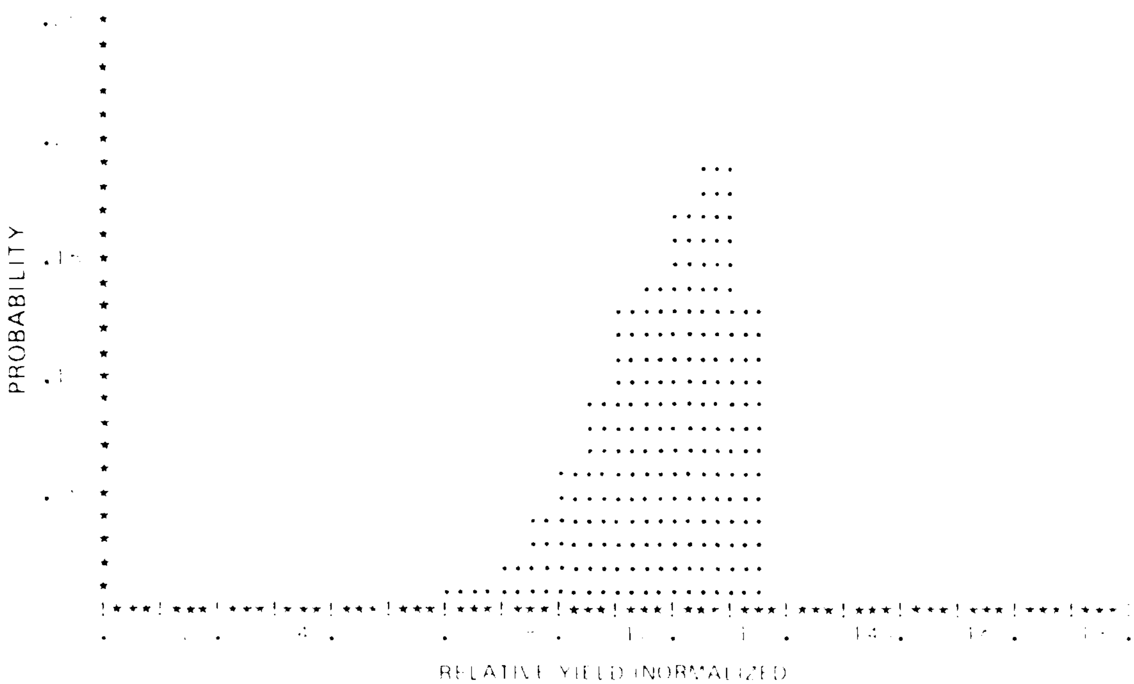
[illegible]

[illegible]

[illegible]

PROJECTED FREQUENCY DISTRIBUTION OF ANNUAL YIELDS IN THE LARGE WARMING SCENARIO -- U.S. CORN (1976 TECHNOLOGY)

[illegible]



[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]						

[illegible] VALUE = [illegible]
STANDARD DEVIATION = [illegible]
COEFFICIENT OF VARIABILITY = [illegible]
[illegible] = [illegible]

matrix (without a shift), and the frequency distribution of annual yields was calculated by the usual summing process. The canonical distribution of U.S. corn yields for the Large Warming Scenario is displayed in Figure I-8. The expected yield of this distribution is 97.48, or 2.52% less than in the Base Period. A decrease in expected yield could have been anticipated from the (unnormalized) annual-yield response surface (Figure I-3), and the amount of the decrease could have been estimated from the (normalized) expected-yield response surface (Figure I-5).

I-13 BOUNDING THE EFFECTS OF UNCERTAINTY IN THE FIVE GLOBAL CLIMATE SCENARIOS

What are the implications of the uncertainty about the precise zonal climate changes in the climate scenarios of Task I? To illustrate how we quantified the climatic uncertainty and its effects on crop yields, we consider again the Large Warming Scenario and U.S. corn, a crop grown in the northern lower middle (N-LM) latitudes.

The Climate Panel's collective uncertainty about zonal climate changes is delineated in tables of joint and marginal probabilities of climate changes (e.g., Table I-9). The tables have the same structure as the expected-yield matrices (e.g., Table I-7). Table I-9 applies to the N-LM latitudes in the Large Warming Scenario. The "marginal" probabilities in the far right-hand column were obtained from Table III-5A; they represent the climate panelists' aggregated probability distribution of ΔT for the N-LM latitudes.[*] The marginal probabilities in the bottommost row represent the analogous distribution of ΔP values.[**] Assuming that ΔT and ΔP are independent within a climate scenario, we obtained the joint probabilities in the main body of Table I-9 by multiplying corresponding pairs of marginal probabilities. We interpret one of the aggregated joint probabilities in Table I-9 as follows: given that the Large Warming Scenario eventuates around the year 2000 (*global* temperatures 0.6°C to 1.8°C warmer than at present), there is a probability of 0.044 that in the U.S. corn belt ΔT will be within one-quarter degree of +1°C and that ΔP will be +10%, plus or minus 2.5%.

The climatic uncertainty described by Table I-9 implies a corresponding uncertainty about the average yield of U.S. corn in large global warming. One calculates a frequency distribution of *expected* yields by superimposing Table I-9 on the expected-yield matrix (Table I-7) and summing the joint probabilities in the same manner that the BND probabilities were summed

[*] To make it compatible with the expected-yield matrix, the climate panelists' original frequency distribution of zonal temperature changes was recomputed for a set of shifted temperature intervals. The computation is described in Section 6.6.

[**] We assumed an underlying uniform distribution of ΔP for the projections submitted by the climatologists. See Section 6.6 for further details.

UNCERTAINTY ABOUT LARGE GLOBAL WARMING -- U.S. CORN BELT

ΔT	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30
3	[illegible]	[illegible]	[illegible]	0	[illegible]	0	0	0	0	0	0	[illegible]	[illegible]
	0	0	0	0	[illegible]	0	0	0	0	0	0	0	[illegible]
2	0	0	1	13	13	13	13	13	13	13	11	[illegible]	[illegible]
	0	0	2	25	25	25	25	25	25	25	23	[illegible]	[illegible]
1	0	0	4	44	44	44	44	44	44	44	[illegible]	[illegible]	[illegible]
	[illegible]	0	4	38	38	38	38	38	38	38	34	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	1	6	6	6	6	6	6	6	6	[illegible]	[illegible]
	0	[illegible]	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]
-1	0	[illegible]	0	0	0	0	0	0	0	0	0	0	[illegible]
	0	[illegible]	0	0	0	0	[illegible]	0	0	0	0	[illegible]	[illegible]
-2	0	0	0	0	0	0	[illegible]	0	0	0		[illegible]	[illegible]
	0	0	0	[illegible]	0	0	[illegible]	0	0	0	0	[illegible]	[illegible]
-3	0	0	0	[illegible]	[illegible]	0	0	0	0	0	[illegible]	[illegible]	[illegible]
	0	[illegible]	12	125	125	125	125	125	125	125	113	[illegible]	[illegible]

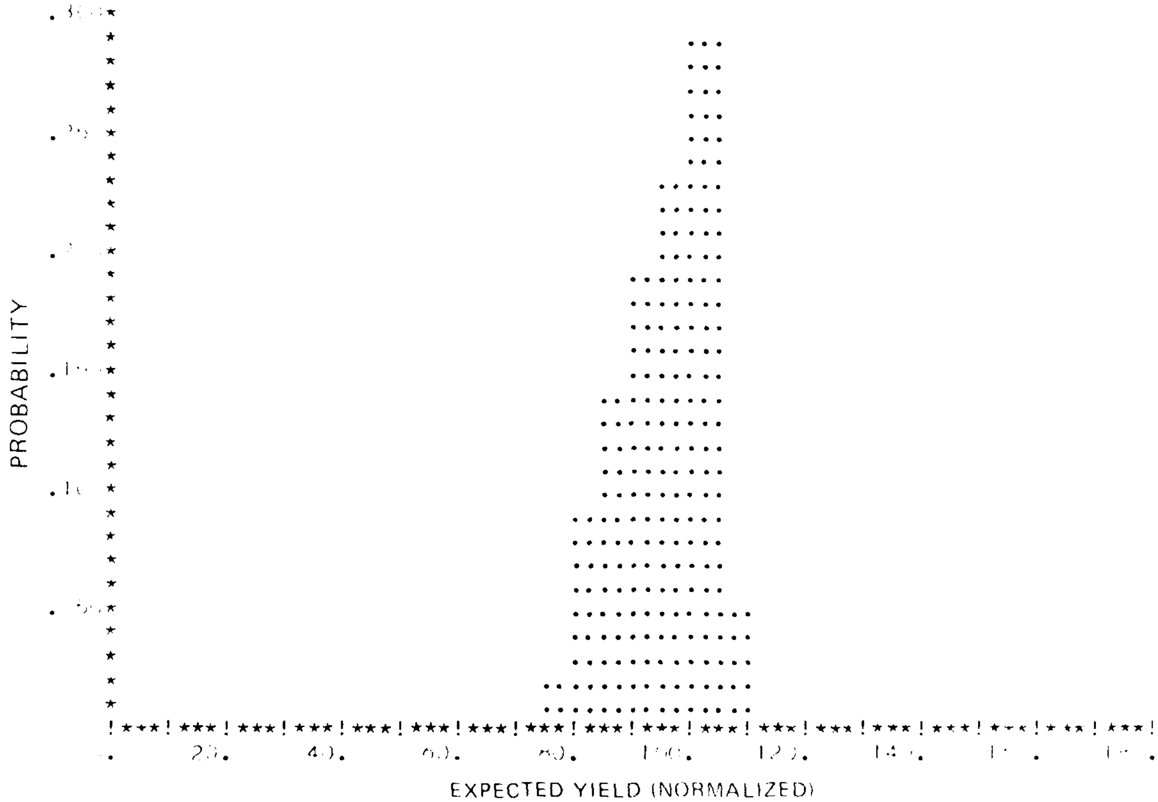
to get a distribution of *annual* yields. The distribution of expected U.S. corn yields formally associated with the large-warming regime is exhibited in Figure I-9. The expected value of this distribution, E(Y), is an average which takes into consideration climatic uncertainty as well as fluctuations of annual crop weather. In Figure I-9, E(Y) is 95.42, which is less than the canonical expected yield projected for the Large Warming Scenario. These two statistics differ because of the convexity of the expected-yield response surface (Figure I-5).

Figure I-9 shows that, even within the Large Warming Scenario, a wide range of expected yields is ostensibly possible in virtue of the uncertainty about the precise values of ΔT and ΔP. However, the climatic uncertainty suggested by Table I-9 is exaggerated by our methodology and assumptions (see Chapter VI and Appendix E-3).

Figure 19

UNCERTAINTY ABOUT EXPECTED YIELDS IN THE LARGE WARMING SCENARIO-- U.S. CORN (1976 TECHNOLOGY)

Histogram of expected value of normalized relative annual yield calculated in consideration of the uncertainty about the precise future climate state (as reckoned by the climatic probabilities in Table 19
(100 = expected value of annual yield in the Base Period)



CUMULATIVE PROBABILITY AND RELATED STATISTICS

PROB	VAL	PROB	VAL	PROB	VAL	PROB	VAL
1	74.3	5	83.3	10	84.4	15	86.2
20	88.9	25	90.1	30	90.9	35	92.7
40	94.3	45	95.9	50	96.3	55	98.3
60	98.6	65	99.8	70	100.5	75	101.2
80	102.4	85	103.0	90	104.1	95	104.7
100	107.5						

EXPECTED VALUE = 95.42
STANDARD DEVIATION = 7.19
COEFFICIENT OF VARIABILITY = .0744
SKEWNESS = -0.48

1-14 RECONCILING RELATIVE AND ABSOLUTE YIELDS

In the technology projections, yields are denominated in *absolute* units. On the other hand, the effects of climate change are assessed in terms of dimensionless normalized *relative* yields, i.e., percentages of Base-Period expected yields. Whether calculated for the recent climate of the Base Period or for a presumed future climate state, the normalized relative yields are "frozen" in current technology and cannot be compared directly with actual historical yields. Therefore, to convert a normalized relative yield to absolute units, one needs a technology-neutral equivalence factor that corresponds to 100, the expected yield for the Base Period. The converted normalized relative yields still must be interpreted as yields which have been "restated" to reflect 1976 technology. Two simple equivalence factors were considered; many others could be proposed. Both of the candidate equivalence factors are based on the historical yield series that were presented to the Agriculture Panel in the crop-yield questionnaire (see Appendix B-1).

The first equivalence factor is the average absolute yield for the period 1972–76. We made the reasonable assumption that technology did not change appreciably over this period, but we also had to assume that the 1972–76 averages of mean heading-period temperatures and crop-year precipitation were the same as the long-term averages of the Base Period.

To get the second yield equivalence factor, we fitted a straight line to the historical yields using the least-squares procedure. We then took the 1976 linear-trend value as the equivalence factor. The assumption here, of course, is that the least-squares trend line represents the effects of technology and that the fluctuation of yields about the trend line is attributable to the variability of annual crop weather. The averages of the annual crop-weather variables from 1950 to 1976 are probably better estimators of the Base-Period averages than the 1972–76 averages. However, the linear-trend method can be challenged because it is possible that the trend line reflects some climate change as well as technology change. But such an objection applies also to the interpretation of the Base-Period BND as a model of "present" climate. Actually, the parameters of the Base-Period BND incorporate the effects of whatever general cooling or warming took place during the Base Period.

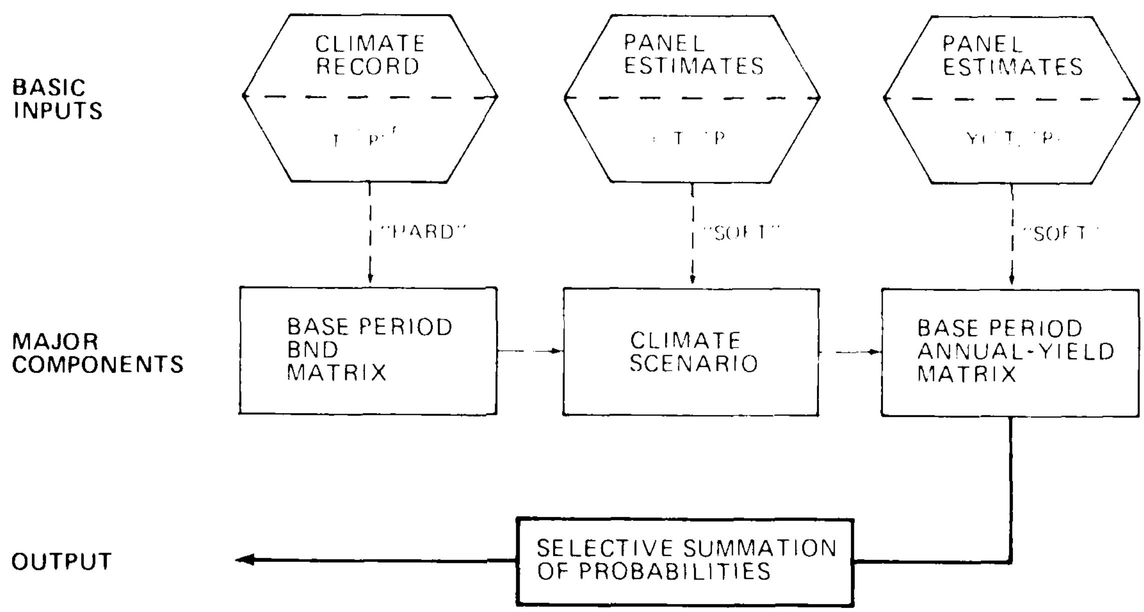
For U.S. corn the 1972–76 average yield is 81.4 bushels per acre, and the 1976 linear-trend value is 86.5 bushels per acre. The equivalence factors for the remaining key crops are listed in Table V-2. At most, the two factors differ by about 6%. The question of yield conversions is discussed further in Sections 4-6 and 5-9.

1-15 SUMMARY OF THE CLIMATE-RESPONSE MODEL

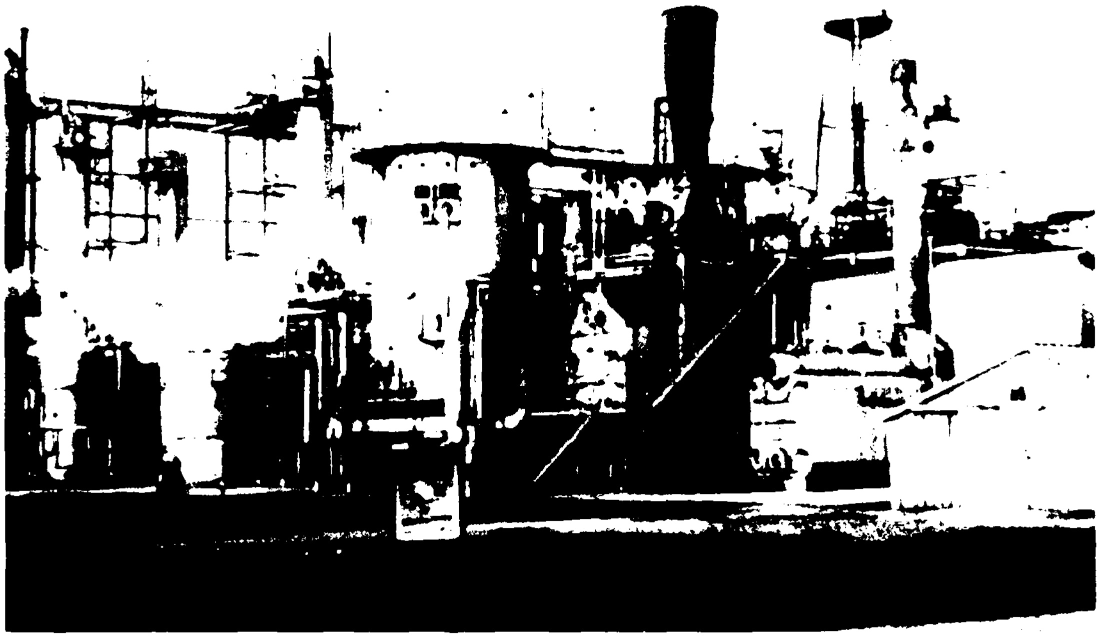
In Figure I-10 we summarize relationships among the major components and inputs of the climate-response model as it was applied to the five global climate scenarios developed in Task I. The basic inputs of "hard" and "soft" data are indicated in the hexagons. For a given country-crop combination, the parameters s_T, s_P, r of the Base-Period bivariate normal distribution (BND) are derived from the climate record. The expected climate change (ΔT, ΔP) affecting the crop region in a given climate scenario determines how to modify the Base-Period BND matrix and offset it on the annual-yield matrix. The output of the model, a projected distribution of normalized relative annual yields, is obtained by selectively summing BND probabilities according to a partition of the yields in the annual-yield matrix.

Figure I-10

SCHEMATIC OF THE CLIMATE-RESPONSE MODEL



CHAPTER TWO



TED CRAMPTON

CHAPTER TWO

THE TECHNOLOGY PROJECTIONS

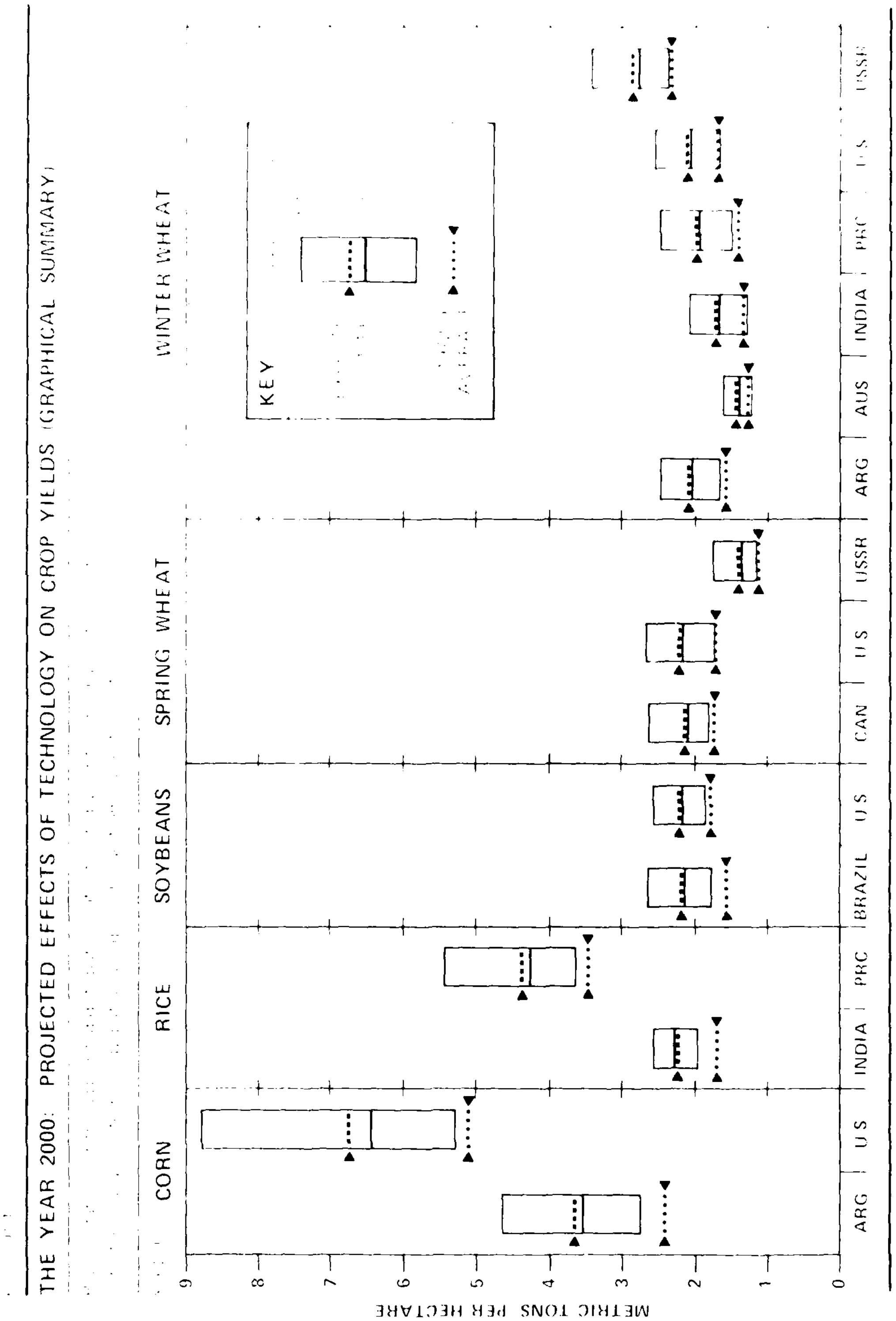
2-1 INTRODUCTION

In the crop-yield survey, members of the Agriculture Panel were asked to make two kinds of estimates for each country-crop combination. The subject of this chapter is the Part I estimates, which dealt with the trend of crop yields to the year 2000, assuming no change from recent climate patterns but taking account of likely changes in agricultural technology. The Part II estimates dealt with yield as a function of annual crop weather, given the technology then prevalent in each country.

2-2 SEPARATING THE EFFECTS OF TECHNOLOGY FROM THE EFFECTS OF WEATHER

The stated goal of Task II was "to estimate the likely effects of possible climate changes on selected crops in specific countries, and to develop a methodology for combining crop responses and climatic probabilities into climate-crop scenarios for the year 2000." Therefore, we were mainly interested in the replies to the Part II questions of the survey, i.e., the panelists' estimates of probable crop responses to selected values of annual temperature and precipitation. But numerous research reports on weather-yield relationships have cited the complex interaction between the weather component of crop yields and the technology component. While most researchers agree that weather and technology are important determinants of yield trends and variability, they frequently disagree as to (1) the composition and relative importance of the factors included in the terms "weather" and "technology," and (2) the nature and extent of the weather-technology interactions.

For our purposes it was necessary somehow to segregate the complicating influences of technology. Thus, the Part I requirements were intended primarily to help the panelists separate their perceptions about the effects of technology from their perceptions about the effects of crop weather. For each key crop we presented a table and a plot of historical yields with these instructions: "Assuming that the climate remains essentially the same as during the period of record (i.e., essentially the same means and variances for the weather variables that affect the crop) but taking into account your best judgment of probable changes in technology for this country-crop combination, indicate your projection of the general trend in yields to the year 2000." The panelists recorded their estimates as three extensions of


THE YEAR 2000: PROJECTED EFFECTS OF TECHNOLOGY ON CROP YIELDS (GRAPHICAL SUMMARY)
CORN
RICE
SOYBEANS
SPRING WHEAT
WINTER WHEAT
KEY
METRIC TONS PER HECTARE
0
1
2
3
4
5
6
7
8
9
ARG
U S
INDIA
PRC
BRAZIL
U S
CAN
U S
USSR
ARG
AUS
INDIA
PRC
U S
USSR

the historical yield series corresponding to the 10th, 50th and 90th percentiles of average yields. See Appendix A-1 for the format of the Part I requirements and Section 1-4 for the methodology by which the panelists' responses were aggregated

2-3 IMPLICATIONS OF THE TECHNOLOGY ESTIMATES

Although they are not strictly essential to our climate impact assessment, the Part I estimates are of considerable interest. They are, after all, relevant to the "most probable" of our five global climate scenarios, namely, the Same as the Last 30 Years Scenario.

However, the technology projections indicate considerable uncertainty on the part of individual panelists, and the aggregation technique reflects the wider range of perceptions held by the panel as a whole. The dispersion of the estimates underscores the need for further research on the future impact of agricultural technology.

Nevertheless, we believe there is enough "truth" in the central tendencies of the aggregated Part I estimates to support a major conclusion: by the year 2000, the effect of changes in technology on most crop yields is likely to be severalfold larger than the effect of climatic change.

2-4 PRESENTATION OF THE TECHNOLOGY ESTIMATES

Appendix B-1 and Appendix B-2 contain the aggregated technology estimates for each of the 15 country-crop combinations. In Appendix B-1 the projections are displayed in the same manner as they were solicited, i.e., aggregated percentile trend curves are shown as extensions of the crop-yield series that appeared in the survey. In Appendix B-2 the aggregated results for the year 2000 are presented as frequency distributions of estimated yields.

The panelists were also requested to comment on the rationale for their technoloy projections. Their verbal responses are quoted in Appendix B-3.

The aggregated technology estimates for the year 2000 are summarized in Figure II-1 and Table II-1. Figure II-1, based on a common metric unit of yield, embodies certain features of the histograms in Appendix B-2. The heights of the individual bars in the figure are measures of the panel's collective uncertainty about the course of technology and its effects on yields. The disparities in the average values of recent yields reflect a number of factors, among them differences in soils and average crop weather, as well as prevailing technology.

[illegible]

THE YEAR 2000: PROJECTED EFFECTS OF TECHNOLOGY ON CROP YIELDS (STATISTICAL SUMMARY)

[illegible]

CROP	1* E(Y)	2* AVG	3 E(Y)/AVG	4 GR	5* STD DEV	6 CV	7 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
CORN														
ARGENTINA	[illegible]	38.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	34.3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
U.S.	107.3	81.4	1.318	1.068	22.4	0.209	0.64	41.4	84.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
RICE														
INDIA	20.3	15.2	1.335	1.116	2.25	0.111	0.32	15.2	17.4	20.4	[illegible]	[illegible]	[illegible]	[illegible]
PRC	39.0	30.7	1.267	0.914	5.77	0.148	0.66	29.3	32.2	38.0	[illegible]	[illegible]		[illegible]
SOYBEANS														
BRAZIL	32.5	23.2	1.402	1.309	5.96	0.184	1.41	21.2	26.3	31.6	[illegible]	[illegible]	[illegible]	[illegible]
U.S.	32.5	26.6	1.220	0.767	4.06	0.125	0.62	24.5	27.5	32.1	[illegible]	[illegible]	[illegible]	[illegible]
SPRING WHEAT														
CANADA	32.2	26.0	1.238	0.825	4.93	0.153	0.82	22.2	26.7	31.5	[illegible]	[illegible]	[illegible]	[illegible]
U.S.	32.4	25.7	1.259	0.889	5.32	0.164	0.15	18.6	25.6	32.1	[illegible]	[illegible]	[illegible]	[illegible]
USSR	20.6	16.5	1.252	0.869	3.51	0.170	1.25	14.0	16.9	20.6	[illegible]	[illegible]		[illegible]
WINTER WHEAT														
ARGENTINA	30.8	23.3	1.321	1.077	5.54	0.180	1.41	18.5	24.9	30.4	[illegible]	[illegible]	[illegible]	[illegible]
AUSTRALIA	[illegible]	18.7	1.111	0.407	2.30	0.111	0.52	14.6	18.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INDIA	[illegible]	19.5	1.290	0.985	4.75	0.188	0.34	14.7	19.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PRC	[illegible]	20.8	1.391	1.277	5.94	0.205	0.42	15.4	22.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
U.S.	30.8	24.5	1.254	0.876	4.86	0.158	0.20	18.8	24.3	30.5	37.5	[illegible]	[illegible]	[illegible]
USSR	42.0	34.2	1.228	0.792	6.39	0.152	0.70	28.9	34.7	41.4	50.5	[illegible]	[illegible]	[illegible]

Column 1: expected yield; Col. 2: average yield for 1972-76; Col. 4: annual growth rate of E(Y); Col. 5: [illegible] ... Col. 7: [illegible] ... Col. 8 & 9: [illegible] respondents and the [illegible] average expect[illegible]

[illegible] In these columns [illegible] others.

Table II-1, like Appendix B-2, is based on English units of yield. An entry in Column 1 can be regarded as the panel's "best" point estimate of the average yield at the turn of the century if current climate were to persist. The entries in Column 2 correspond to the points labeled "A" in the graphs of Appendix B-1. For each key crop, the entry in Column 3 is an expected technological improvement factor. An equivalent annual growth rate is shown in Column 4; annual compounding of this rate from 1974 (the midyear of the 1972–76 average) to 2000 AD results in the improvement factor listed in Column 3. The next eight columns, which pertain to the shapes of the histograms in Appendix B-2, evince the panelists' uncertainty about technology. For example, in the case of Argentine corn, one could interpret the 10th percentile as follows: in the collective judgment of the panel there is a 10% "probability" that the average yield around the year 2000 will be less than 43.5 bu/acre, assuming no change in climate. Being dimensionless, the entries in Columns 3, 4, 6 and 7 apply also to the distribution of metric yields in Figure II-1.

2-5 DISCUSSION OF THE TECHNOLOGY PROJECTIONS

Figure II-1 deals with mass of food or fodder harvested per unit area. By this measure, U.S. corn and Chinese rice held a commanding advantage in the years 1972–76. If the expected yields can be taken as reliable estimates of future average yields, the two crops should retain their lead for the remainder of the century, and Argentine corn should join them in a position of relative advantage. However, the corn crops are precisely the ones about which there is the greatest range of uncertainty (see Section 4-7). At the other end of the scale, the panelists foresaw very limited improvement on the current low yields of Australian wheat. The yield bars in Figure II-1 reflect the positive skewness of the distributions: generally, the expected yield is greater than the median yield, and the distance between the 90th and 50th percentiles exceeds the distance between the 50th and 10th percentiles.[1] The positive skewness stems from the tendency of the panelists to regard recent average yields as lower bounds for their technology projections.

The technology projections for 2000 AD are summarized more precisely in Table II-1. There is some correlation between current yields and the expected technological improvement factors. In the corn, rice and soybean groups the country with the lower current yield has the higher expected improvement factor. If one excludes Australia, a rather special case, a similar pattern holds in the winter wheat group: the three lowest current yields and the three highest improvement factors are associated with the same countries—Argentina, India and the PRC.

[1] A positively skewed histogram is skewed to the right, i.e., it has a "tail" toward the higher values of yield. Positive skewness indicates an excess in the number of items smaller than the mean; this excess draws the peak of the frequency distribution toward the left.

In the corn group, Argentina's expected technological improvement factor (1.51) is the highest among all the country-crop combinations, yet not high enough to close the gap between U.S. and Argentine corn yields by the year 2000. The 1972-76 average yield for the nine U.S. corn states was more than double that of Argentina's. This head start and a respectable improvement factor for U.S. corn result in the expected U.S. yield being about 185 of the expected Argentine yield at the turn of the century.

The expected improvement factor for Indian rice is only slightly higher than for Chinese rice. Consequently, the ratio of Chinese yields to Indian yields changes little by 2000 AD. These projections suggest that the PRC could maintain a yield advantage of almost 2 1.

Although recent U.S. soybean yields were about 15 higher than those of Brazil, the panelists projected the same expected yield for the two countries by the year 2000. This implies an annual Brazilian growth rate of 1.31 , compared to about 0.77 for the U.S. The higher coefficient of variability for Brazil, however, indicates less of a consensus about the outlook for Brazilian yields.

In the spring wheat group, the projections for Canada and the U.S. are markedly alike in most respects, as one would expect for contiguous crop areas farmed under similar economic systems and levels of technological development. The only notable difference is in the skewness: 0.82 for Canada and 0.15 for the U.S. This difference could reflect a small subgroup of panelists who perceive a relatively greater likelihood for Canadian yield improvements through technology. This in turn could be a reflection of a smaller data base (22 estimates for Canada, 26 for the U.S.), lower expertise (2.6 for Canada, 2.8 for the U.S.), and therefore less cognizance of possible constraints on technology in Canada. Soviet spring wheat has an improvement factor, growth rate and coefficient of variability similar to those of the Canadian and U.S. crops, but it starts from a 1972-76 base that is about 35 lower than the North American average. Also, the Soviet distribution is more positively skewed than Canada's. One could attribute this again to fewer respondents with lower expertise.

Except for Australia, the improvement factors in the winter wheat group are fairly homogeneous. The Australian improvement factor (1.11) and coefficient of variability (0.11) are the lowest for any country-crop combination, suggesting a consensus that weather, not technology, is likely to be the limiting factor for Australian wheat. Of the remaining winter wheat countries, the Soviet Union has the lowest improvement factor (1.23)—not so low, however, that the USSR would lose its lead in yields. Argentina, the PRC and the selected six-state area of the U.S. have expected yields of about 30 bu/acre, some 29% below the Soviet yield of 42 bu/acre. India follows with about 25 bu/acre, still a 29% improvement over 1972–76. Australia trails with less than half the expected Soviet yield.

In Chapter IV we compare the technology projections with the projected effects of the extreme climate scenarios (Section 4-5). We also point out that the technology estimates take on a different aspect when they are expressed as relative rather than absolute yield changes (Section 4-6).

2-6 PARTICIPATION AND EXPERTISE

There is considerable variation among the 15 country-crop combinations with respect to the numbers and expertise of the panelists who submitted acceptable technology projections (Table II-1).

Chinese rice and wheat have the lowest average expertise (2.1), which is understandable in view of the paucity of information about Chinese agriculture. The rice group is exceptional for the small number of respondents and relatively low expertise. Otherwise, the average number of respondents for the countries within the crop groups ranges from 19.5 (soybeans) to 22.7 (spring wheat), while the average expertise ranges from 2.5 (winter wheat, including the PRC) to 3.0 (corn).

There is a "nesting" phenomenon within the crop groups that include the U.S. The preponderance of respondents were from the U.S. and hence more knowledgeable about a crop as grown in the U.S. than in foreign countries. For example, of the 22 panelists who submitted qualifying Part I estimates on U.S. soybeans, 17 also submitted estimates on Brazilian soybeans, but most of the latter gave themselves a lower expertise rating on the Brazilian crop. The average expertise for Brazilian soybeans was 2.6 compared to 3.2 for the U.S. The nesting effect due to U.S. panelists is partially offset by foreign panelists who rated themselves higher on, say, Canadian wheat than on U.S. spring wheat.

In Section 4-9 we compare participation and expertise between the Part I and Part II responses to the crop-yield survey.

2-7 THE NEED FOR ADDITIONAL RESEARCH

When analyzing the Part I results of the survey—estimated yield changes *due solely to technology*—one should consider that the agriculture panelists were chosen primarily for their knowledge of the Part II weather-yield

[illegible] accounts for about one half of total U.S. winter wheat pro[illegible] yields. The 1972–76 average yield for this area was 24.5 bu/acre [illegible] about 3[illegible] bu/acre.

relationships, the principal focus of the study.) There is some question, however, whether the panelists *perceived themselves as more expert on* the Part II requirements than on the Part I requirements (see Appendix C-1). It is possible that a panel selected chiefly for expertise in extrapolating crop technology would have produced different technology projections.

Since no panelist was an expert on all 15 of the country-crop combinations, some of the dispersion in the technology estimates can be attributed to less-than-expert judgments. Yet, dispersion is in the nature of things. To project the effects of technology, one needs a range of *scenarios* that take account of: (1) existing but unused technology, (2) the potential for scientific discoveries, and (3) the many factors that influence the adoption of technology. A number of panelists commented that major technological advances could be made in some countries given the solution of economic, political, social and demographic problems, plus the establishment of more effective agricultural education systems.

The dispersion in the Part I projections permits one to say with some confidence that the "right" technology answers lie somewhere in the broad distributions of yield estimates. On the other hand, in view of the dispersion, one must be cautious about accepting the expected values of the distributions as point estimates. Obviously, expert perceptions of low, median and high technology payoffs would be more meaningful if they were based on a common set of explicit assumptions.

As for the interaction between weather-climate factors and technological factors, the crop-yield survey was not designed to elicit information about the *combined* effects of technological and climatic change on crop yields. Nevertheless, some panelists felt that climatic conditions were unfavorable enough in certain cases to preclude significant yield increases, given any foreseeable technological advances.

Many panelists noted the possible negative impact of rising energy prices (with direct effects on fuel costs and indirect effects through increased cost of nitrogen fertilizer). The uncertainty surrounding the cost of energy and its implications for agricultural technology may partially explain why some of the projections are lower than earlier ones made by the U.S. Department of Agriculture, the United Nations Food and Agricultural Organization, the World Bank, and various national governments. The panel's relatively "pessimistic" views on yield trends serve as a reminder of assertions that the leading edge of agricultural technology may be slowing down (as in the *1977 World Food and Nutrition Study* of the National Academy of Sciences).

Taken together, the climate-neutral technology projections and technology-neutral climate-crop scenarios (Chapter III) plainly suggest that by the year 2000 technological change will have affected most crop yields to a substantially greater degree than climatic change. We therefore strongly recommend an in-depth analysis of the possible impact of new technology and its rate of adoption on the levels and variability of yields in major crop-producing areas of the world.

An initial phase might examine historical yields to assess the relative impacts of technological and climatic factors. Energy use should receive special attention. A suggested second phase would be an expanded, systematic survey of expert judgments about future yields, emphasizing the roles of the diverse elements of technology under various assumptions about climate change. The panel of experts should be broadly based and multidisciplinary; it might include members of the NDU Agriculture Panel, scientists who worked on the *World Food and Nutrition Study*, specialists at the international agricultural research institutes, and authorities in individual countries. Various disciplines ought to be represented: agronomists (geneticists, crop-fertility experts), agricultural engineers, agricultural economists, irrigation specialists, agribusiness representatives, etc. The answers to a carefully structured set of questions could provide the nearest thing to a consensus on the specific elements of technology likely to be bottlenecks in particular yield situations, and the probabilities of overcoming those bottlenecks.

CHAPTER THREE

USDA

CHAPTER THREE

THE CLIMATE-CROP SCENARIOS

3-1 INTRODUCTION

The climate-response model (Chapter I) was used to generate five scenarios concerning climate and crop yields around the year 2000. Each of them recapitulates one of the climate scenarios developed in Task I and summarizes its estimated effects on the annual yields of 15 "key" crops. The climate-crop scenarios are distinguished by global temperature changes ranging from a "large" cooling to a "large" warming (see Figure I-7).

3-2 THE NATURE OF THE SCENARIOS

Each scenario consists of a two-part narrative amplified by two pages of data. The first part of the narrative and the first page of data, taken from *Climate Change to the Year 2000*, deal with the posited change in climate. The climate narrative seeks to delineate average climatic conditions as they might exist in a period of years around 2000 AD. These average conditions, called the *expected climate change*, do not refer specifically to the year 2000; the climate of that year is likely to differ from the scenario projection to an extent consistent with normal year-to-year climate variability. The "probability" of the climate scenario's occurrence is an expertise-weighted average of subjective probabilities that were solicited from a panel of climatologists. Inasmuch as a scenario describes a possible "slice of future history," it downplays uncertainty. Thus, for stylistic reasons, the climate narrative contains assertions that reflect a higher degree of certainty than was expressed by the Climate Panel as a whole. The range of uncertainty about specifics of the expected climate change is indicated in the appended table of aggregated subjective probabilities.

The second part of the scenario narrative and the second page of data deal with the response of crop yields to the climate change. The yield projections are sensitive to the zonal details of the expected climate change, especially to the expected changes in average annual precipitation. Therefore, there is uncertainty about the projected yields due to uncertainty about the precise climate change that might affect the crops in a particular zone of latitude. Aside from the uncertainty about *average* zonal climate conditions, there is uncertainty with respect to fluctuations in annual crop weather and the response of crops to these fluctuations.

[illegible]

SCENARIOS

The effects of a given climate scenario on the annual yields of a key crop are assessed in terms of *normalized relative* yields, i.e., yields expressed as percentages of the average annual yield computed for the Base Period (the recent past). In calculating a distribution of these annual yields, we assumed, *inter alia,* no change from the indigenous agricultural technology of 1976. Although the scenarios dwell on the response of crop yields to climatic change as of 2000 AD, we believe that climate is likely to have a second-order effect on most crops compared with applied technology. Indeed, a necessary (but dubious) pretense of the narratives is that the "pure" effects of climate change will be distinguishable from the effects of other factors—technological, politico-economic, etc.—which influence crop yields directly or indirectly.

In our model, all the crops common to a zone of latitude are subject to the same climatic challenge, and they generally respond in the same direction.* Therefore, the crop-yield narratives have been organized according to latitude zone. (The boundaries of the zones are given in Table S-1.) The crop-yield data tables, on the other hand, have been organized by crop group (corn, rice, etc.) to facilitate country-to-country and crop-to-crop comparisons. The tabulated expected yields (Y) are interpreted in the narrative as average annual yields restated for 1976 technology. Listed in the last column of each crop-yield table is "PROB Y < 0.9Y," the probability (in percent) that an annual yield will fall below nine tenths of the expected yield for the scenario. The entries in this column are the bases for narrative statements about the incidence of "crop shortfalls." That is, we have defined a "crop shortfall" to be an annual yield at least 10% under the projected average yield.

In the crop-yield portions of the narratives, the following adjectives are used to describe the magnitudes of the projected changes in Y due solely to the expected climate changes:

- Change of 3% or less: small, slight, marginal, negligible.
- Change of 3% to 6%: moderate, appreciable, considerable.
- Change of 6% to 9%: significant, substantial, large.

At the end of the chapter are two additional tables of crop-yield data. Table III-6 is a summary containing the expected values (Y) and the coefficients of

*There are some apparent discrepancies between the climate narratives in this chapter and the climate narratives in *Climate Change* concerning the expected changes of zonal temperatures. In *Climate Change* the expected temperature change for a particular latitude zone was based on the climate panelists' aggregated temperature probabilities *before* they were rounded for publication. In this chapter the corresponding expected change was calculated from the rounded probabilities (which are the same in the tables of both reports). The difference (if any) between two such expected changes is small and it has little effect on the yield projections because the key crops are relatively insensitive to temperature.

variability of the yield distributions that were calculated for the climate-crop scenarios and the Base Period. Table III-6 also has a column of scenario-weighted yields (the sums of the products p Y, where p is the "probability" of the scenario). If taken literally, the scenario-weighted yield of a key crop indicates that the expected payoff from climate in the year 2000 is the current average yield, give or take a small fraction. Finally, in Table III-7, we list yield statistics for the Base Period, our model of recent climate. The tables of projected yields in the scenarios should be viewed as climate-induced perturbations of Table III-7. Regarded as a sixth climate scenario (no climate change whatever), the Base Period fits into the sequence of Task I scenarios between moderate global cooling and the "Same" scenario, which describes a slight global warming.

3-3 THE LARGE COOLING SCENARIO

The Climate Setting

The global cooling trend that began in the 1940s accelerated rapidly in the last quarter of the 20th century. The average global temperature reached its lowest value of the past century a few years before 2000 AD. Climate conditions were strikingly similar to the period around 1820. Climatologists explained the large global cooling in terms of natural climatic cycles, partly solar induced and partly attributable to several major volcanic eruptions that occurred between 1980 and 2000. Although many climatologists had expected a continued increase in carbon dioxide to result in global warming, this influence was overwhelmed by the natural cooling in the period.

While temperature decreased over the entire globe, the largest decreases occurred in the higher latitudes of the northern hemisphere. The north polar latitudes, marked by an expansion of arctic sea ice and snow cover (especially in the North Atlantic sector), had cooled by about 2 C since the early 1970s.[4] The northern higher and lower middle latitudes cooled by about 1 C. The subtropical latitudes in both hemispheres showed a 0.5 C decrease in average temperature, while the remainder of the southern latitudes showed a 1 C decrease. The large global cooling trend caused significantly shorter and more variable growing seasons in the higher middle latitudes.

[3] The coefficient of variability is the ratio of the standard deviation to the expected value of a distribution.

[4] One climatologist who contributed to this scenario reasoned that the north polar regions would cool only about 0.5 C, considerably less than the cooling in the northern middle latitudes.

By the year 2000, it was also raining less in the higher middle and subtropical latitudes, although precipitation in the lower middle latitudes changed little or possibly increased sightly

Precipitation also became more variable. The westerlies showed a pronounced shift from the higher middle to the lower middle latitudes. This shift brought brief, yet severe, "hit-and-run" droughts as well as severe cold spells (including early and late killing frosts) in the lower middle latitudes. The higher middle latitudes, particularly Canada, from which the westerlies and their associated storm tracks were displaced, suffered an increased incidence of long-term drought and winter cold. In the subtropical latitudes, the subtropical highs tended to displace the tropical easterly rainbelt and, hence, increased the incidence of long periods of hot, dry weather. The center and intensity of the Asiatic monsoon changed dramatically between the late 1970s and the turn of the century. The frequency of monsoon failure in northwest India increased to such an extent that the last decade of the 20th century bore a resemblance to the period from 1900 to 1925. Droughts were also more frequent in the Sahel region.

Most average crop yields at the turn of the century had risen well above the levels of the mid-1970s, primarily due to the diffusion of improved agricultural technology. As for the climate component of yields, the global cooling had mixed effects on world agriculture. The climate change *per se* tended to diminish the gains from technology in some crop regions, and to augment these gains in others. Moreover, the droughts and monsoon failures drastically reduced agricultural yields in the years they occurred.

Crops of the Northern Higher Middle Latitudes

In the northern higher middle latitudes, the deteriorating climate was generally detrimental to crop yields. The adverse effects of shorter and cooler growing seasons, reinforced by a small reduction in average annual precipitation, depressed the yields of Canadian and Soviet grains to a significant degree. When restated for 1976 technology, the average annual yields of Canadian wheat, Soviet spring wheat and Soviet winter wheat were 6% to 9% lower than in the mid-1970s. The magnitudes of these climate-induced yield changes were the largest of any noted for the 15 key crops. Spring wheat yields in the U.S., however, were reduced only slightly by the climate change, and the year-to-year variability of yields appeared to be less than it was in the mid-1970s. Soviet winter wheat yields, on the other hand, became considerably more variable, and the incidence of crop shortfalls (yields no greater than nine tenths the average) increased over the last quarter century from about 2 years in 9 to 2 years in 7.

Crops of the Lower Middle Latitudes

With the exception of Chinese winter wheat, the key crops grown in the lower middle latitudes responded positively to the climate change. In the PRC, the lower temperatures had an adverse effect on winter wheat that was only partially offset by the beneficial, but small, increase in precipitation. The net effect was a small reduction in Chinese winter wheat yields and somewhat less frequent crop shortfalls. For the other crops in these latitude zones, the lower temperatures and moister conditions both contributed to higher yields. In the southern lower middle latitudes, the climate increments of average yields for Australian wheat and Argentine corn and wheat were 4% to 6% on a technology-adjusted basis, about double those for U.S. corn, soybeans and winter wheat in the north. The differences between the two hemispheres may have been due to the slightly greater cooling of the southern zone and the fact that the crops of both zones (except Chinese winter wheat) have similar positive responses to cooler temperatures. The annual yields of the U.S. crops grown in the zone became noticeably less variable. Crop shortfalls became less frequent: about 2 years in 15 for U.S. corn, soybeans and winter wheat, compared with 2 years in 11 or 12, 25 years earlier. Although the crops of the southern zone realized larger yield enhancements from the climate change than the U.S. crops, they did not enjoy as great a reduction in the incidence of shortfalls.

Crops of the Subtropical Latitudes

The key crops of the subtropical latitudes were stimulated by the modestly lower temperatures but inhibited by the somewhat drier conditions. On balance, the climate change had a small depressant effect on Brazilian soybeans and the rice crops of India and the PRC. Indian wheat benefited slightly because of its relatively stronger response to cooler temperatures.

Summary by Crop

The cooler climate favored Argentine and U.S. corn: Argentina experienced an appreciable yield increase from the climate change, about twice that of the U.S., where corn yields became less variable. The climate change had a negligibly suppressive effect on Indian and Chinese rice. Brazilian soybeans were virtually unaffected; U.S. soybeans enjoyed small gains and became less prone to shortfalls.

Canadian and Soviet spring wheat yields were depressed significantly, but U.S. yields were impaired only slightly, by the climate change.

The new climate regime eroded average Soviet winter wheat yields significantly, and it imposed a small penalty on Chinese winter wheat. Elsewhere there were compensatory climatic enhancements of winter wheat yields moderate in Argentina and Australia, small in India and the U.S. Shortfalls of winter wheat were less frequent in the PRC and U.S., and more frequent in the USSR, than in the mid-1970s.

The effects of the climate change on crop yields were masked by the gains due to technology and by the year-to-year variability of yields due to fluctuations of annual crop weather. Nevertheless, after adjustment for technological advances, the yield decrements attributable to climate were substantial in the most northerly grain regions. Offsetting these losses were some small-to-moderate yield increments in the lower latitudes.

3-4 THE MODERATE COOLING SCENARIO

The Climate Setting

The global cooling trend that began in the 1940s continued at a slackened pace through the last quarter of the 20th century. Climatologists explained this trend principally in terms of a natural cooling cycle, moderated by the warming effects of increasing amounts of carbon dioxide in the atmosphere. The cooling cycle was partly solar in origin and partly associated wth an increase in volcanic activity.

While temperature decreased over the entire globe, the largest temperature decreases occurred in the higher latitudes of both hemispheres. The cooling of the northern hemisphere ranged from about 1 C in the polar latitudes to about 0.3 C in the subtropical latitudes. The southern hemisphere, with its more zonal circulation and larger ocean area, cooled more uniformly and slowly. The extent of the cooling in the higher middle latitudes was not sufficiently large to cause a significant change in the mean length or interannual variability of the growing season.

The levels of growing-season precipitation as well as annual precipitation remained unchanged in the lower middle latitudes but decreased slightly in the higher middle and subtropical latitudes. The variability of annual and growing-season precipitation increased slightly compared to the 1950–75 period, with the strongest tendency toward increased variability in the subtropical latitudes.

Drought conditions again plagued the mid-latitude areas of the U.S., corroborating the 20- to 22-year drought cycle hypothesis. In the other mid-latitude areas of the world, there were intermittent drought conditions comparable to those of the 1970s. Droughts were also more frequent in the Sahel region, as was monsoon failure in Asia. The droughts and monsoon failures slashed agricultural yields in the years they occurred.

The widespread adoption of improved agricultural technology in the final quarter of the century raised the average yields of most key crops well above the levels of the mid-1970s. The global cooling, although moderate, was sufficient to modify the gains from technology. For most key crops the climate component of yield change was small, but the yields of some northerly grain crops were depressed to a considerable degree by the climate change.

Crops of the Northern Higher Middle Latitudes

Generally, crop yields in the northern higher middle latitudes were impaired by the moderately cooler and slightly drier conditions. Most affected were Canadian and Soviet grains. When restated for 1976 technology, the average annual yields of Canadian wheat, Soviet spring wheat and Soviet winter wheat fell about 3.0 to 4.5 below the levels that had prevailed 25 years before. The magnitudes of these climate-induced yield changes were three to four times those of the other key crops. The lower temperatures as well as the decreased precipitation were harmful to these three crops. The climate change also appeared to cause somewhat more frequent shortfalls of the Soviet spring and winter wheat crops. Shortfalls were occurring about 2 years in 8 compared with a rate of 2 years in 9 during the mid-1970s. U.S. spring wheat fared better: the lower temperatures had practically no effect on yields, while the slight drop in average precipitation exacted a small toll from annual yields.

Crops of the Lower Middle Latitudes

The slight cooling of the lower middle latitudes, unaccompanied by any noticeable trend in precipitation, was marginally favorable for U.S. corn, soybeans and winter wheat, Argentine corn and wheat, and Australian wheat. Chinese winter wheat, however, experienced a very small decrease in yields as a result of the cooling. The three U.S. crops seemed to be slightly less prone to shortfalls than in the mid-1970s.

Crops of the Subtropical Latitudes

The climate change was manifested in the subtropical latitudes by small decreases in both temperature and precipitation. The cooling had a benign or neutral effect on all the key crops of these latitudes, but the drier conditions were deleterious. The precipitation change governed the climatic responses of Indian rice, Chinese rice and Brazilian soybeans, but the yield decrements were negligible. The yields of Indian wheat, which has a rather strong positive response to lower temperatures, were elevated slightly by the climate change.

Summary by Crop

The cooling was responsible for small enhancements in the yields of Argentine and U.S. corn. Rice yields in India and the PRC were impaired slightly. As for soybeans, the climate change was marginally beneficial in the U.S. and marginally detrimental in Brazil.

Canadian and Soviet spring wheat yields were reduced considerably by the cooler, drier conditions. U.S. spring wheat losses were small by comparison. The Soviet crop became slightly more prone to shortfalls.

Yields of Soviet winter wheat were inhibited to a considerable degree, and the incidence of crop shortfalls rose somewhat. Elsewhere, the climate change had negligible effects on winter wheat: discounted for technology, yields were down slightly in the PRC and up slightly in Argentina, Australia, India and the U.S.

The generally small effects of the climate change on key crops were masked by the effects of improved agricultural technology and fluctuating crop weather. After adjusting for advances in technology, however, one could attribute appreciable losses of Canadian and Soviet wheat yields to the moderate cooling.

3-5 THE SAME AS THE LAST 30 YEARS SCENARIO

The global cooling trend that began in the 1940s leveled out in the 1970s. Average global temperature in the last quarter of the 20th century increased slightly; thus, temperatures were more consistent with those in the period from 1940 to 1970. Climatologists explained that the warming effects of the increasing amounts of atmospheric carbon dioxide had balanced a natural cooling cycle. Temperature increases were nearly uniform throughout both hemispheres, with slightly more warming in the northern hemisphere than in the southern. No significant changes in the mean length or interannual variability of the growing season were noted in the higher middle latitudes.

Annual precipitation levels as well as growing-season precipitation remained unchanged from the 1941–70 period. Also unchanged was the variability of annual precipitation. However, a small shift toward increased variability of growing-season precipitation was detected.

Drought conditions again plagued the mid-latitude areas of the U.S., corroborating the 20- to 22-year drought cycle hypothesis. In other mid-latitude areas of the world, drought conditions recurred also, but not to the same extent as in the U.S. On the other hand, favorable climatic conditions returned to India and other parts of Asia. Monsoon failures became more infrequent. Also, the Sahel region, which had suffered severe drought from 1965 to 1973, returned to average weather conditions.

The slight warming had virtually no effect on agriculture. However, the average yields of most key crops had increased markedly in the past 25 years due to technological factors.

3-6 THE MODERATE WARMING SCENARIO

The Climate Setting

Average global temperature increased moderately in the last quarter of the 20th century. Climatologists explained that the reversal of the mid-century cooling trend was due principally to rising levels of atmospheric carbon dioxide. The warming effects of the carbon dioxide, they said, had predominated over a slow, natural cooling trend.

The largest temperature increases came in the higher latitudes. The northern hemisphere warmed slightly more than the southern hemisphere due to its greater land area and the larger thermal inertia of the southern oceans. The warming of the northern hemisphere ranged from about 1.2°C in the polar latitudes to about 0.4°C in the subtropical latitudes. The corresponding temperature increases for the southern hemisphere were 0.7°C and 0.4°C. The increase in global temperature was reflected in a moderate increase in the length of the growing season in higher middle latitudes, but no significant change in the interannual variability of the growing season was noted.

Annual precipitation levels increased slightly in the higher middle latitudes but showed little change for lower latitudinal bands. Growing-season precipitation also increased slightly in the higher middle latitudes and subtropical regions but remained unchanged in the lower middle latitudes. Both annual and growing-season precipitation variability remained essentially unchanged except for a slight increase in the variability of growing-season precipitation in subtropical latitudes.

Drought conditions again plagued the mid-latitude areas of the U.S., corroborating the 20- to 22-year drought cycle hypothesis. Crop yields fell sharply during the droughts. Rain patterns were somewhat more favorable in the Asiatic region and in subtropical North Africa. The frequency of monsoon failure, especially in northwest India, resembled more closely the long-term average, as did the frequency of drought in the Sahel region.

Most average crop yields at the turn of the century had risen well above the level of the mid-1970s, primarily due to the wide diffusion of improved agricultural technology. As for the climate component of yields, the global warming had mixed effects on world agriculture. The climate change *per se* tended to diminish the gains from technology in some crop regions and to augment these gains in other regions.

Crops of the Northern Higher Middle Latitudes

Two manifestations of the climate change in the northern higher middle latitudes—a noticeable increase in temperature and a small increase in precipitation—reinforced each other to enhance the yields of key grain crops in Canada and the Soviet Union. When restated for 1976 technology, the average annual yields of Canadian spring wheat and Soviet spring and winter wheat were about 3 to 4 higher than the averages of the mid-1970s. The magnitudes of these climate-induced increments were the largest among the key crops. Shortfalls of Soviet winter wheat crops were occurring less frequently (about 3 years in 16) than a quarter century earlier (3 years in 14), while Soviet spring wheat shortfalls were occurring somewhat more frequently (3 years in 12 versus 3 years in 13). The higher temperatures had a negative effect on U.S. spring wheat yields, but this was just balanced by the positive effect of the moister conditions.

Crops of the Lower Middle Latitudes

In the lower middle latitudes the climate change took the form of a small rise in temperature without a net change in precipitation. Alone among the key crops grown in these latitudes, Chinese winter wheat had a positive, but very small, response to the higher temperatures. There were hemispheric differences in the negative responses of the other key crops. In the northern hemisphere, U.S. corn, soybean and winter wheat yields were, after correction for technological advances, about 1 below the levels of the mid-1970s, and shortfalls of U.S. corn and soybean crops were slightly more frequent. The climatic effects were more pronounced in the southern hemisphere. On a technology-adjusted basis, the yields of Argentine corn and wheat and Australian wheat had declined by 2 to 3.

Crops of the Subtropical Latitudes

Temperatures rose slightly in the subtropics, but there was no perceptible trend in annual precipitation. Indian wheat, being quite sensitive to temperature changes, was the most affected of the subtropical key crops: net of technology, the climate change was responsible for a 2 to 3 reduction in average yields. On the same basis, yields of Indian rice, Chinese rice and Brazilian soybeans were down 1 to 2

Summary by Crop

The warmer climate depressed the average annual yields of Argentine and U.S. corn by a small fraction, yields of the latter became somewhat more variable. Rice yields in India and the PRC were impaired only slightly by the climate change. Brazilian soybean yields were adversely affected to a small degree. U.S. soybean yields were inhibited to a lesser extent, and the frequency of crop shortfalls increased slightly.

Canadian and Soviet spring wheat yields were enhanced moderately by the warmer, moister conditions. Shortfalls afflicted Soviet spring wheat somewhat more often than 25 years before. U.S. spring wheat was virtually unaffected by the climate change.

Soviet winter wheat yields were elevated appreciably by the warming, and crop shortfalls occurred less frequently than in the mid-1970s. The climate change also induced a small improvement in Chinese winter wheat. On the other hand, it had a small negative effect on winter wheat yields in Argentina, Australia, India and the U.S.

The effects of the modest climate change on crops were masked by the effects of technological advances and by the year-to-year variability of yields resulting from fluctuations in annual crop weather. When adjusted for technological changes, however, the yields of three northerly wheat crops were 3 to 4 higher than in the mid-1970s, and the yields of four other key grain crops were 2 to 3 lower.

3-7 THE LARGE WARMING SCENARIO

The Climate Setting

The global cooling trend that began in the 1940s was dramatically reversed in the last quarter of the 20th century. Climatologists attributed the warming trend principally to the warming effects of increasing amounts of carbon dioxide in the atmosphere.

While temperature increased over the entire globe, the warming was more pronounced at higher latitudes. The subtropical latitudes warmed on the average by about 0.8 C, the lower middle latitudes by 1 C, the higher middle latitudes by 1.4 C, and the polar latitudes by a remarkable 3.0 C, compared to the early 1970s. Symmetry prevailed as similar temperature changes were observed in both the northern and southern hemispheres. The increase in temperature was accompanied by a significant increase in the length of the growing season in the higher middle latitudes, as well as by substantially less year-to-year variability in the length of the growing season.

Precipitation levels generally increased, especially in the subtropical and higher middle latitudes. Annual precipitation variability decreased slightly compared to the 1950–75 period; precipitation variability during the growing season similarly decreased in the higher middle latitudes, but increased slightly in the lower middle and subtropical latitudes.

The warming trend brought more favorable climatic conditions to India and other parts of Asia. These conditions were similar to those of the 1930–60 period. Monsoon failure was infrequent, especially in northwest India. But in the mid-latitude areas of the U.S., extending from the Rockies to the Appalachians, drought conditions similar to the mid-1930s and the early- to mid-1950s prevailed. Crop yields dropped sharply in the drought years. In other mid-latitude areas of the world, notably Europe, the probability of drought declined. The increased levels of precipitation also returned the Sahel region to wetter conditions.

The adoption of improved agricultural technology in the last quarter of the century had boosted the average yields of most crops well above the levels of the mid-1970s. The global warming modified the gains from technology in different ways. The climatic changes by themselves tended to enhance yields in some growing regions and to reduce them in others.

Crops of the Northern Higher Middle Latitudes

In the northern higher middle latitudes, grain yields were stimulated by the climate change. The higher temperatures *per se* had a slightly positive effect on Canadian spring wheat and Soviet winter wheat, a neutral effect on Soviet spring wheat, and a negative effect on U.S. spring wheat. The rather large increase in average precipitation, on the other hand, was favorable to all these crops. The opposing effects of the changes in temperature and precipitation canceled each other so far as U.S. spring wheat was concerned. The other three key wheat crops, however, enjoyed large yield increments as a result of the climate change. When restated for 1976 technology, the average yields of Canadian spring wheat and Soviet spring and winter wheat were 6 to 8 higher than in the mid-1970s. The magnitudes of these climate-induced yield changes were the greatest of any noted for the 15 key crops. Canadian wheat yields appeared to have become somewhat more variable, but Soviet winter wheat yields were less variable than 25 years before, with the incidence of crop shortfalls decreasing dramatically from 2 years in 9 to 2 years in 13. There was little change in the variability of Soviet spring wheat.

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CROP YIELDS AND CLIMATE CHANGE TO THE YEAR 2000, VOLUME I. REPO--ETC(U)
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Crops of the Lower Middle Latitudes

With the exception of winter wheat in the PRC, yields of the key crops grown in the lower middle latitudes were depressed by the climate change. The neutral effect of the warmer temperatures and the beneficial effect of the slightly moister climate combined to produce a small increase in the climate component of Chinese winter wheat yields. For the other crops, the higher temperatures had a detrimental effect, and the favorable increases in precipitation were insufficient to counter the inroads of the temperature changes. In the southern lower middle latitudes, the climate-induced yield decrements were appreciable—3% to 4.5% on a technology-adjusted basis for Australian wheat, Argentine corn and Argentine wheat. In the northern hemisphere, the declines in U.S. soybean and winter wheat yields were only 1%, but U.S. corn yields were impaired almost as much as Argentine corn yields. The larger yield decrements of the southern hemisphere did not seem to be accompanied by changes in the variability of annual yields. U.S. corn and soybean yields, however, became more variable, and the frequency of crop shortfalls rose from 1 year in 6 to 1 year in 5 over the final quarter of the century.

Crops of the Subtropical Latitudes

All the key crops of the subtropical latitudes were affected adversely by the warmer temperatures. The benign effects of the small increases in precipitation offset most of the negative temperature effects on Indian and Chinese rice. On the other hand, when discounted for technology advances, the average annual yields of Brazilian soybeans and Indian wheat were down by about 2% and 4%, respectively. There were no apparent changes in the variability of crop yields in the subtropical latitudes.

Summary by Crop

The warming was responsible for small contractions in the yields of Argentine and U.S. corn; yields of the latter became more variable. Indian and Chinese rice yields were inhibited to a very small degree. Soybean yields in Brazil were eroded slightly; U.S. soybean yields fell only half as much, but became more variable and prone to shortfalls.

Canadian and Soviet spring wheat yields were elevated significantly by the climate change; U.S. spring wheat was unaffected. Canadian shortfalls occurred somewhat more frequently than in the mid-1970s.

The warmer regime substantially raised the yields of winter wheat in the Soviet Union and lowered the frequency of crop shortfalls. Chinese winter wheat benefited slightly. Elsewhere, winter wheat had suffered from the climate change. Climate-induced losses were appreciable in Argentina, Australia and India, but small in the U.S.

The effects of the climate change on crop yields were masked by the gains due to technology and by the year-to-year variability of yields due to fluctuations of annual crop weather. Nevertheless, after adjustment for technological advances, substantial yield increases could be attributed to the climate change in the most northerly grain regions. These were offset by some small-to-moderate yield decreases in the lower latitudes of both hemispheres.

TABLES TO ACCOMPANY THE SCENARIOS

Table III-1A

LARGE COOLING SCENARIO: THE CLIMATE SETTING

PROBABILITY OF SCENARIO 0.10
MEAN NORTHERN HEMISPHERE TEMPERATURE CHANGE SINCE 1969 between 0.3 and 1.2 C colder

PROBABILITY OF TEMPERATURE CHANGE (ΔT) BY LATITUDE
(Compared with 1970 75)

		2.0 3.0 C colder	1.5 2.0 C colder	1.0 1.5 C colder	0.5 1.0 C colder	0.0 0.5 C colder	0.0 0.5 C warmer	0.5 1.0 C warmer	1.0 1.5 C warmer	1.5 2.0 C warmer
Northern hemisphere	Polar	0.2	0.6	0.1	0.1					
	Higher mid latitude*		0.1	0.5	0.3	0.1				
	Lower mid latitude			0.4	0.4	0.2				
	Subtropical				0.5	0.5				
Southern hemisphere	Subtropical				0.5	0.5				
	Lower mid latitude			0.5	0.4	0.1				
	Higher mid latitude*			0.6	0.3	0.1				
	Polar			0.6	0.3	0.1				

*Growing season in higher middle latitudes Probability of an increase (decrease) in the *length* of growing season exceeding 10 days is 0.0 (0.9); probability of an increase (decrease) in the *variability* of the length of the growing season in excess of 25% is 0.8 (0.0)

PROBABILITY OF MID LATITUDE DROUGHT* 1991-2000

	Frequent	Average	Infrequent
United States	0.7	0.2	0.1
Other mid latitude	0.7	0.2	0.1

*Frequent similar to early to mid 1930s and early to mid 1950s average similar to the frequency over the longest period of record available infrequent similar to 1940s and 1960s

PROBABILITY OF PRECIPITATION CHANGE (ΔP) BY LATITUDE
(Compared with 1941 70)

	ANNUAL			GROWING SEASON		
	Increase > 10%	Change < 10%	Decrease > 10%	Increase > 10%	Change < 10%	Decrease > 10%
Higher mid-latitude	0.2	0.5	0.3	0.2	0.5	0.3
Lower mid latitude	0.3	0.5	0.2	0.3	0.5	0.2
Subtropical	0.2	0.5	0.3	0.2	0.4	0.4

PROBABILITY OF MONSOON FAILURE 1991-2000**

	Frequent	Average	Infrequent
Northwest India	0.5	0.5	
Other India	0.6	0.3	0.1
Other Monsoon Asia	0.5	0.4	0.1

**Frequent similar to 1900 25 period, average similar to the frequency over the longest period of record available, infrequent similar to 1930 60 period

Table III 18

LARGE COOLING SCENARIO: PROJECTED EFFECTS ON CROP YIELDS

Data relating to the calculated frequency distributions of normalized relative annual yields (100 = expected yield in the Base Period)

CROP	ZONE OF LAT	EXP CLIMATE CHANGE ΔT °C	EXP CLIMATE CHANGE ΔP %	YIELD STATISTICS Y	YIELD STATISTICS CV	YIELD STATISTICS SKEW	PERCENTILES OF YIELD 5	25	50	75	95	PROB Y < .9Y
CORN												
ARGENTINA	S LM	0.95	+2.0	105.1	0.160	0.95	71.7	96.2	108.0	118.1	125.9	23.3
U.S.	N LM	0.85	+2.0	102.3	0.085	1.27	85.7	97.4	104.7	109.0	112.1	13.0
RICE												
INDIA	N ST	0.50	2.0	99.2	0.107	0.66	79.8	92.8	102.5	106.7	113.4	19.7
PRC	N ST	0.50	2.0	99.2	0.104	1.08	79.8	92.9	103.3	107.6	110.2	20.1
SOYBEANS												
BRAZIL	S ST	0.50	2.0	99.8	0.112	0.93	78.4	93.9	102.3	107.9	113.2	18.6
U.S.	N LM	0.85	+2.0	101.5	0.090	0.92	84.3	95.9	103.0	108.0	113.7	13.7
SPRING WHEAT												
CANADA	N HM	1.05	2.0	91.5	0.119	0.28	72.8	84.7	92.4	99.5	108.0	21.4
U.S.	N HM	1.05	2.0	99.0	0.103	0.62	80.0	92.8	100.8	106.9	113.0	20.1
USSR	N HM	1.05	2.0	93.6	0.144	0.60	68.9	84.7	95.5	103.9	112.0	23.8
WINTER WHEAT												
ARGENTINA	S LM	0.95	+2.0	104.1	0.134	-1.40	74.4	97.5	109.0	115.1	117.7	20.5
AUSTRALIA	S LM	0.95	+2.0	105.5	0.234	0.71	58.4	89.3	111.0	124.7	137.4	30.8
INDIA	N ST	-0.50	2.0	101.6	0.120	-0.60	79.7	92.8	104.1	111.3	117.8	22.2
PRC	N LM	-0.85	+2.0	98.7	0.145	-0.89	72.1	91.5	102.1	108.7	117.4	21.7
U.S.	N LM	0.85	+2.0	102.6	0.092	-0.57	84.4	97.2	103.8	109.9	116.2	13.9
USSR	N HM	-1.05	-2.0	93.8	0.154	-0.37	68.6	82.9	95.2	106.3	114.7	27.5

Y, CV and SKEW are the expected value, the coefficient of variability and the skewness of the respective yield distributions
HM = higher middle, LM = lower middle, ST = subtropical (see Table S-1).

Table III-2A

MODERATE COOLING SCENARIO: THE CLIMATE SETTING

PROBABILITY OF SCENARIO 0.25
MEAN NORTHERN HEMISPHERE TEMPERATURE CHANGE SINCE 1969. between 0.05 and 0.3 C colder

PROBABILITY OF TEMPERATURE CHANGE (ΔT) BY LATITUDE
(Compared with 1970 75)

		2.0 3.0 C colder	1.5 2.0 C colder	1.0 1.5 C colder	0.5 1.0 C colder	0.0 0.5 C colder	0.0 0.5 C warmer	0.5 1.0 C warmer	1.0 1.5 C warmer	1.5 2.0 C warmer
Northern hemisphere	Polar		0.1	0.6	0.1	0.1	0.1			
	Higher mid latitude*			0.1	0.4	0.4	0.1			
	Lower mid latitude			0.1	0.1	0.7	0.1			
	Subtropical				0.2	0.7	0.1			
Southern hemisphere	Subtropical				0.2	0.6	0.1	0.1		
	Lower mid latitude			0.1	0.2	0.3	0.3	0.1		
	Higher mid latitude*			0.1	0.2	0.3	0.3	0.1		
	Polar			0.2	0.2	0.2	0.3	0.1		

*Growing season in higher middle latitudes Probability of an increase (decrease) in the *length* of growing season exceeding 10 days is 0.1 (0.2); probability of an increase (decrease) in the *variability* of the length of the growing season in excess of 25% is 0.2 (0.1).

PROBABILITY OF MID-LATITUDE DROUGHT* 1991-2000

	Frequent	Average	Infrequent
United States	0.6	0.3	0.1
Other mid latitude	0.5	0.4	0.1

*Frequent similar to early to mid 1930s and early to mid 1950s, average similar to the frequency over the longest period of record available, infrequent similar to 1940s and 1960s

PROBABILITY OF PRECIPITATION CHANGE (ΔP) BY LATITUDE
(Compared with 1941 70)

	ANNUAL			GROWING SEASON		
	Increase ≥ 10%	Change < 10%	Decrease ≥ 10%	Increase ≥ 10%	Change < 10%	Decrease ≥ 10%
Higher mid latitude	0.2	0.5	0.3	0.2	0.5	0.3
Lower mid latitude	0.2	0.6	0.2	0.2	0.6	0.2
Subtropical	0.2	0.5	0.3	0.2	0.5	0.3

PROBABILITY OF MONSOON FAILURE 1991-2000**

	Frequent	Average	Infrequent
Northwest India	0.4	0.6	
Other India	0.5	0.4	0.1
Other Monsoon Asia	0.4	0.5	0.1

**Frequent–similar to *1900 25 period*, average–similar to the frequency over the longest period of record available, infrequent–similar to 1930-60 period

Table III 2B

MODERATE COOLING SCENARIO: PROJECTED EFFECTS ON CROP YIELDS

Data relating to the calculated frequency distributions of normalized relative annual yields (100 expected yield in the Base Period)

CROP	ZONE OF LAT	EXP CLIMATE CHANGE		YIELD STATISTICS			PERCENTILES OF YIELD					PROB Y· .9Y
		T C	P	Y	CV	SKEW	5	25	50	75	95	
CORN												
ARGENTINA	S LM	-0.20	0.0	100.8	0.173	-0.84	66.5	91.1	104.0	113.6	124.1	24.5
U.S.	N LM	0.35	0.0	100.7	0.098	-1.15	81.4	95.8	102.6	108.4	112.1	15.2
RICE												
INDIA	N ST	0.30	2.0	99.0	0.108	-0.65	79.2	91.9	102.3	106.6	113.3	20.0
PRC	N ST	0.30	-2.0	99.2	0.106	-1.03	79.7	92.8	103.1	107.8	110.5	20.3
SOYBEANS												
BRAZIL	S ST	0.20	2.0	99.1	0.114	-0.87	77.7	92.1	100.7	107.8	113.1	19.7
U.S.	N LM	-0.35	0.0	100.3	0.101	-0.92	80.6	95.3	102.0	107.7	113.6	15.0
SPRING WHEAT												
CANADA	N HM	-0.50	-2.0	95.7	0.118	-0.44	75.4	88.1	96.5	104.0	111.8	19.0
U.S.	N HM	-0.50	-2.0	99.0	0.110	-0.64	79.3	92.3	101.5	107.1	113.6	20.3
USSR	N HM	-0.50	-2.0	96.3	0.150	-0.71	69.5	86.9	98.9	107.9	115.2	24.4
WINTER WHEAT												
ARGENTINA	S LM	-0.20	0.0	100.8	0.149	-1.13	70.6	92.3	104.7	113.1	117.0	22.6
AUSTRALIA	S LM	-0.20	0.0	100.9	0.255	-0.56	53.0	83.1	104.8	120.9	135.5	32.7
INDIA	N ST	-0.30	-2.0	100.6	0.123	-0.58	78.3	91.8	102.7	110.6	117.1	22.9
PRC	N LM	-0.35	0.0	99.1	0.159	-0.77	68.1	87.8	103.4	110.5	119.7	26.3
U.S.	N LM	-0.35	0.0	100.6	0.100	-0.50	82.2	93.8	102.2	107.7	114.9	17.0
USSR	N HM	-0.50	-2.0	96.6	0.140	-0.53	72.1	87.2	98.6	107.4	115.2	24.5

Y, CV and SKEW are the expected value, the coefficient of variability and the skewness of the respective yield distributions
HM higher middle, LM lower middle, ST subtropical (see Table S 1)

Table III-3A

SAME AS THE LAST 30 YEARS SCENARIO: THE CLIMATE SETTING

PROBABILITY OF SCENARIO 0.30
MEAN NORTHERN HEMISPHERE TEMPERATURE CHANGE SINCE 1969 between 0.05 colder and 0.25 C warmer

PROBABILITY OF TEMPERATURE CHANGE (ΔT) BY LATITUDE
(Compared with 1970-75)

		1.0-1.5 C colder	0.5-1.0 C colder	0.0-0.5 C colder	0.0-0.5 C warmer	0.5-1.0 C warmer	1.0-1.5 C warmer	1.5-2.0 C warmer	2.0-3.0 C warmer	3.0-5.0 C warmer
Northern hemisphere	Polar	0.1	0.1	0.1	0.3	0.2	0.2			
	Higher mid latitude*		0.1	0.2	0.4	0.2	0.1			
	Lower mid latitude		0.1	0.2	0.4	0.2	0.1			
	Subtropical		0.1	0.2	0.5	0.1	0.1			
Southern hemisphere	Subtropical		0.1	0.3	0.4	0.1	0.1			
	Lower mid latitude		0.1	0.3	0.4	0.1	0.1			
	Higher mid latitude*		0.1	0.3	0.4	0.1	0.1			
	Polar	0.1	0.1	0.3	0.3	0.1	0.1			

*Growing season in higher middle latitudes. Probability of an increase (decrease) in the *length* of growing season exceeding 10 days is 0.2 (0.1); probability of an increase (decrease) in the *variability* of the length of the growing season in excess of 25% is 0.1 (0.1).

PROBABILITY OF MID-LATITUDE DROUGHT* 1991-2000

	Frequent	Average	Infrequent
United States	0.5	0.4	0.1
Other mid latitude	0.4	0.5	0.1

*Frequent similar to early to mid 1930s and early to mid 1950s, average similar to the frequency over the longest period of record available, infrequent similar to 1940s and 1960s.

PROBABILITY OF PRECIPITATION CHANGE (ΔP) BY LATITUDE
(Compared with 1941-70)

	ANNUAL			GROWING SEASON		
	Increase > 10%	Change < 10%	Decrease > 10%	Increase > 10%	Change < 10%	Decrease > 10%
Higher mid latitude	*0.2*	*0.6*	*0.2*	*0.2*	*0.6*	*0.2*
Lower mid latitude	0.2	0.6	0.2	0.2	0.6	0.2
Subtropical	0.2	0.6	0.2	0.2	0.6	0.2

PROBABILITY OF MONSOON FAILURE 1991-2000**

	Frequent	Average	Infrequent
Northwest India	0.2	0.5	0.3
Other India	0.2	0.5	0.3
Other Monsoon Asia	0.2	0.6	0.2

***Frequent similar to 1900-25 period,* average similar to the frequency over the longest period of record available, infrequent similar to 1930-60 period.

Table III 3B

SAME AS THE LAST 30 YEARS SCENARIO: PROJECTED EFFECTS ON CROP YIELDS

Data relating to the calculated frequency distributions of normalized relative annual yields (100 = expected yield in the Base Period)

CROP	ZONE OF LAT	EXP CLIMATE CHANGE ΔT °C	EXP CLIMATE CHANGE ΔP %	YIELD STATISTICS Y	YIELD STATISTICS CV	YIELD STATISTICS SKEW	PERCENTILES OF YIELD 5	25	50	75	95	PROB Y<.9Y
CORN												
ARGENTINA	S LM	+0.15	0.0	99.4	0.176	0.81	65.2	89.5	102.2	112.4	123.1	24.9
U.S.	N LM	+0.25	0.0	99.3	0.110	1.03	78.7	92.7	101.4	108.1	112.1	18.0
RICE												
INDIA	N ST	+0.20	0.0	99.6	0.107	0.73	79.4	92.5	102.6	108.2	113.5	20.2
PRC	N ST	+0.20	0.0	99.8	0.111	0.98	79.2	92.2	103.8	109.2	111.5	21.1
SOYBEANS												
BRAZIL	S ST	+0.15	0.0	99.4	0.113	0.92	77.5	93.2	101.9	107.9	113.1	19.0
U.S.	N LM	+0.25	0.0	99.6	0.114	0.87	77.5	93.1	101.7	108.0	114.3	18.5
SPRING WHEAT												
CANADA	N HM	+0.25	0.0	100.9	0.125	0.67	76.4	93.0	103.1	110.7	118.2	19.6
U.S.	N HM	+0.25	0.0	99.5	0.118	0.70	77.4	92.1	102.5	108.7	115.3	21.1
USSR	N HM	+0.25	0.0	100.5	0.155	0.88	69.8	91.0	105.9	111.8	119.4	24.5
WINTER WHEAT												
ARGENTINA	S LM	+0.15	0.0	99.4	0.154	1.05	69.1	90.2	103.2	119.9	116.6	23.6
AUSTRALIA	S LM	+0.15	0.0	99.2	0.263	0.50	51.1	80.9	102.6	119.8	135.0	33.2
INDIA	N ST	+0.20	0.0	98.8	0.129	0.58	75.6	90.3	100.8	108.7	115.8	22.9
PRC	N LM	+0.25	0.0	100.3	0.174	0.69	67.6	87.7	105.0	113.4	123.5	27.5
U.S.	N LM	+0.25	0.0	99.4	0.107	0.44	79.5	93.0	100.6	107.4	114.9	18.9
USSR	N HM	+0.25	0.0	100.6	0.121	0.74	77.5	93.0	103.5	109.9	116.4	20.7

Y, CV and SKEW are the expected value, the coefficient of variability and the skewness of the respective yield distributions.
HM = higher middle, LM = lower middle, ST = subtropical (see Table S 1)

Table III-4A

MODERATE WARMING SCENARIO: THE CLIMATE SETTING

PROBABILITY OF SCENARIO 0.25
MEAN NORTHERN HEMISPHERE TEMPERATURE CHANGE SINCE 1969 between 0.25 and 0.6 C warmer

PROBABILITY OF TEMPERATURE CHANGE (ΔT) BY LATITUDE
(Compared with 1970-75)

		1.0-1.5 C colder	0.5-1.0 C colder	0.0-0.5 C colder	0.0-0.5 C warmer	0.5-1.0 C warmer	1.0-1.5 C warmer	1.5-2.0 C warmer	2.0-3.0 C warmer	3.0-5.0 C warmer
Northern hemisphere	Polar			0.1	0.1	0.2	0.2	0.2	0.2	
	Higher mid latitude*			0.1	0.3	0.4	0.1	0.1		
	Lower mid latitude			0.1	0.5	0.3	0.1			
	Subtropical			0.1	0.6	0.2	0.1			
Southern hemisphere	Subtropical			0.1	0.6	0.2	0.1			
	Lower mid latitude			0.1	0.5	0.3	0.1			
	Higher mid latitude*			0.1	0.3	0.5	0.1			
	Polar			0.1	0.2	0.5	0.1	0.1		

*Growing season in higher middle latitudes. Probability of an increase (decrease) in the *length* of growing season exceeding 10 days is 0.4 (0.2); probability of an increase (decrease) in the *variability* of the length of the growing season in excess of 25 is 0.1 (0.2)

PROBABILITY OF MID-LATITUDE DROUGHT* 1991-2000

	Frequent	Average	Infrequent
United States	0.5	0.3	0.2
Other mid latitude	?	?	?

*Frequent-similar to early to mid 1930s and early to mid 1950s; average-similar to the frequency over the longest period of record available; infrequent-similar to 1940s and 1960s

PROBABILITY OF PRECIPITATION CHANGE (ΔP) BY LATITUDE
(Compared with 1941-70)

	ANNUAL			GROWING SEASON		
	Increase > 10%	Change < 10%	Decrease > 10%	Increase > 10%	Change < 10%	Decrease > 10%
Higher mid latitude	0.3	0.5	0.2	0.3	0.5	0.2
Lower mid latitude	0.2	0.6	0.2	0.2	0.6	0.2
Subtropical	0.2	0.6	0.2	0.3	0.5	0.2

PROBABILITY OF MONSOON FAILURE 1991-2000**

	Frequent	Average	Infrequent
Northwest India	0.2	0.5	0.3
Other India	?	?	?
Other Monsoon Asia	?	?	?

**Frequent-similar to 1900-25 period; average-similar to the frequency over the longest period of record available; infrequent-similar to 1930-60 period

Table III 4B

MODERATE WARMING SCENARIO: PROJECTED EFFECTS ON CROP YIELDS

Data relating to the calculated frequency distributions of normalized relative annual yields (100 = expected yield in the Base Period)

CROP	ZONE OF LAT	EXP CLIMATE CHANGE ΔT °C	EXP CLIMATE CHANGE ΔP %	YIELD STATISTICS Ȳ	YIELD STATISTICS CV	YIELD STATISTICS SKEW	PERCENTILES OF YIELD 5	25	50	75	95	PROB Y<.9Ȳ
CORN												
ARGENTINA	S LM	+0.45	0.0	98.0	0.179	0.77	64.1	88.1	100.7	111.3	122.0	25.2
U.S.	N LM	+0.45	0.0	98.6	0.114	0.98	77.0	91.9	100.8	107.7	112.0	18.5
RICE												
INDIA	N ST	+0.40	0.0	99.2	0.108	0.72	79.0	91.6	102.3	107.5	113.3	20.9
PRC	N ST	+0.40	0.0	99.4	0.114	0.92	78.4	91.7	103.1	109.2	111.6	21.1
SOYBEANS												
BRAZIL	S ST	+0.40	0.0	98.3	0.117	0.87	76.8	91.1	100.4	107.5	112.8	20.0
U.S.	N LM	+0.45	0.0	99.2	0.118	0.83	76.6	92.2	100.9	108.0	114.4	19.3
SPRING WHEAT												
CANADA	N HM	+0.65	+2.0	103.8	0.129	0.78	76.8	95.9	106.9	113.6	121.5	21.3
U.S.	N HM	+0.65	+2.0	100.1	0.120	0.74	77.3	92.5	102.8	109.7	116.1	21.4
USSR	N HM	+0.65	+2.0	103.1	0.155	0.98	70.2	93.2	108.1	115.0	121.6	24.5
WINTER WHEAT												
ARGENTINA	S LM	+0.45	0.0	97.9	0.158	0.99	67.8	88.8	101.7	110.4	115.8	24.0
AUSTRALIA	S LM	+0.45	0.0	97.5	0.270	0.45	49.3	79.0	100.6	118.3	134.6	34.2
INDIA	N ST	+0.40	0.0	97.4	0.132	0.53	73.9	88.3	99.5	107.6	115.0	23.8
PRC	N LM	+0.45	0.0	100.4	0.178	0.66	67.0	87.4	105.0	114.0	123.9	27.9
U.S.	N LM	+0.45	0.0	98.9	0.109	-0.41	79.0	92.0	99.8	107.2	114.8	19.2
USSR	N HM	+0.65	+2.0	102.9	0.110	0.87	81.0	95.8	105.8	111.4	117.8	18.9

Ȳ, CV and SKEW are the expected value, the coefficient of variability and the skewness of the respective yield distributions
HM: higher middle, LM: lower middle, ST: subtropical (see Table S 1)

Table III-5A

LARGE WARMING SCENARIO: THE CLIMATE SETTING

PROBABILITY OF SCENARIO 0.10
MEAN NORTHERN HEMISPHERE TEMPERATURE CHANGE SINCE 1969 between 0.6 and 1.8 C warmer

PROBABILITY OF TEMPERATURE CHANGE (°C) BY LATITUDE
(Compared with 1970–75)

		1.0–1.5 C colder	0.5–1.0 C colder	0.0–0.5 C colder	0.0–0.5 C warmer	0.5–1.0 C warmer	1.0–1.5 C warmer	1.5–2.0 C warmer	2.0–3.0 C warmer	3.0–5.0 C warmer
Northern hemisphere	Polar						0.1	0.1	0.2	0.6
	Higher mid latitude*					0.1	0.5	0.4		
	Lower mid latitude				0.1	0.5	0.2	0.2		
	Subtropical				0.1	0.8	0.1			
Southern hemisphere	Subtropical				0.1	0.8	0.1			
	Lower mid latitude				0.1	0.5	0.2	0.2		
	Higher mid latitude*					0.1	0.5	0.4		
	Polar					0.1	0.1	0.1	0.2	0.5

*Growing season in higher middle latitudes. Probability of an increase (decrease) [illegible] length of growing season exceeding 10 days is 0.8 (0.0); probability of an [illegible] (decrease) in the variability of the length of the growing season [illegible] is 0.0 (0.7).

PROBABILITY OF MID LATITUDE DROUGHT*
1991–2000

	Frequent	Average	Infrequent
United States	0.7	0.2	0.1
Other mid latitude	0.3	0.3	0.4

*Frequent [illegible] mid 1930s [illegible] 1950 average [illegible] over the [illegible] period [illegible] infrequent [illegible] 1940 and 1960s

PROBABILITY OF PRECIPITATION CHANGE (%) BY LATITUDE
(Compared with 1941–70)

	Annual: Increase >10%	Annual: Change <10%	Annual: Decrease >10%	Growing Season: Increase >10%	Growing Season: Change <10%	Growing Season: Decrease >10%
Higher mid latitude	0.4	0.5	0.1	0.3	0.5	0.2
Lower mid latitude	0.3	0.5	0.2	0.3	0.4	0.3
Subtropical	0.3	0.5	0.2	0.4	0.5	0.1

PROBABILITY OF MONSOON FAILURE**
1991–2000

	Frequent	Average	Infrequent
[illegible]	[illegible]	0.2	0.8
[illegible]	0.1	0.2	0.7
[illegible]	0.1	0.2	0.7

**[illegible]

Table III 5B

LARGE WARMING SCENARIO: PROJECTED EFFECTS ON CROP YIELDS

Data relating to the calculated frequency distributions of normalized relative annual yields (100 = expected yield in the Base Period)

CROP	ZONE OF LAT	EXP CLIMATE CHANGE T C	EXP CLIMATE CHANGE P %	YIELD STATISTICS Y	YIELD STATISTICS CV	YIELD STATISTICS SKEW	PERCENTILES OF YIELD 5	25	50	75	95	PROB Y< .9Y
CORN												
ARGENTINA	S LM	+1.00	+2.0	97.1	0.180	0.75	63.6	86.9	99.3	110.2	121.2	25.8
U.S.	N LM	+1.00	+2.0	97.5	0.120	0.91	74.9	90.3	99.5	107.1	111.9	19.4
RICE												
INDIA	N ST	+0.75	+2.0	99.7	0.105	0.83	80.2	92.9	102.5	107.6	113.0	20.2
PRC	N ST	+0.75	+2.0	99.4	0.115	0.93	78.2	91.7	103.1	109.3	111.5	21.2
SOYBEANS												
BRAZIL	S ST	+0.75	+2.0	97.8	0.116	0.91	75.2	90.7	100.0	106.5	111.8	19.7
U.S.	N LM	+1.00	+2.0	99.0	0.124	0.76	75.9	91.4	100.9	108.7	114.9	20.6
SPRING WHEAT												
CANADA	N HM	+1.40	+6.0	107.9	0.132	0.88	80.9	99.1	111.3	119.4	125.0	21.8
U.S.	N HM	+1.40	+6.0	100.3	0.122	0.72	77.3	92.7	102.7	109.6	116.5	21.2
USSR	N HM	+1.40	+6.0	106.7	0.150	1.08	72.9	98.2	111.2	117.9	126.1	21.7
WINTER WHEAT												
ARGENTINA	S LM	+1.00	+2.0	96.4	0.158	1.01	66.5	87.3	100.3	108.7	113.9	24.1
AUSTRALIA	S LM	+1.00	+2.0	95.7	0.280	-0.37	47.4	76.6	98.2	116.7	134.7	35.0
INDIA	N ST	+0.75	+2.0	96.0	0.135	0.53	72.4	86.6	98.6	106.0	114.0	24.6
PRC	N LM	+1.00	+2.0	101.5	0.186	-0.63	66.9	87.2	105.4	115.9	126.5	29.0
U.S.	N LM	+1.00	+2.0	98.8	0.112	-0.36	78.7	91.2	99.8	107.1	115.0	20.0
USSR	N HM	+1.40	+6.0	106.1	0.094	-1.05	86.2	100.8	108.1	113.2	118.6	15.2

Y, CV and SKEW are the expected value, the coefficient of variability and the skewness of the respective yield distributions.
HM = higher middle, LM = lower middle, ST = subtropical (see Table S 1).

SCENARIOS

Table III 6

YIELD SUMMARY FOR ALL THE CLIMATE SCENARIOS AND THE BASE PERIOD

CROP	LARGE COOLING p_1 0.10		MODERATE COOLING p_2 0.25		SAME p_3 0.30		MODERATE WARMING p_4 0.25		LARGE WARMING p_5 0.10		SCENARIO WEIGHTED YIELD	BASE PERIOD	
	$\bar{Y}_1$	CV	$\bar{Y}_2$	CV	$\bar{Y}_3$	CV	$\bar{Y}_4$	CV	$\bar{Y}_5$	CV	$\Sigma p_i \bar{Y}_i$	$\bar{Y}$	CV
CORN													
ARGENTINA	105.1	0.160	100.8	0.173	99.4	0.176	98.0	0.179	97.1	0.180	99.74	100.0	0.174
U.S.	102.3	0.085	100.7	0.098	99.3	0.110	98.6	0.114	97.5	0.120	99.60	100.0	0.105
RICE													
INDIA	99.2	0.107	99.0	0.108	99.6	0.107	99.2	0.108	99.7	0.105	99.33	100.0	0.106
PRC	99.2	0.104	99.2	0.106	99.8	0.111	99.4	0.114	99.4	0.115	99.47	100.0	0.108
SOYBEANS													
BRAZIL	99.8	0.112	99.1	0.114	99.4	0.113	98.3	0.117	97.8	0.116	98.95	100.0	0.111
U.S.	101.5	0.090	100.3	0.101	99.6	0.114	99.2	0.118	99.0	0.124	99.81	100.0	0.108
SPRING WHEAT													
CANADA	91.5	0.119	95.7	0.118	100.9	0.125	103.8	0.129	107.9	0.132	100.09	100.0	0.120
U.S.	99.0	0.103	99.0	0.110	99.5	0.118	100.1	0.120	100.3	0.122	99.57	100.0	0.114
USSR	93.6	0.144	96.3	0.150	100.5	0.155	103.1	0.155	106.7	0.150	100.02	100.0	0.151
WINTER WHEAT													
ARGENTINA	104.1	0.134	100.8	0.149	99.4	0.154	97.9	0.158	96.4	0.158	99.53	100.0	0.152
AUSTRALIA	105.5	0.234	100.9	0.255	99.2	0.263	97.5	0.270	95.7	0.280	99.49	100.0	0.260
INDIA	101.6	0.120	100.6	0.123	98.8	0.129	97.4	0.132	96.0	0.135	98.88	100.0	0.125
PRC	98.7	0.145	99.1	0.159	100.3	0.174	100.4	0.178	101.5	0.186	100.01	100.0	0.168
U.S.	102.6	0.092	100.6	0.100	99.4	0.107	98.9	0.109	98.8	0.112	99.85	100.0	0.104
USSR	93.8	0.154	96.6	0.140	100.6	0.121	102.9	0.110	106.1	0.094	100.06	100.0	0.126

Expected yields ($\bar{Y}_i$) and coefficients of variability (CV) are extracted from Tables III-1B through III-5B. p_i is the "probability" of the climate scenario.

Table III-7

THE BASE PERIOD: CROP-YIELD DATA FOR RECENT CLIMATE

Data relating to the calculated frequency distributions of normalized relative annual yields (100 = expected yield in the Base Period)

CROP	ZONE OF LAT	EXP CLIMATE CHANGE T °C	EXP CLIMATE CHANGE P	YIELD STATISTICS Y	YIELD STATISTICS CV	YIELD STATISTICS SKEW	PERCENTILES OF YIELD 5	25	50	75	95	PROB Y<.9Y
CORN												
ARGENTINA	S LM	0.0	0.0	100.0	0.174	0.82	66.0	90.0	103.5	113.1	123.5	25.0
U.S.	N LM	0.0	0.0	100.0	0.105	1.09	79.9	93.7	102.0	108.3	112.1	16.6
RICE												
INDIA	N ST	0.0	0.0	100.0	0.106	-0.74	80.1	92.8	102.8	109.0	113.6	20.1
PRC	N ST	0.0	0.0	100.0	0.108	1.04	79.8	92.9	104.2	108.9	111.4	20.2
SOYBEANS												
BRAZIL	S ST	0.0	0.0	100.0	0.111	0.95	78.2	93.8	102.7	108.2	113.2	19.2
U.S.	N LM	0.0	0.0	100.0	0.108	-0.90	78.2	94.3	101.9	108.0	114.0	16.8
SPRING WHEAT												
CANADA	N HM	0.0	0.0	100.0	0.120	-0.62	76.8	92.7	100.7	108.2	117.2	19.5
U.S.	N HM	0.0	0.0	100.0	0.114	-0.72	78.3	93.0	103.0	109.2	115.2	20.6
USSR	N HM	0.0	0.0	100.0	0.151	-0.87	70.1	91.0	103.9	111.5	118.4	22.8
WINTER WHEAT												
ARGENTINA	S LM	0.0	0.0	100.0	0.152	-1.09	69.5	91.5	104.0	112.4	116.8	23.2
AUSTRALIA	S LM	0.0	0.0	100.0	0.260	-0.53	51.8	82.2	104.1	120.3	135.3	33.5
INDIA	N ST	0.0	0.0	100.0	0.125	-0.62	76.8	91.1	102.2	109.9	116.5	22.3
PRC	N LM	0.0	0.0	100.0	0.168	-0.73	68.0	87.8	104.8	113.1	121.6	26.6
U.S.	N LM	0.0	0.0	100.0	0.104	-0.47	80.6	93.5	101.3	107.6	114.9	18.6
USSR	N HM	0.0	0.0	100.0	0.126	-0.72	76.1	91.9	102.0	109.9	116.2	21.5

Y, CV and SKEW are the expected value, the coefficient of variability and the skewness of the respective yield distributions.
HM = higher middle, LM = lower middle, ST = subtropical (see Table S-1).

CHAPTER FOUR

DAVE ROSE

CHAPTER FOUR

DISCUSSION OF THE CLIMATE-CROP SCENARIOS AND TECHNOLOGY PROJECTIONS

4-1 INTRODUCTION

In this chapter we summarize and collate the projected agricultural effects of the global climate scenarios that were developed in Task I We also compare the isolated effects of climate and technology on yields, call attention to the distinction between relative and absolute technology projections, and examine the uncertainty about the technology projections Finally, we consider the average expertise and the number of respondents who contributed to the technology projections and the annual-yield functions

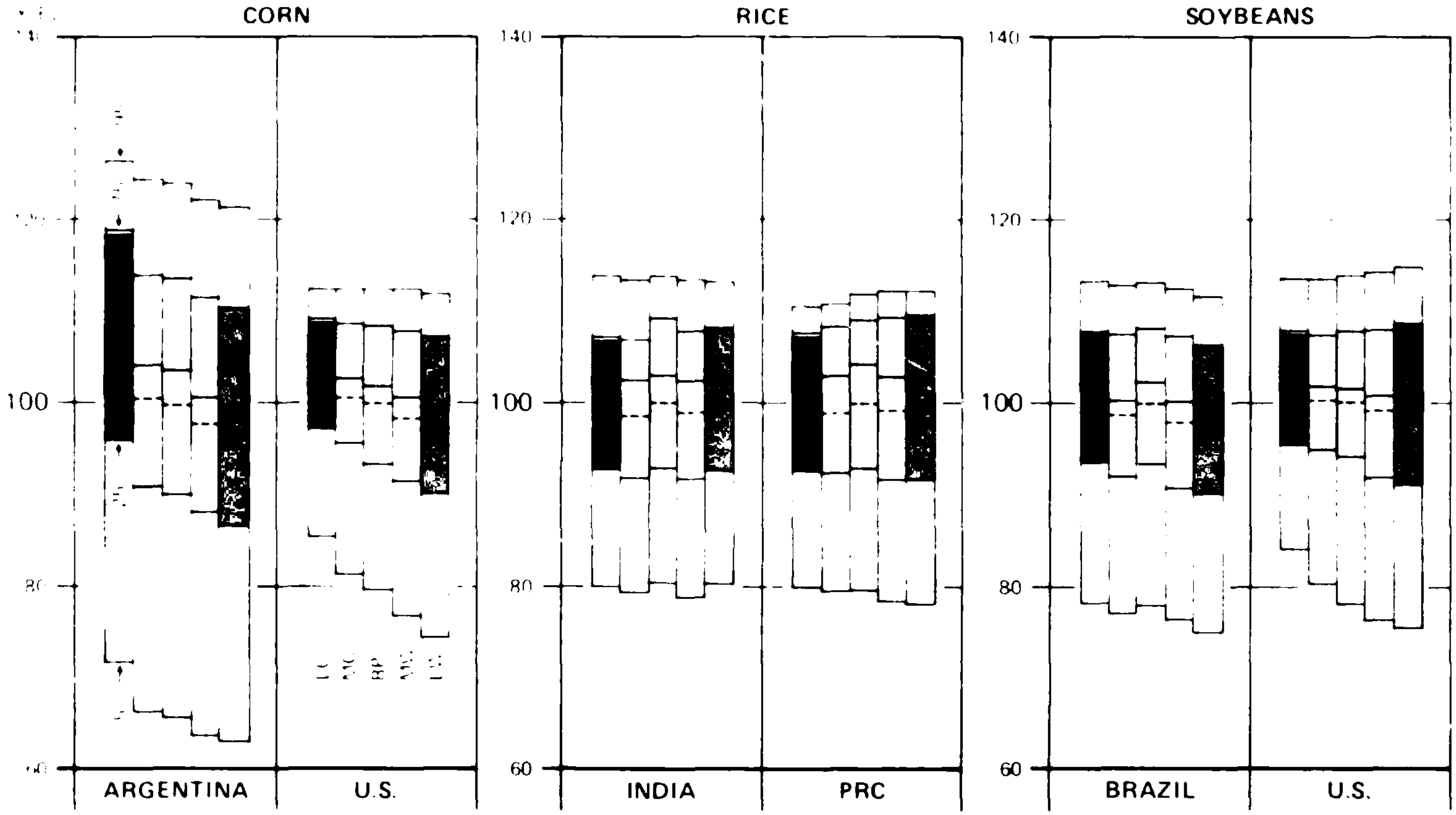
4-2 THE CLIMATE CROP SCENARIOS: A PERSPECTIVE

Figures IV-1 and IV-2A contain representations of the annual-yield distributions generated by the climate-response model for the nontrivial climate scenarios and the Base Period (the "present") The four yield projections for the year 2000 are based on an assumption of no change from current agricultural technology The yield distributions for the fifth climate-crop scenario ("Same as the Last 30 Years") are not shown they are very similar to the Base-Period distributions

Each bar in the figures encompasses 90 of the calculated annual yields while its colored inner portion encompasses 50 Note, for example, that the projected 25th and 75th percentiles of relative Argentine corn yields are about 96 and 118, respectively, in the Large Cooling Scenario Thus, in this scenario, a fourth of the annual yields would fall at least 4 below the expected yield of the Base Period, which is the model s equivalent of the current average annual yield Likewise, discounting any change in technology a fourth of the annual yields would be at least 18 greater than the current average

It can be seen that all the distributions are skewed toward the lower yields The median yields, for instance, exceed the respective expected yields, and in each bar the distance between the 25th and 5th percentiles is greater than the distance between the 95th and 75th percentiles

CORN RICE SOYBEANS DISTRIBUTIONS OF RELATIVE ANNUAL YIELDS FOR FIVE GLOBAL CLIMATE STATES



EXPLANATION OF FIGURES IV-3-2A [illegible] *Climate states* [illegible] U.S. [illegible] [illegible] Base Period [illegible] climate changes: moderate warming, large [illegible] *Horizontal* [illegible] vertical bar [illegible] Argentine corn) [illegible] 5th, 25th, 50th, 75th [illegible] 95th percentiles [illegible] expected or average yield (dashed [illegible]) [illegible] [illegible] 100 [illegible] the Base Period expected yield calculated [illegible] The agricultural technology of 1976 is assumed for all [illegible]

Figure IV 2A

WHEAT: DISTRIBUTIONS OF RELATIVE ANNUAL YIELDS FOR FIVE GLOBAL CLIMATE STATES

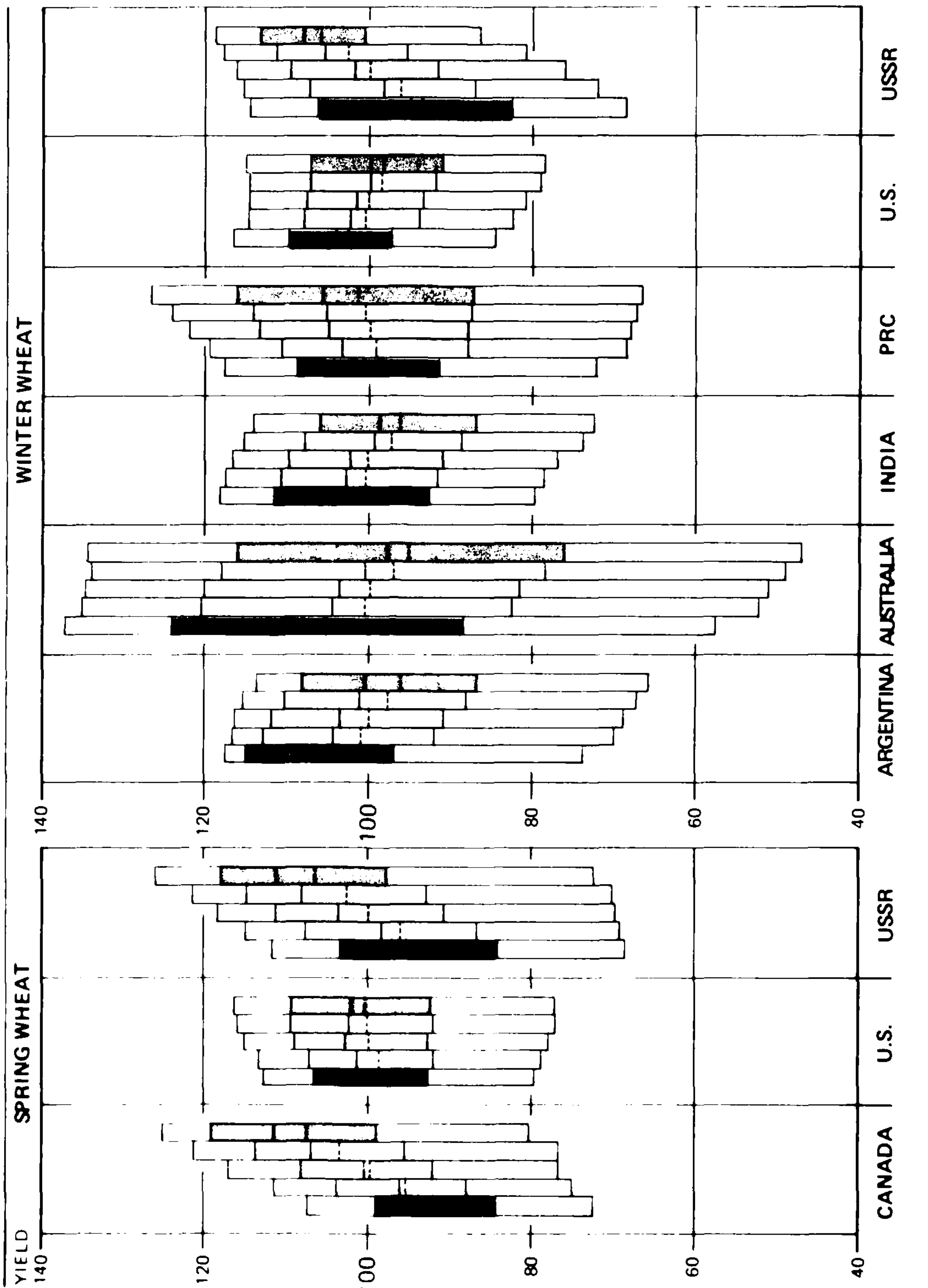
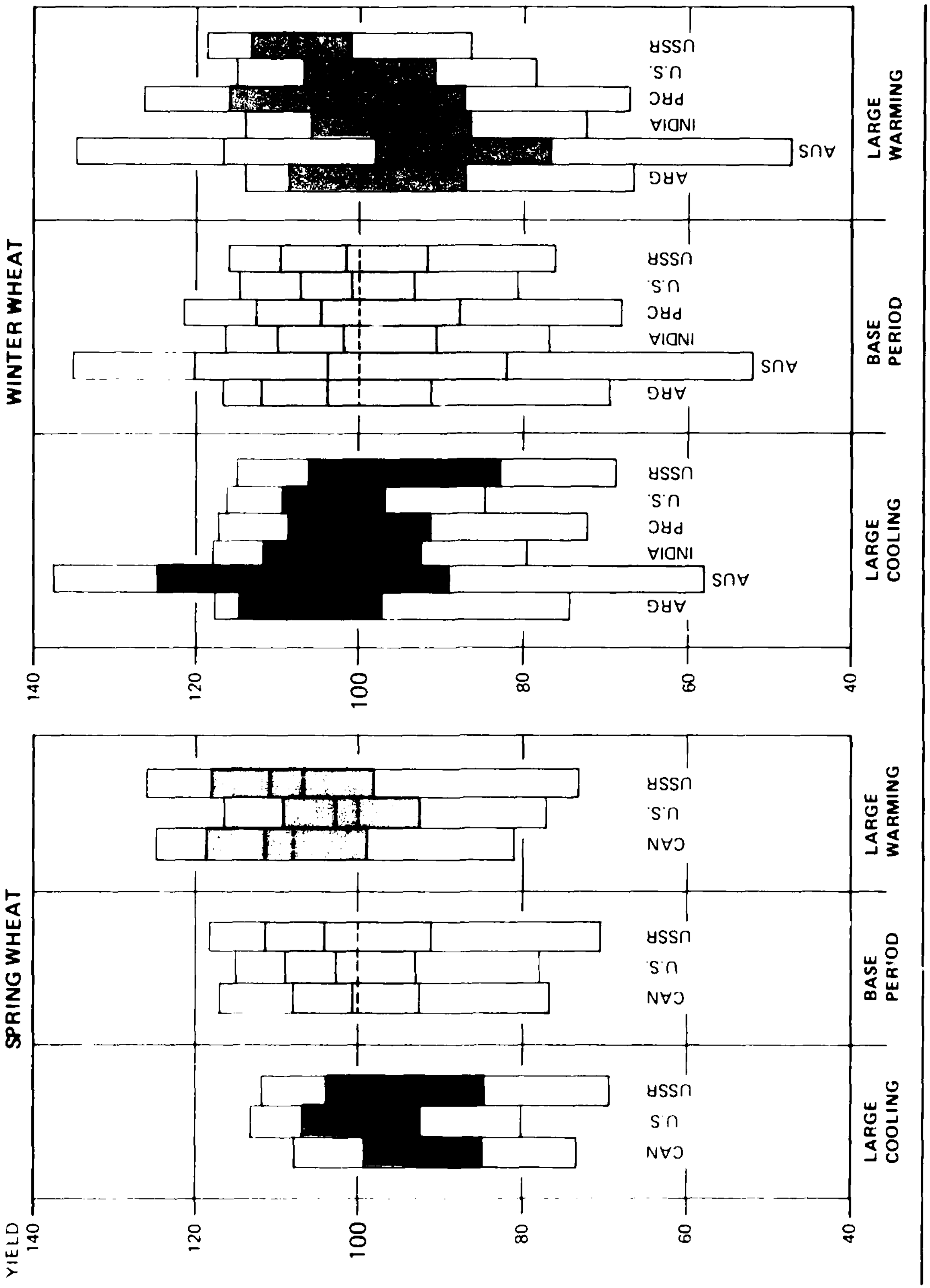


Figure IV 2B

WHEAT: COUNTRY-TO-COUNTRY COMPARISONS OF YIELD DISTRIBUTIONS FOR THREE GLOBAL CLIMATE STATES



Several patterns are evident in Figures IV-1 and IV-2A. The five bars for a crop may be echeloned downward from left to right (Argentine corn), echeloned upward (Canadian wheat), or just partially echeloned downward (U.S. corn). In two instances the bars diverge from left to right (U.S. spring wheat and Chinese winter wheat). Three of the four crops grown in the subtropical latitudes—the two rice crops and Brazilian soybeans—have essentially rectangular envelopes, indicating litle change in the yield distributions from scenario to scenario. Aside from these three cases, a key crop can also be classified according to whether its expected yield is enhanced in the cooling scenarios and depressed in the warming scenarios, or vice versa. The first class of crops, for which cooling is beneficial and warming is detrimental, is typified by the two corn crops, whose expected yields are echeloned downward. The second category, with an upward echeloning of expected yields, is typified by the spring wheat crops.

The variability of annual yields is reflected by the heights of the bars and the distances between the horizontal divisions. According to the model, the relative annual yields of Australian wheat are the most variable of all the key crops.[1] Relative yields of U.S. corn, spring wheat and winter wheat are seen to be less variable than their foreign counterparts. Also, the yields of most key crops are less variable in the cooling scenarios than in the Base Period, but more variable in the warming scenarios. Soviet winter wheat is a notable exception; its bars contract from left to right. (The exceptional behavior of Soviet winter wheat is discussed in Appendixes D-3 and D-4).

Country-to-country differences are stressed in Figure IV-2B; it indicates how the wheat-growing countries fare relative to each other in the Base Period and the two extreme climate scenarios.

[1] *Crop to crop comparisons of variability* based on *relative* yields may differ from comparisons based on absolute yields. See Section 5.9

DISCUSSION

4-3 THE CLIMATE-CROP SCENARIOS: FOCUS ON EXPECTED RELATIVE YIELDS

The impacts of large cooling and large warming on the expected normalized relative yields of the key crops are shown in Figure IV-3. The crops are ordered from greatest loss of yield to greatest gain of yield in the Large Cooling Scenario. For the top seven crops this is also the order of the greatest to least algebraic gain in the Large Warming Scenario. Canadian wheat, Soviet spring wheat and Soviet winter wheat, in that order, are the most sensitive of all key crops to the extreme climate scenarios. In the Large Cooling Scenario there are seven "gainers" and eight "losers." In the Large Warming Scenario the tally shifts to five gainers and ten losers.

The expected-yield data displayed in Figure IV-3 are replotted by crop group in Figure IV-4 along with additional data from the Moderate Cooling and Moderate Warming Scenarios.[2] The Same as the Last 30 Years Scenario is omitted because its effects on yields are insignificant—the changes in expected yield are less than 1%, except for Indian wheat (−1.2%). Defining "small", "moderate" and "large" projected yield changes to be in the approximate ranges of 0% to 3%, 3% to 6%, and 6% to 9%, respectively, we discern the following patterns:

- There is a mirror-image symmetry between the two cooling scenarios and the two warming scenarios. That is, in terms of the yield definitions, a cooling scenario and the corresponding warming scenario (large or moderate) generally have opposite and equal effects on expected yields.

- "Small" yield changes are in the majority, even in the two extreme climate scenarios, which have the most-pronounced effects on yields.

- "Large" yield changes are confined to Canadian and Soviet wheat in the extreme scenarios.

- In the two less extreme scenarios, Canadian and Soviet wheat account for all of the "moderate" yield changes. The Argentine and Australian crops account for all but one of the "moderate" changes in large cooling and large warming.

- Within each scenario there is considerable compensation between gains and losses in the combined wheat groups.

- All the yield charges of U.S. crops are "small."

[2]The content of Figure IV-4 is summarized in a different form in Table S-2, where the key crops are combined by zone of latitude rather than by crop group

Figure IV 3

IMPACT OF THE EXTREME CLIMATE SCENARIOS ON THE EXPECTED VALUES OF NORMALIZED RELATIVE ANNUAL YIELDS

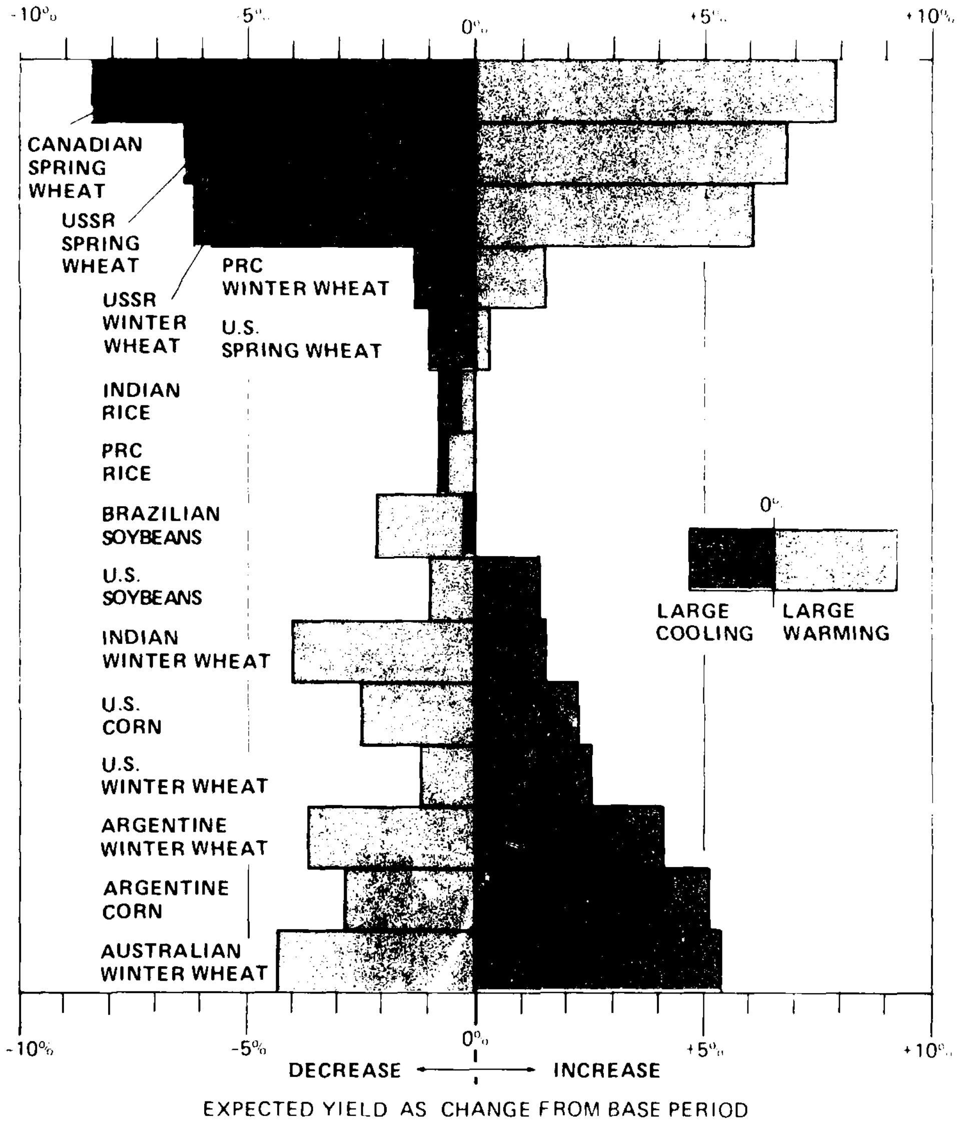
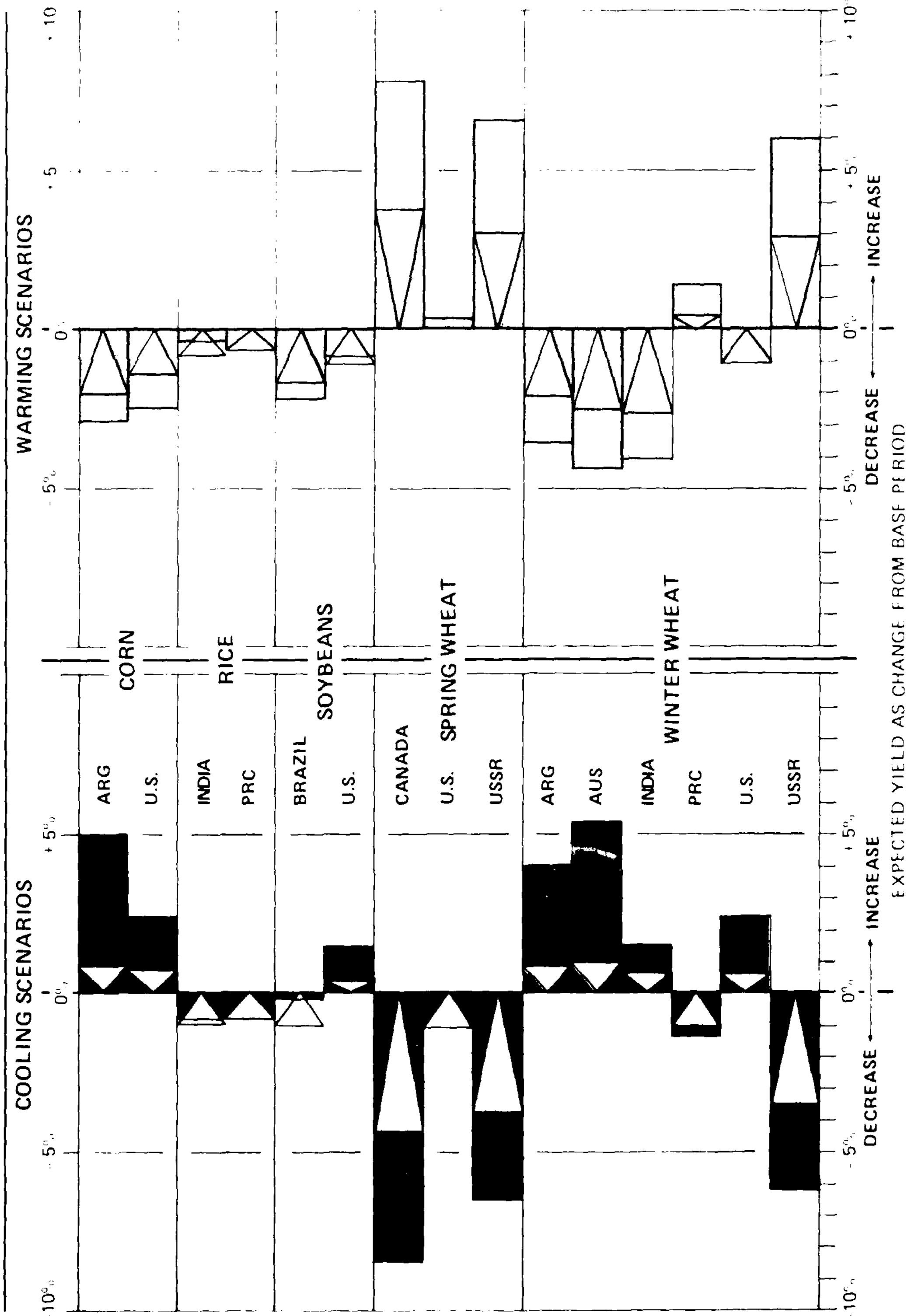


Figure IV 4

IMPACT OF THE NONTRIVIAL CLIMATE SCENARIOS ON THE EXPECTED VALUES OF NORMALIZED RELATIVE ANNUAL YIELDS



Rectangles: Large Cooling and Large Warming Scenarios. Triangles: Moderate Cooling and Moderate Warming Scenarios

The two rice crops and Brazilian soybeans are exceptions to the pattern of opposite yield changes. They experience "small" losses not only in the four scenarios depicted in Figure IV-4 but also in the Same as the Last 30 Years Scenario. As for the apparent anomaly of crops that are adversely affected by all the climate scenarios, we refer the reader to their expected-yield response surfaces (Figures VI-3,4,5): the traces of the expected climate changes applicable to the subtropical latitudes run roughly parallel to, and slightly below, the 100-yield contour curves of the three crops.

Regarding the observation about U.S. crops, the changes in U.S. corn and spring wheat yields are smaller than those of their foreign counterparts. In the soybean group, U.S. yields have a small upside potential in the cooling scenarios while Brazilian yields do not; in the warming scenarios, the U.S. losses are about half the Brazilian losses. Among the six winter wheat crops, the changes in expected U.S. yields range from smallest to third smallest. Thus, while the key U.S. crops are spared from serious erosion in the unfavorable scenarios, the model indicates that they also have little to gain in the benign scenarios.

4-4 THE CLIMATE-CROP SCENARIOS: FOCUS ON THE VARIABILITY OF RELATIVE ANNUAL YIELDS

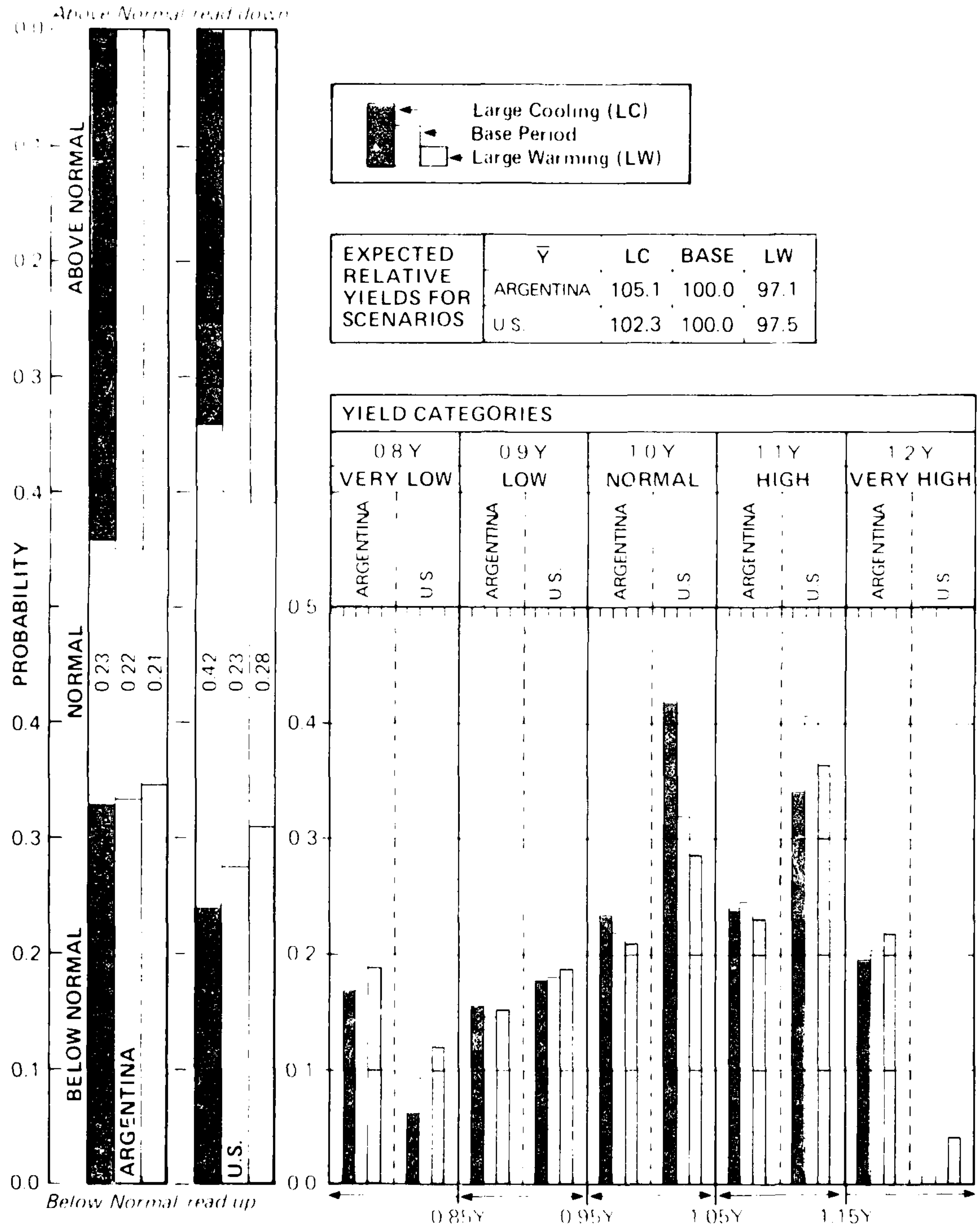
In considering the variability of yields, one is concerned with the details of a frequency distribution (or probability density function), whereas an expected yield is an average (or integral) that tends to smooth out errors in the underlying frequency distribution. Thus, the following discussion about variability is on somewhat shakier ground than the discussion about expected yields. As pointed out in Section 5-11, we place more confidence in statements about expected relative yields and *relative* measures of variability than we do in assertions about *absolute* measures of variability.

The present approach to the variability question might warrant an intermediate level of confidence. In this section, we avoid specific measures of variability by directly examining aggregated and renormalized versions of the annual-yield distributions. One assumes that the coarseness of these distributions washes out some of the "error" in the underlying, detailed distributions. At any rate, the renormalization of yields highlights scenario-to-scenario and country-to-country differences that would be hard to perceive from the original distributions.

The renormalized yield distributions associated with the two extreme climate scenarios and the Base Period (the "present") are shown in Figures IV-5 through IV-9. The renormalized annual yields are expressed as decimal fractions of Y the expected yield *peculiar to the scenario of interest*. This additional normalization should not be confused with the standard scale of normalized relative yields used heretofore. For example, one sees from

Figure IV-5

CORN: DISTRIBUTIONS OF RENORMALIZED ANNUAL YIELDS FOR THREE CLIMATE STATES



EXPECTED RELATIVE YIELDS FOR SCENARIOS	$\bar{Y}$	LC	BASE	LW
	ARGENTINA	105.1	100.0	97.1
	U.S.	102.3	100.0	97.5

Figure IV-5 that Y for Argentine corn in the Large Cooling Scenario is 105.1 on the standard scale. Therefore, an Argentine corn yield of 1.1Y in large cooling is equivalent to 1.1 × 105.1 = 115.6 on the standard yield scale, i.e., 115.6% of the Base-Period expected yield.

The Y-scale, which is common to all country-crop-scenario combinations, lends itself to the following kind of question about world agriculture in the year 2000: Given that climate change has resulted in a new average yield for each crop, what are the probabilities of realizing other than average yields, and how do they differ from the corresponding probabilities of the present?

To structure this question further, we arbitrarily define the following categories of annual yields based on the Y-scale:

- Very High (VH) Yields: 1.15Y or higher
- High (H) Yields: 1.1Y ± 5%
- Normal (N) Yields: 1.0Y ± 5%
- Low (L) Yields: 0.9Y ± 5%
- Very Low (VL) Yields: 0.85Y or lower

Thus, a "Normal" yield has the same meaning for all crops in large cooling, large warming and the Base Period; it is a yield that lies within 5% of Y, the expected normalized relative yield for the climate state of interest. "Below Normal" and "Above Normal" yields are respectively smaller and larger than "Normal" yields. A different choice of yield boundaries would result in different conclusions about the variability of yields. Moreover, the significance of a given fractional departure from average yield depends on the inherent variability of the particular country-crop combination.

There are two sets of bar graphs for each crop group. The first deals with the probabilities of "Below Normal" (BN), "Normal" (N) and "Above Normal" (AN) annual yields in the three climate states. These probabilities, which sum to unity, are presented as portions of a single bar with unit length. In the second set of graphs, the probabilities of VL-L-N-H-VH yields are shown as conventional histograms interdigitated to facilitate comparisons between countries and scenarios. It is difficult to visualize the yield distributions of a single winter-wheat country in this format, so the distributions of individual countries are plotted in Figure IV-9C.

DISCUSSION

To illustrate the kinds of observations that can be made about the figures, we consider the two key corn crops (Figure IV-5). According to the table of Y values, both Argentina and the U.S. enjoy higher expected relative yields in large cooling than in the Base Period, and both suffer lower expected yields in large warming. As for the BN-N-AN yields, we note that

- In all cases, N yields are in the minority, and AN yields are more likely than BN yields.
- The U.S. has a higher probability of N yields than Argentina in all three climate states.
- In Argentina, large cooling and large warming have little effect on the probabilities of BN-N-AN yields.
- In the U.S., large cooling increases the probability of N yields to 42 . about a third higher than in the Base Period and about 80 greater than Argentina's chances for N yields in the same scenario.

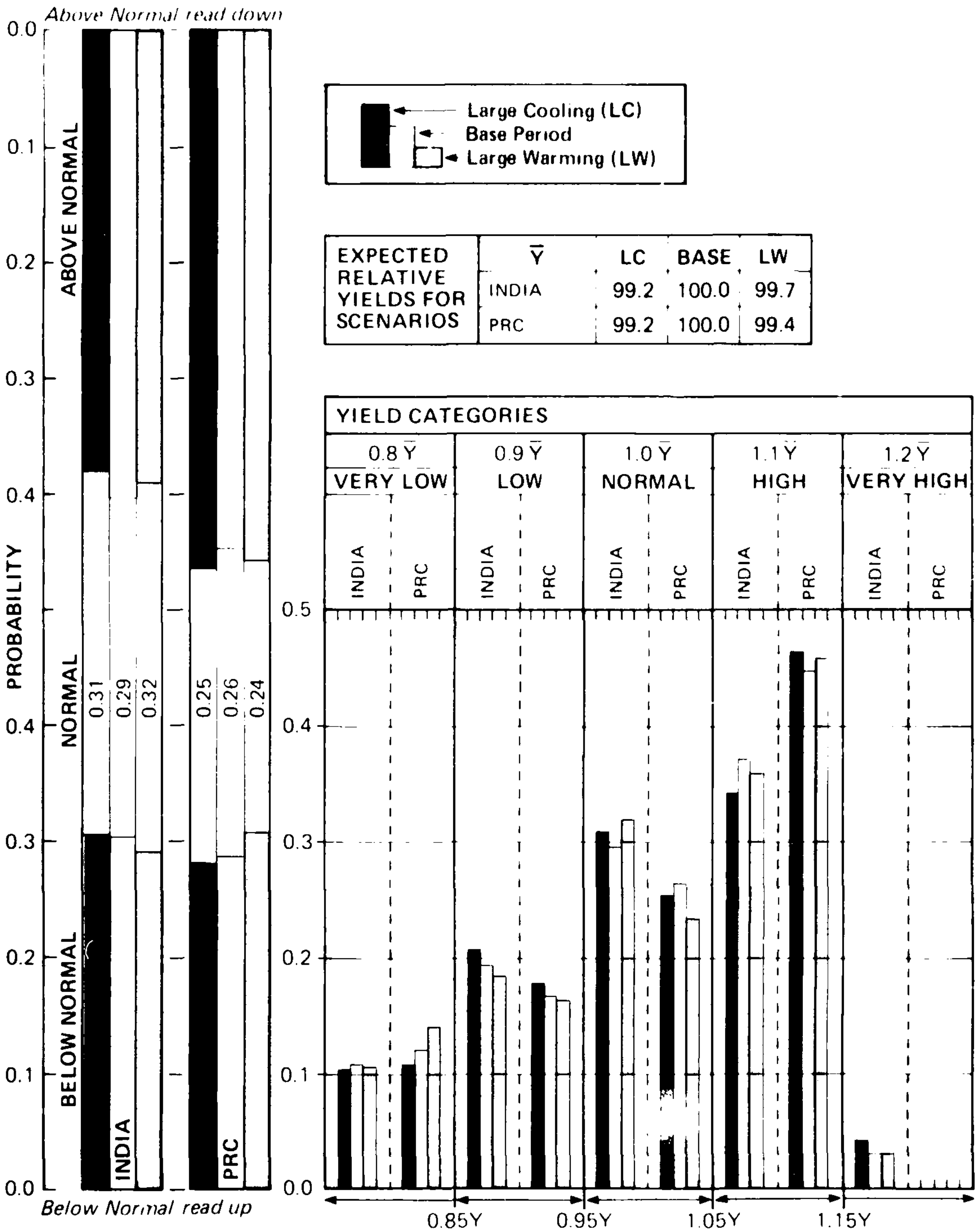
Looking at the VL-L-N-H-VH histograms, one sees that Argentina has essentially the same uniform distribution of yields in each climate state. The flatness of the Argentine distributions is due to the relatively high probabilities for the catchall tails, i.e., the VL and VH yields. These tails, of course, provide a clue to the overall variability of a crop. Again, the U.S. presents a different picture:

- In each climate state the distribution has a pronounced peak and is skewed toward the lower yields.
- The probabilities of N and H yields are large relative to the other yield categories (and much larger than the corresponding probabilities for Argentina).
- Except for L yields, the yield probabilities differ noticeably from scenario to scenario. In fact, the mode shifts from H yields in large warming and the Base Period to N yields in the favorable Large Cooling Scenario.

Whether the scenario-to-scenario differences in the yield distributions are economically significant is an issue that we have had to skirt because of its dimensions. The simplest question, perhaps, is how an assumed climate change would affect the year-to-year variability of total world grain production, relative to a no-change scenario. If the distribution of annual world grain production could be projected, would the average of that distribution be the same as the global production that was computed in Task III on the basis of the projected average yields of the individual crops?

Figure IV 6

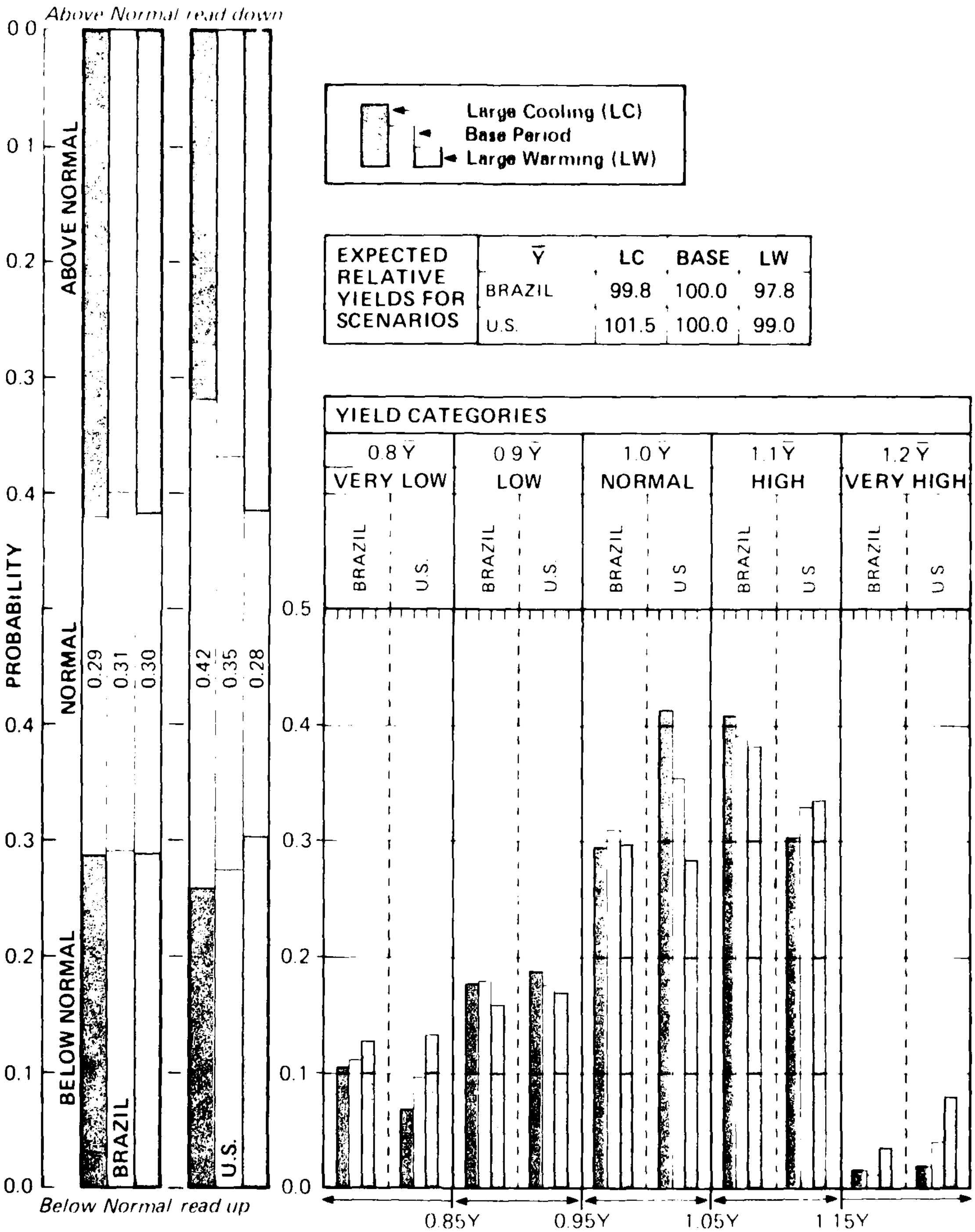
RICE: DISTRIBUTIONS OF RENORMALIZED ANNUAL YIELDS FOR THREE CLIMATE STATES



EXPECTED RELATIVE YIELDS FOR SCENARIOS	LC	BASE	LW
INDIA	99.2	100.0	99.7
PRC	99.2	100.0	99.4

Figure IV 7

SOYBEANS: DISTRIBUTIONS OF RENORMALIZED ANNUAL YIELDS FOR THREE CLIMATE STATES



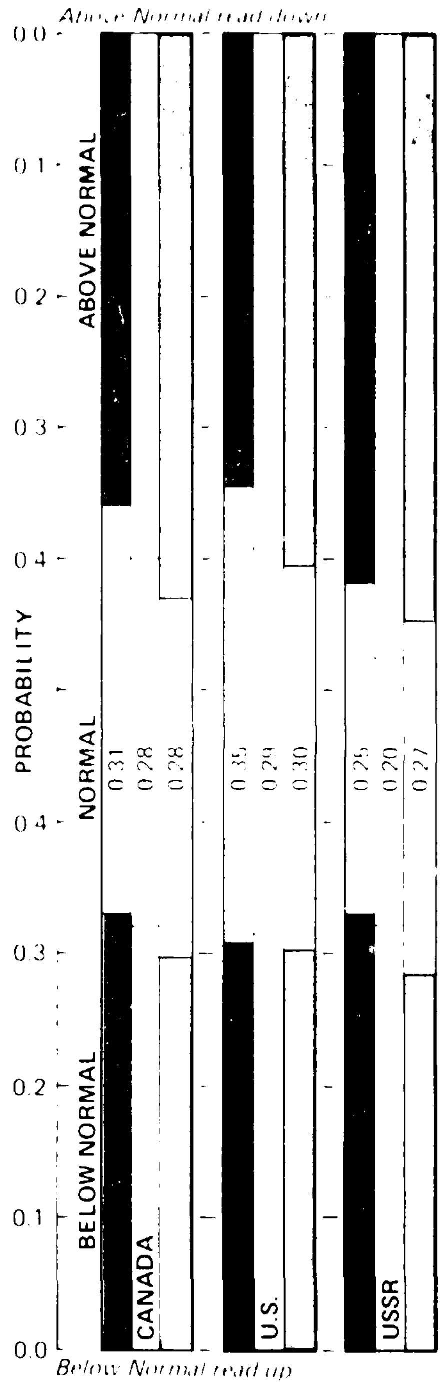
EXPECTED RELATIVE YIELDS FOR SCENARIOS	Ȳ	LC	BASE	LW
	BRAZIL	99.8	100.0	97.8
	U.S.	101.5	100.0	99.0

Figure IV 8A

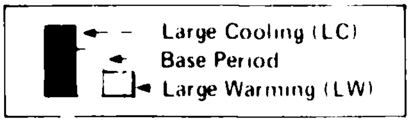
SPRING WHEAT PROBABILITIES OF "NORMAL" YIELDS FOR THREE CLIMATE STATES

Large Cooling (LC)
Base Period
Large Warming (LW)

EXPECTED RELATIVE YIELDS FOR SCENARIOS	$\bar{Y}$	LC	BASE	LW
	CANADA	91.5	100.0	107.9
	U.S.	99.0	100.0	100.3
	USSR	93.6	100.0	106.7



SPRING WHEAT DISTRIBUTIONS OF RENORMALIZED ANNUAL YIELDS
FOR THREE CLIMATE STATES



EXPECTED RELATIVE YIELDS FOR SCENARIOS	$\bar{Y}$	LC	BASE	LW
	CANADA	91.5	100.0	107.9
	U.S.	99.0	100.0	100.3
	USSR	93.6	100.0	106.7

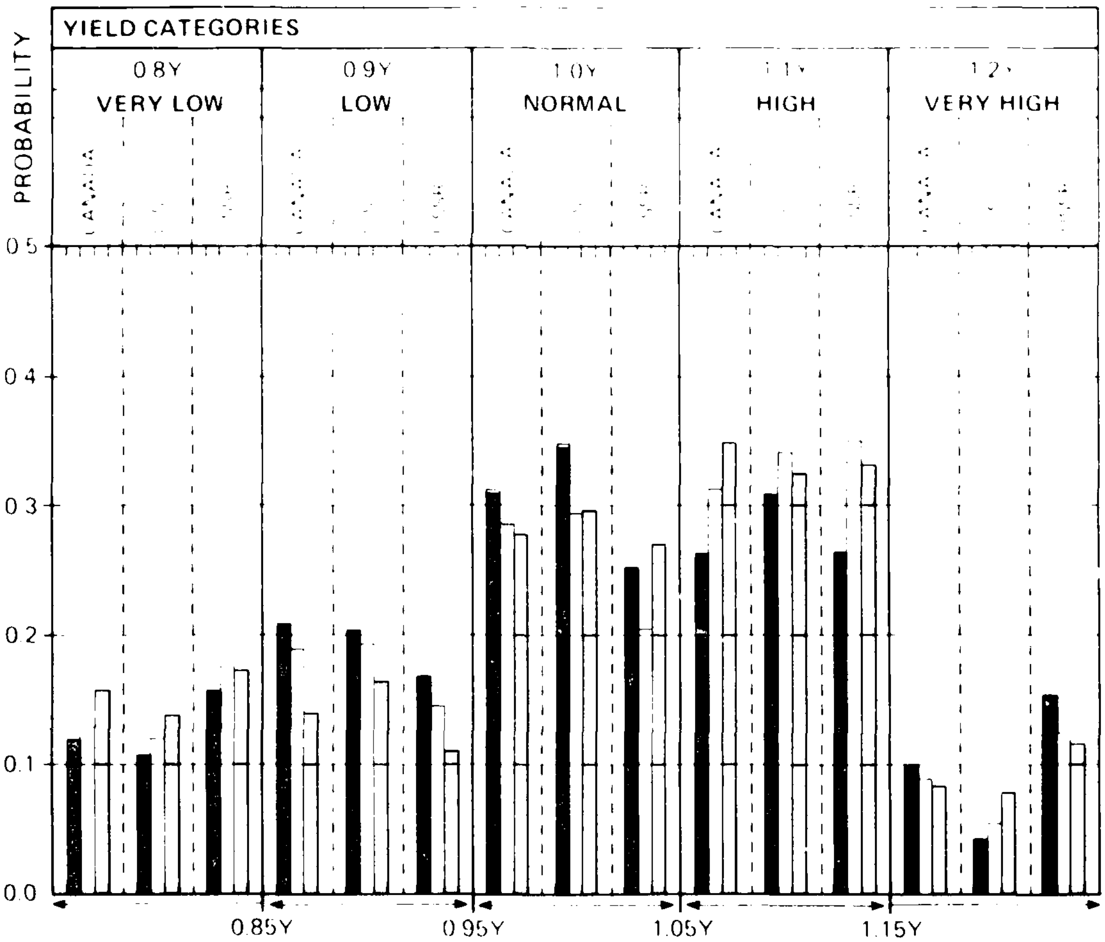
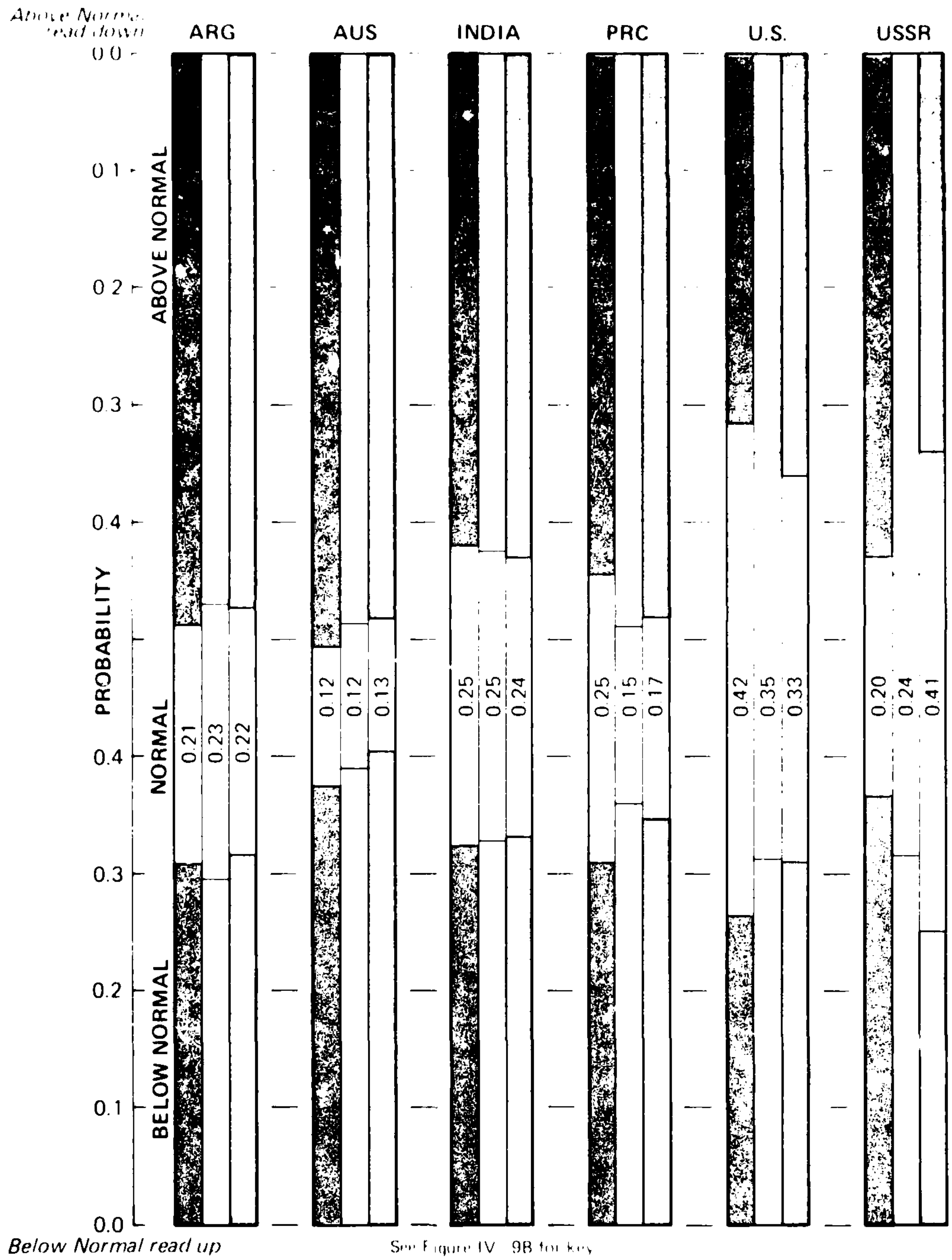


Figure IV-9A

WINTER WHEAT   PROBABILITIES OF "NORMAL" YIELDS FOR THREE CLIMATE STATES



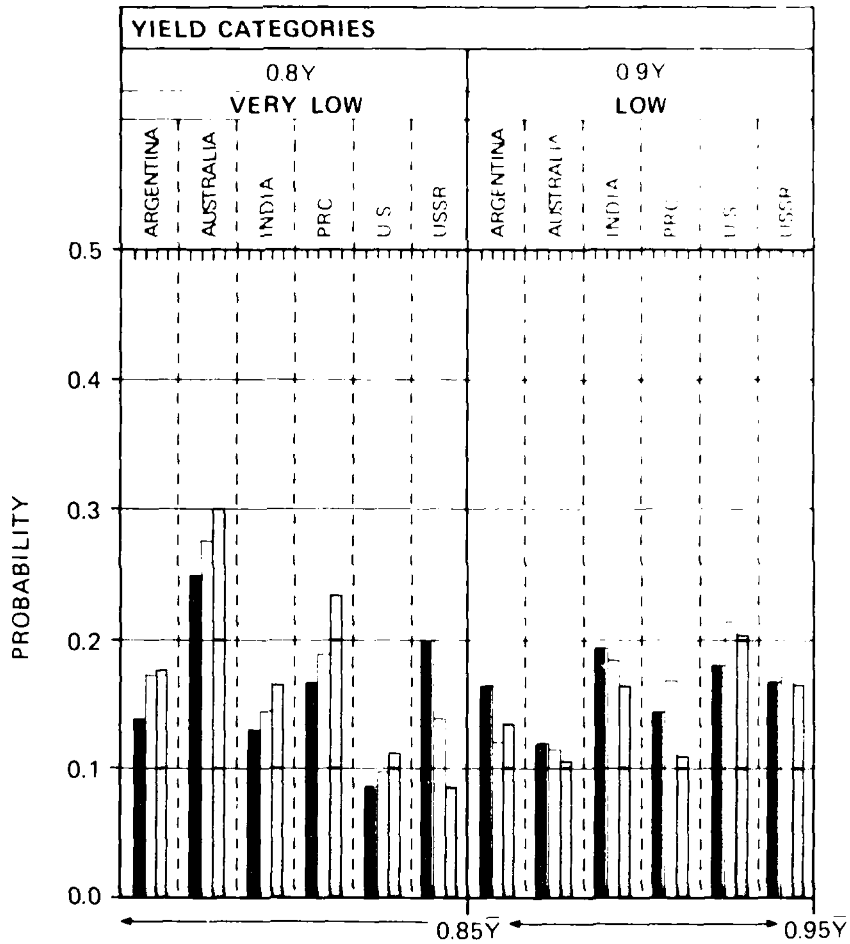
See Figure IV-9B for key

Figure IV 9B

WINTER WHEAT: DISTRIBUTIONS OF RENORMALIZED ANNUAL YIELDS FOR THREE CLIMATE STATES

Large Cooling (LC)
Base Period
Large Warming (LW)

EXPECTED RELATIVE YIELDS FOR SCENARIOS	$\bar{Y}$	LC	BASE	LW
	ARGENTINA	104.1	100.0	96.4
	AUSTRALIA	105.5	100.0	95.7
	INDIA	101.6	100.0	96.0
	PRC	98.7	100.0	101.5
	U.S	102.6	100.0	98.8
	USSR	93.8	100.0	106.1



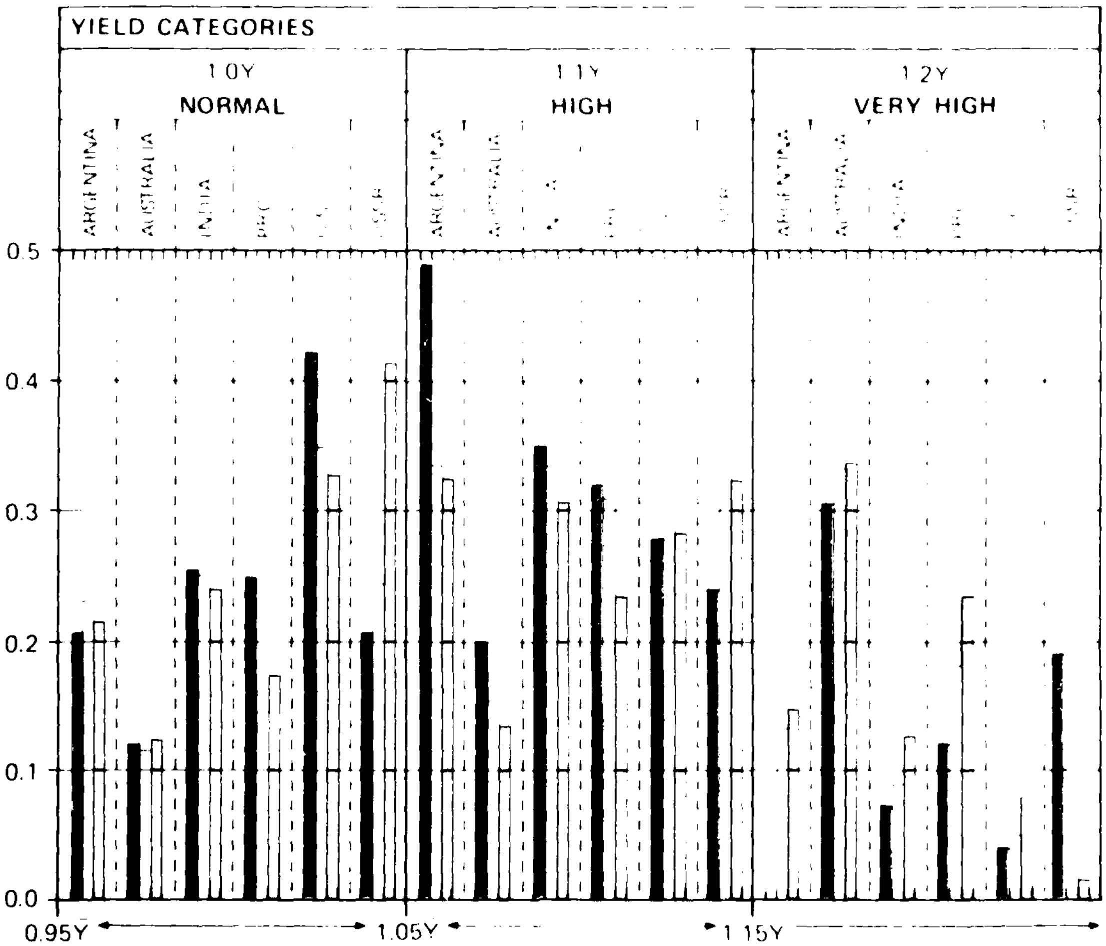

YIELD CATEGORIES
1.0Y
NORMAL
1.1Y
HIGH
1.2Y
VERY HIGH
ARGENTINA
AUSTRALIA
INDIA
ARGENTINA
ARGENTINA
0.5
0.4
0.3
0.2
0.1
0.0
0.95Y
1.05Y
1.15Y

Figure IV 9C

WINTER WHEAT: DISTRIBUTIONS OF RENORMALIZED ANNUAL YIELDS FOR THREE CLIMATE STATES (BY COUNTRY)

Large Cooling (LC)
Base Period
Large Warming (LW)

EXPECTED RELATIVE YIELDS FOR SCENARIOS	Y	LC	BASE	LW
	ARGENTINA	104.1	100.0	96.4
	AUSTRALIA	105.5	100.0	95.7
	INDIA	101.6	100.0	96.0
	PRC	98.7	100.0	101.5
	U.S.	102.6	100.0	98.8
	USSR	93.8	100.0	106.1

RANGES OF ANNUAL YIELDS	
VERY LOW	= Less than 0.85$\bar{Y}$
LOW	= 0.85$\bar{Y}$ to 0.95$\bar{Y}$
NORMAL	= 0.95$\bar{Y}$ to 1.05$\bar{Y}$
HIGH	= 1.05$\bar{Y}$ to 1.15$\bar{Y}$
VERY HIGH	= More than 1.15$\bar{Y}$

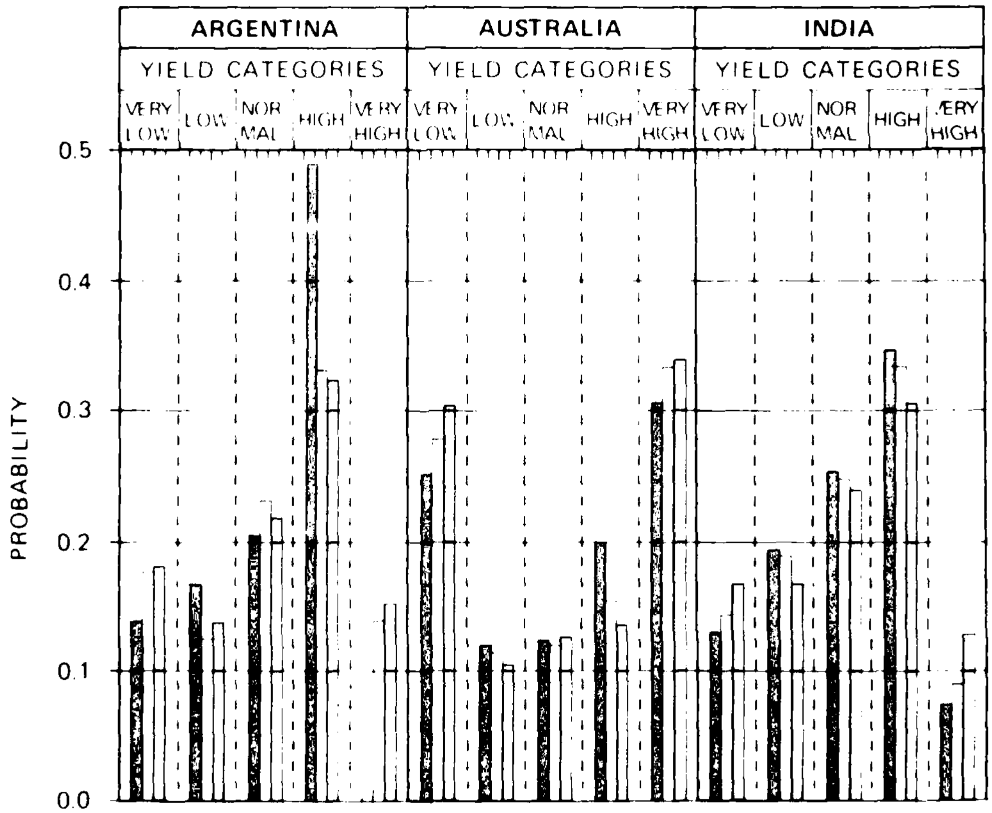
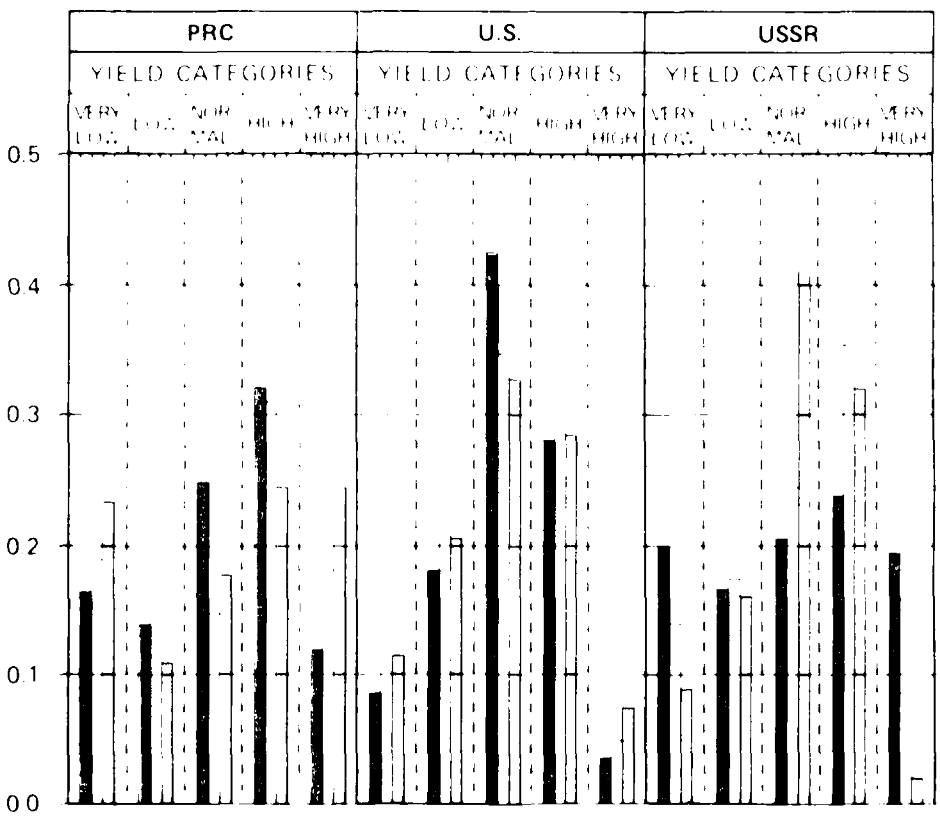
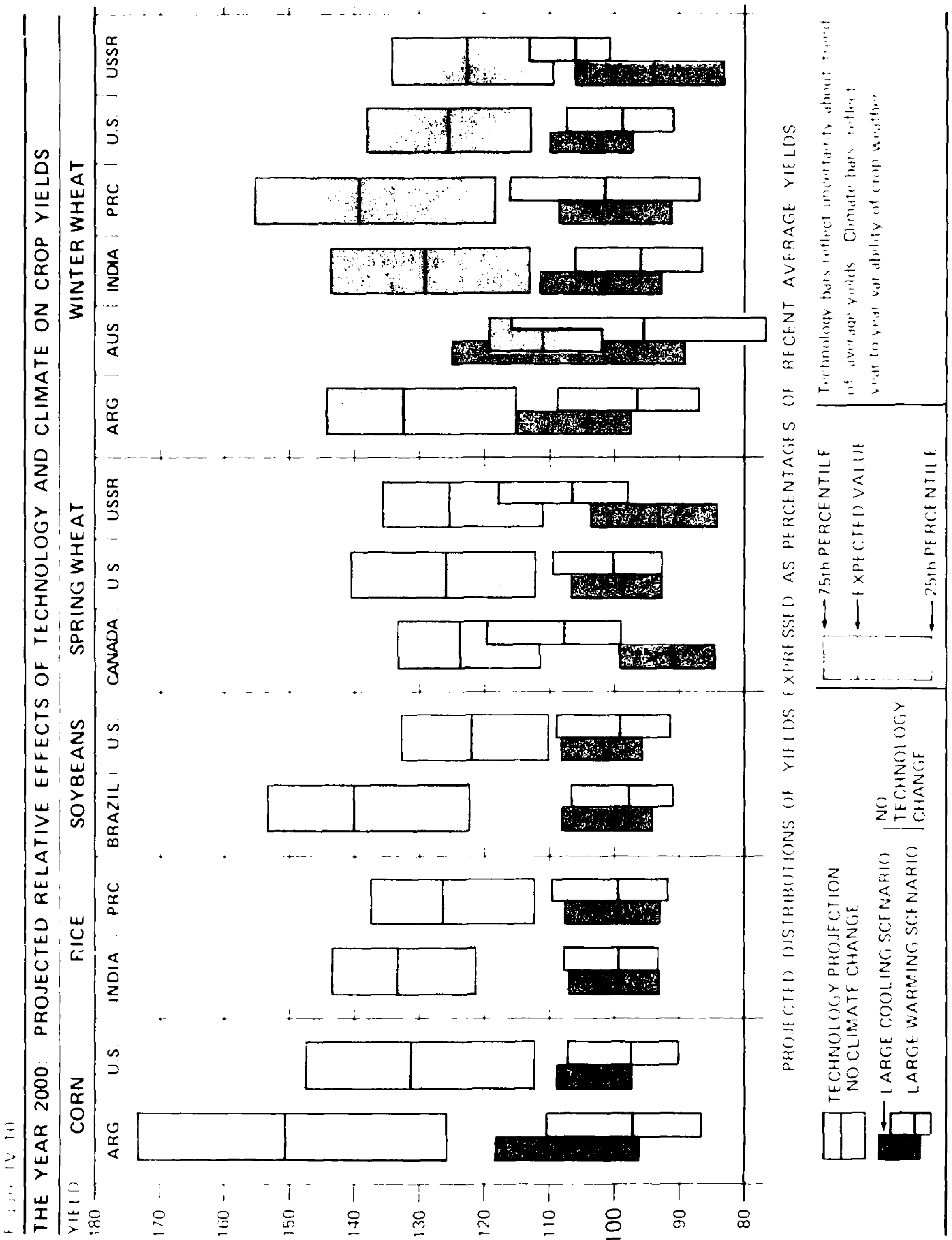


Figure IV-9C (Cont'd)




THE YEAR 2000: PROJECTED RELATIVE EFFECTS OF TECHNOLOGY AND CLIMATE ON CROP YIELDS
YIELD
180
170
160
150
140
130
120
110
100
90
80
CORN
ARG
U.S.
RICE
INDIA
PRC
SOYBEANS
BRAZIL
U.S.
SPRING WHEAT
CANADA
U.S.
USSR
WINTER WHEAT
ARG
AUS
INDIA
PRC
U.S.
USSR
PROJECTED DISTRIBUTIONS OF YIELDS EXPRESSED AS PERCENTAGES OF RECENT AVERAGE YIELDS
TECHNOLOGY PROJECTION
NO CLIMATE CHANGE
LARGE COOLING SCENARIO
LARGE WARMING SCENARIO
NO TECHNOLOGY CHANGE
75th PERCENTILE
EXPECTED VALUE
25th PERCENTILE
Technology bars reflect uncertainty about trend of average yields. Climate bars reflect year to year variability of crop weather.

Given a fast-running economic model suitable for Monte Carlo calculations, such questions could be answered if one had joint distributions of the annual-yield events for the several country-crop combinations. How, then, can joint yield distributions be synthesized from individual yield distributions like those in Figure IV-5? To a first approximation, the probabilities of joint yield events could be calculated using the assumption of independence except where contiguity is a factor.[1] In a given year, for example, the yields of U.S. corn and U.S. soybeans would probably fall in the same yield category. But even after reducing the number of cases by contiguity considerations and after the liberal exercise of judgment, there would remain a formidable number of cases to analyze.

4-5 COMPARISON OF TECHNOLOGY AND CLIMATE EFFECTS

Figure IV-10 brings together two independent sets of yield projections for the year 2000: the *relative* effects of possible changes in technology (assuming that recent climate persists), and the normalized relative yields implied by the Large Cooling and Large Warming Scenarios (assuming 1976 technology). For convenience we shall refer to these two projections as "technology yields" and "climate yields," respectively.

The yield data in Figure IV-10 have been normalized to "current" average annual yields. The technology yields for each crop are expressed as percentages of the average yield for 1972–76.[2] The climate yields are expressed in the standard way as percentages of the expected yields calculated for the Base Period (our approximation of present climate). While the common reference yield of 100 has different meanings for the technology yields and the climate yields, it constitutes a reasonable basis for making rough comparisons between the independent effects of technology and climate as they were assessed in the study.

Each yield bar in Figure IV-10, whether for technology or climate yields, represents the semiquartile range of relative yields.[3] In the case of technology yields, the semiquartile range reflects the Agriculture Panel's collective uncertainty about the technology which might be applied in the year 2000, as well as the panel's uncertainty about the effects of that technology on yields. The semiquartile range of climate yields, on the other hand, reflects our assumptions about the year-to-year variability of crop weather.

[1] An investigation conducted by P. R. Hayes at the request of the Kettering Foundation and the National Defense University tends to support this assumption. See the section on annual crop weather in Appendix F-4.

[2] The average yields for 1972–76 are listed in Table V-2.

[3] The *semiquartile range* of a distribution is the distance between the 25th and 75th percentiles; it encompasses half the population.

DISCUSSION

In order to make generalizations about Figure IV-10, we defer discussion of Australian wheat, an exception that requires separate consideration. The following observations concern the other 14 country-crop combinations.

- The magnitude of the greatest change in expected relative climate yields is 8.5% (the expected annual yield of Canadian wheat decreases by that amount in the Large Cooling Scenario). By contrast, all 14 crops have expected relative technology yields which are more than 20% above current levels. Six of them have increases exceeding 30%.

- As measured by the semiquartile ranges in Figure IV-10, the dispersion of the technology yields exceeds that of the respective climate yields. In this sense, the panelists' uncertainty about technology yields is greater than the spread of climate yields due to fluctuations in annual crop weather.

- There is little overlap of technology-yield bars and climate-yield bars. The overlap in the Canadian and Soviet wheat crops stems from modest increases in technology yields and large positive yield responses to global warming (which are accompanied by comparable yield penalties in global cooling).

In terms of expected relative yields, the effects of technology and climate are most nearly commensurate for the Canadian and Soviet wheat crops. Still, the effects of technology on these crops are about three times greater than the effects of the extreme climate scenarios.

Returning to Australian wheat, we note that:

- The expected technology-yield increment is about twice the magnitudes of the two expected climate-yield increments. This factor is the smallest of all the key crops because Australian wheat has the smallest expected relative technology yield and at the same time ranks high (fourth, to be exact) in the magnitude of its responses to the two extreme climate scenarios.

- Unlike the other 14 crops, the semiquartile range of technology yields is smaller than the semiquartile ranges of the climate yields. This is borne out by the coefficients of variability (CVs).* Australian wheat has the smallest CV of technology yields (0.111) and the largest CVs of climate yields (0.234 in large cooling and 0.280 in large warming).

* The ratios of the standard deviations to the expected values of the distributions.

- The overlap of the yield bars is the greatest among the 15 key crops. This is due to the proximateness of the expected technology and climate yields, the small spread of the technology yields, and the large spread of the climate yields.

The observations on Australian wheat reflect different facets of a rare consensus reached by the Agriculture Panel: technology is not likely to have much effect on Australian wheat yields because the large variability of annual crop weather limits the expected return from technology inputs.

The projections for Australian wheat bring to mind the interaction between weather and climate on the one hand and technology on the other. The technology projections might have been higher if the panelists had been asked to assume the more benign climate of the Large Cooling Scenario, rather than current climate.

4-6 RELATIVE TECHNOLOGY YIELDS VERSUS ABSOLUTE TECHNOLOGY YIELDS

When making crop-to-crop comparisons of yield distributions, one must appreciate the distinction between relative yields and absolute yields. In this section we examine some implications of the distinction as it applies to technology yields; climate yields are considered in Section 5-9.

If the countries within a crop group are ranked according to the expected values of their technology-yield distributions, the ranking associated with *relative* yield distributions will generally differ from the ranking associated with *absolute* yield distributions. The difference in the rankings can be seen by comparing Figures IV-10 and II-1. For example, Argentine corn ranks above U.S. corn with respect to the expected values of the *relative* technology projections (Figure IV-10). This is the reversal of the situation for *absolute* yields (Figure II-1). The difference hinges on the growth rate of expected technology yields, which is the same for both relative and absolute yields. Argentina has the higher growth rate, giving it primacy in expected *relative* yield, but this growth rate is insufficient to negate its lower *absolute* base yield for 1972–76.

In every crop group, the ranking of countries by expected *relative* technology yields is determined by the rank order of the technology growth rates listed in Table II-1. On the other hand, the ranking by expected *absolute* technology yields in the year 2000 is generally the same as the rank order of the 1972–76 base yields. Exceptions occur when a growth rate is sufficiently high to disturb the starting order. This happens in soybeans, where Brazil pulls abreast of the U.S., and in spring wheat, where the U.S. moves from a close second in 1972–76 to a slim lead over Canada by the year 2000.

Consider next the ranking of relative and absolute technology-yield distributions with respect to measures of dispersion. The heights of the technology-yield bars for Argentine and U.S. corn in Figures II-1 and IV-10 suggest two different rankings.[*] Indeed, the standard deviation of the *absolute* yield projections for Argentine corn is 12.5 bu/acre compared to 22.4 bu/acre for U.S. corn, while the standard deviations switch order for *relative* yields (32.6 and 27.5, respectively).

In Table II-1, which deals with *absolute* yields, the rank of a country within a crop group may differ according to whether the dispersion criterion is the standard deviation or the coefficient of variability. What, then, is a suitable dispersion criterion for making crop-to-crop comparisons of the panelists' "inherent" uncertainty about the potential effects of technology? The standard deviation of *relative* technology projections has an advantage over the standard deviation of *absolute* technology projections in that the normalization of the relative yields effectively eliminates disparities among current average yields due to differences in prevailing technology and growing conditions. Even better is the coefficient of variability because it also subsumes differences in perceived growth rates. The coefficient of variability is doubly attractive because it is the same whether one considers technology projections on an absolute scale or on the scale of relative yields.

4-7 UNCERTAINTY IN THE TECHNOLOGY PROJECTIONS

As indicated by the coefficients of variability (CVs) in Table II-1, the agriculture panelists were most uncertain about the technology projections for Argentine corn (CV = 0.216), U.S. corn (0.209), and Chinese winter wheat (0.205). The presence of the last crop in this set of high uncertainty is understandable since the 16 panelists represented in the data base had an average expertise of 2.12 on the 4-3-2 arithmetic scale of expertise, the lowest for any crop. In fact, only two panelists rated themselves 3 (Quite Familiar); the others rated themselves 2 (Familiar). Thus, it is likely that the panel's relative ignorance about Chinese winter wheat accounts for much of the large spread of technology yields. The volatile political situation in the PRC at the time of the survey might also have contributed to the spread.

U.S. corn is instructive because the situation with respect to expertise is the opposite of Chinese winter wheat:

[*] The two figures are not strictly comparable with respect to questions of dispersion; the bars in Figure IV-10 are determined by the 25th and 75th percentiles of relative yield, those in Figure II-1 by the 10th and 90th percentiles of absolute yield.

- The average expertise of the 22 respondents in the U.S. corn data base is 3.41, the highest of any crop.

- Only U.S. spring and winter wheat have more respondents.

- Of the 22 respondents, 14 rated themselves "Expert" (expertise = 4), the most for any crop.

Given the high expertise for U.S. corn, one might expect a fairly narrow distribution of technology-yield projections. However, such an expectation would be unwarranted unless the panelists held common views about the many factors affecting technology choices. We attribute the relatively large spread of U.S. corn technology yields not only to the inherent difficulty of predicting the adoption of technology but also to the tendency of our methodology to exaggerate uncertainty (the more respondents, the greater the potential range of yield projections).

In a sense, Argentine corn inherits the broad range of perceptions that were submitted for U.S. corn, and those relatively expert perceptions probably were broadened further by an additional element of ignorance about Argentine corn:

- The 19 respondents for Argentine corn form a subset of the 22 respondents for U.S. corn.

- All but four of the 19 panelists gave themselves a lower expertise rating on the Argentine crop; the other four were only "Familiar" with both crops.

- Argentina has no corn "Experts," 12 "Quite Familiars" and seven "Familiars," compared with 14, three and five respondents in these respective categories for U.S. corn.

- The net result is an average expertise of 2.63 for Argentine corn, 3.41 for U.S. corn.

This is another instance of the "nesting" phenomena noted in Chapter II: the same panelists, highly knowledgeable about one country in a crop group, making technology projections for another country about which they are less informed. Such nesting, of course, also obtains in the panel's estimates of how yields respond to annual crop weather, the estimates which underlie the climate yields.

4-8 WILL THE EFFECT OF CLIMATE ON CROP YIELDS BE DETECTABLE?

At this point one must question the perceptibility of the climate-induced yield changes that are projected in Section 4-3. Would it be possible to observe such changes in view of (1) the yield-enhancing effects of technology and (2) the variability of yields arising from year-to-year fluctuations of annual temperature and precipitation? For two reasons we incline toward *a negative answer.*

The first, and we believe most important, reason is that climate probably will have a second-order effect on yields over the next few decades. For most crops, the Agriculture Panel's projections point toward technology-related yield increments several times greater than the average effects of climate change. The second reason is basically statistical. In the year 2000, if one could somehow factor out the effects of technology over the previous quarter century—not to mention the effects of other nonclimatic determinants of yields—there would remain the problem of resolving the projected changes in average yields from short series of fluctuating annual yields.

Some appreciation of the masking effect of weather-induced yield variations can be gained from Figures IV-1, 2A. Observe the positions of the projected 25th and 75th yield percentiles for a scenario relative to the position of the expected yield. In most cases, the half of the relative annual yields which fall outside these two percentiles are farther removed from the expected value than that value is removed from the expected value of the Base Period. Hence, it is unlikely that one could detect, much less measure accurately, a change in average yields on the evidence of a small sample of annual yields.

For the key crops most sensitive to climate change—Canadian *and* Soviet wheat—the effects of climate would be more evident. In the Large Cooling Scenario, for instance, the 75th percentile of Canadian wheat yields is less than 100. That is, three fourths of the relative annual yields are projected to be less than the expected yield of the Base Period. Therefore, if the climate yields could be seen as clearly as portrayed in Figure IV-2A—a big "if" considering the obscurant effects of nonclimatic yield determinants—it would be obvious that Canadian wheat yields had been adversely affected by large global cooling. However, the mean of a small sample of annual yields would be unlikely to give a sharp estimate of the change in average yield due solely to the climate change.

R. A. Ambroziak has made the following estimate for the projected effects of the climate scenarios on most of the key crops: if, around the year 2000, one could correct for technological changes, it would require decades—in some cases centuries—to detect the climate-induced change in average yield with a 95% probability of being correct. It would even require a pentad or more of annual observations to detect the impact of the two extreme climate scenarios on the comparatively sensitive wheat crops of Canada and the USSR.

If the impact of climate change on average crop yields is likely to defy measurement and possibly even escape detection, can climate make a practical difference in agriculture by 2000 AD? We think so.

Domestic and international agricultural affairs are driven largely by "extreme" events, by departures from "normal" yields and production. Hence, if the patterns of "good" and "bad" crop years were to change in countries which are important exporters or importers of food, then the patterns of short-term strains and surges in world agricultural trade would differ from those witnessed recently, and policymakers would face new challenges. We made an attempt to raise this issue in Section 4-4.

Thus, in the shorter term, changes in the variability of yields might be more noticeable than the elusive changes in average yields. Nevertheless, the long-term average impact of a climate change could be profound. For example, agricultural trade patterns would be altered with far-reaching economic and political consequences if climate were responsible, on the margin, for transforming certain traditional importers of food and feed into net exporters.

The global climate scenarios encompass most of the reasonable possibilities for the year 2000. At the turn of the century, the world agricultural situation will differ according to which scenario eventuates. In that sense climate will have made a difference, whether or not causes and effects are correctly perceived at the time, and whether or not our projections are wide of the mark.

4-9 EXPERTISE AS A FIGURE OF MERIT

Having seen in Section 4-7 how expertise was distributed in certain technology data bases, we now consider some broader aspects of expertise.

In the absence of "hard" data, we used the *judgments* of the agriculture panelists to develop the annual-yield matrices that express spatially averaged yields as functions of annual crop weather. In a more oblique manner, we aggregated individual *subjective* probabilities to develop the technology projections. An annual-yield matrix estimates an unknown function which nonetheless is manifestly defined within bounds set only by the vagueness of the question posed in the survey of the Agriculture Panel. In the case of the technology yields, however, we are presuming to quantify the effects of inherently unpredictable technology trends. Obviously, the worth of a technology projection or a yield matrix—and the inferences drawn from it—is linked to the quality, and perhaps the quantity, of the individual estimates from which it was derived. Therefore, in combination, the numbers and self-assigned expertise ratings of the respondents to the many parts of the crop-yield survey provide a rough measure of merit for the various findings of this study.

Expertise is a fairly unambiguous figure of merit for the technology yields since the yield projections were aggregated directly from the agriculture panelists' responses without regard to other considerations. The climate yields are less clear-cut because they depend not only on the expertise-weighted annual-yield matrices but also on several externals and premises. For instance, the climate yields are quite sensitive to the precipitation changes portrayed in the climate scenarios, and these scenarios are themselves distilled from the perceptions of a different panel of experts. In addition, climate yields are affected by the parameters of the bivariate normal distributions and by the assumption that the parameters are valid for all the climate scenarios (see Sections 5-10 and 5-11).

Figure IV-11 contains information about the panelists who submitted acceptable responses to some or all of the 30 parts of the crop-yield survey. The lowest expertise rating of any individual entry in the data bases is 2 (Familiar). The numerical entries on the left hand side of the figure are arithmetic averages of the expertise *weights* associated with the data bases.[d]

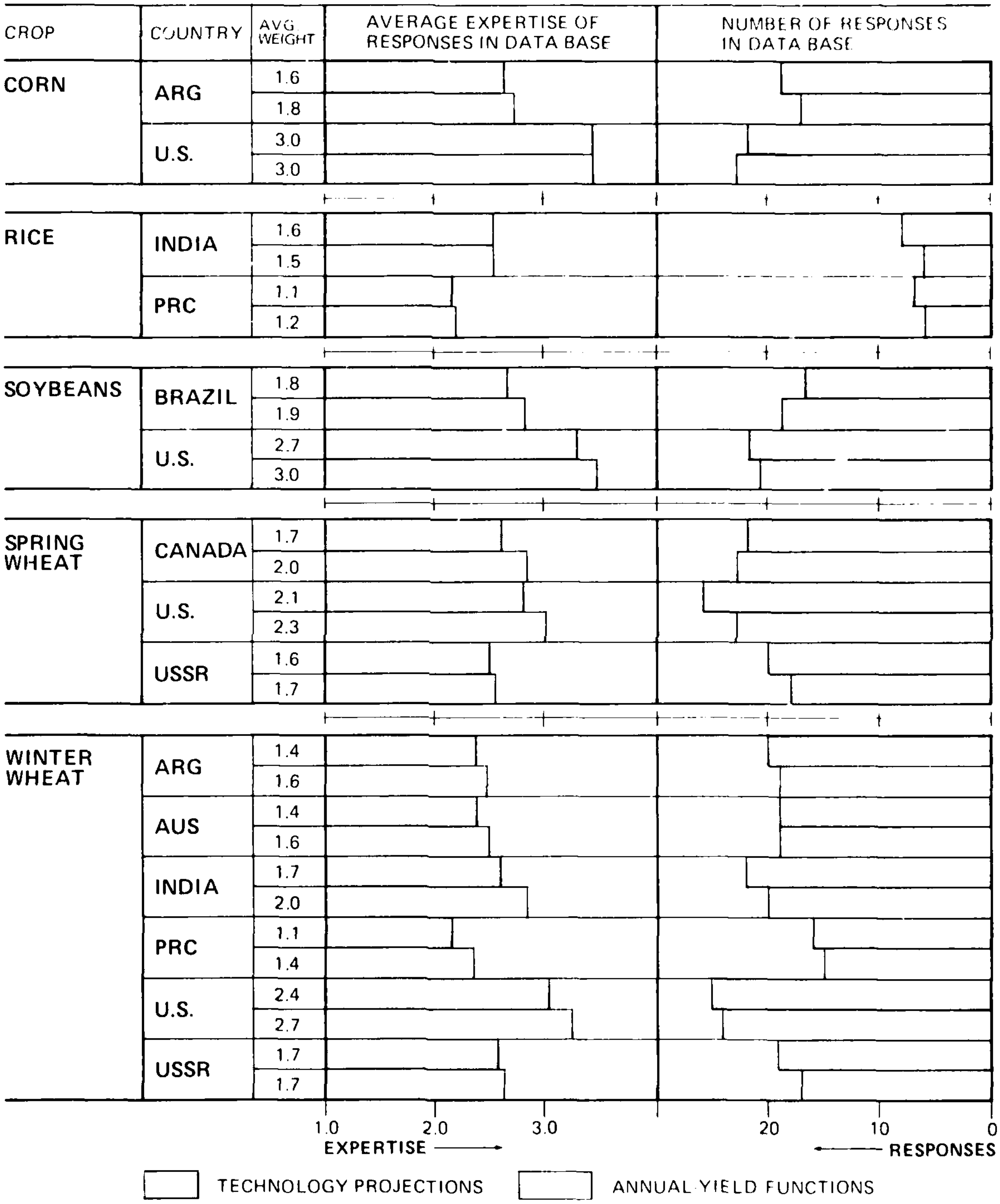
In Figure IV-11 there is a loose correlation between average expertise and level of participation, i.e. within a crop group the countries with the highest and lowest expertise averages are respectively the countries with the biggest and smallest participation, and this applies to both data bases. The figure reflects the imbalance of nationalities on the Agriculture Panel; the U.S. crops have the biggest participation and the highest expertise in their respective crop groups. Canadian wheat is the only crop with expertise close to that of its U.S. counterpart. Ranking low either by participation or expertise are Chinese rice, Chinese winter wheat and Indian rice. Indian wheat, however, has median or higher standing among the 15 country-crop combinations with respect to both participation and expertise.

The technology data bases have an edge over the annual-yield data bases with respect to participation. (There are 12 cases where the number of replies in a crop's technology data base exceeds or equals the number in its annual-yield data base.) On the other hand, the average expertise and average weight generally are higher for the annual-yield data base than for the technology data base. Thus, the expertise bars in Figure IV-11 would

[d] For a single question, a panelist's numerical expertise x is related to his expertise weight w by the expression $w = 2^{x-1}$. It can be shown that the same relation holds between the average expertise $\bar{x}$ and average weight $\bar{w}$ for the question if and only if all the expertise values x are equal. Moreover, if the expertise values are not all identical, then $\bar{w}$ is greater than $2^{\bar{x}-1}$.

Figure IV-11

PARTICIPATION AND EXPERTISE IN THE TASK II DATA BASES



The admissible expertise ratings of 4,3,2 carried respective weights of 4,2,1.

appear to reflect the criteria used to nominate members to the Agriculture Panel: the panelists were chosen with the annual-yield functions uppermost in mind. However, one could argue from the totality of expertise ratings (rather than the expertise in the final data bases) that the panelists considered themselves to be at least as competent on the technology questions as on the annual-yield questions (see Appendix C-1). Such an argument, of course, does not detract from the somewhat superior expertise of the annual-yield data bases.

A dichotomy occurs when one ranks the 15 technology data bases and the 15 annual-yield data bases first by participation and then by average expertise. In the case of corn, rice and soybeans, a country's rank-by-expertise exceeds or equals its rank-by-participation. This situation is reversed for all the wheat crops except Soviet winter wheat, i.e., a country's rank-by-participation exceeds or equals its rank-by-expertise.

The remaining remarks are directed toward groupings of the data bases by crop and country. One sees from Figure IV-11 that participation is fairly homogeneous among the crop groups if rice is excluded; average participation for the members of the corn, soybean and wheat groups varies from 19 to 23. By country group, average participation is biggest for the U.S. and Canadian crops, and smallest for the Chinese and Indian crops.

Table IV-1

RANK OF CROPS AND COUNTRIES BY AVERAGE EXPERTISE

		Data Bases			
	Rank	Technology		Annual-Yield Functions	
CROP GROUP (All Countries)	1	CORN	(3.05)	SOYBEANS	(3.13)
	2	SOYBEANS	(2.98)	CORN	(3.10)
	3	SPRING WHEAT	(2.65)	SPRING WHEAT	(2.82)
	4	WINTER WHEAT	(2.52)	WINTER WHEAT	(2.68)
	5	RICE	(2.33)	RICE	(2.34)
COUNTRY GROUP (All Crops)	1	U.S.	(3.10)	U.S.	(3.25)
	2	BRAZIL	(2.65)	CANADA	(2.83)
	3	CANADA	(2.59)	BRAZIL	(2.79)
	4	INDIA	(2.54)	INDIA	(2.73)
	5	USSR	(2.51)	ARGENTINA	(2.58)
	6	ARGENTINA	(2.49)	USSR	(2.57)
	7	AUSTRALIA	(2.37)	AUSTRALIA	(2.47)
	8	PRC	(2.13)	PRC	(2.28)

The average expertise of all entries in each grouped data base is shown in parentheses.
The admissible expertise ratings were 4(Expert), 3(Quite Familiar), 2(Familiar).

In Table IV-1 the crop groups and country groups are ranked by the average expertise of the technology data bases and by the average expertise of the annual-yield data bases. By either criterion, the corn and soybean groups, with averages at the "Quite Familiar" level (expertise = 3), are superior to the two wheat groups. The wheat groups, in turn, stand a cut above the last-place rice group, for which the expertise approaches the "Familiar" level (expertise = 2), the lowest admissible.

Among the country groups in Table IV-1 the U.S. crops lead, and the Chinese crops trail, by sizable margins of expertise. The technology data bases of the next five countries after the U.S.—Brazil, Canada, India, the USSR and Argentina—are clustered in an interval of 0.16 units of expertise, while the jump between Argentina and seventh-place Australia is 0.12 units. The annual-yield data bases are bunched differently with respect to expertise. Canada, Brazil and India are closely ranked but separated by a gap from Argentina, the USSR and Australia.

Finally, we note that Table IV-1 reflects the quality of the annual-yield data bases relative to the technology data bases. Namely, for each crop and country the average expertise of the grouped annual-yield data bases is higher than that of the corresponding grouped technology data bases.

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TED CRAMPTON

INDEX OF SYMBOLS AND SPECIAL TERMS

Listed below are symbols, abbreviations and terms used in this report. Italics indicate that a term is employed in a special or nonstandard sense. A citation such as 1-2:15 or S-2:3 refers to chapter, section and page where the item is introduced in the main text or the Summary. A boldface citation, e.g., **Chap I, 1-2** or **A-1,** refers to a chapter, section or appendix where the item is discussed at length. *The brief definitions are not necessarily complete.*

SYMBOLS AND ABBREVIATIONS

ΔT = *annual temperature.* S-2:2; **1-5; A-2**

ΔP = *annual precipitation.* S-2:2; **1-5; A-2**

$(\Delta T, \Delta P)$ = *an occurrence of annual crop weather;* an "annual crop-weather point." S-2:2; 1-5:21

$\Delta\bar{T}$ = long-term change in temperature; the expected value of ΔT after an assumed *climate change.* S-2:3; **1-9; A-2**

$\Delta\bar{P}$ = long-term change in precipitation; the expected value of ΔP after an assumed *climate change.* S-2:3; **1-9; A-2**

$(\Delta\bar{T}, \Delta\bar{P})$ = a *climate change.* 1-9:31

BND$(\Delta T, \Delta P)$ = probability of the joint occurrence of ΔT and ΔP in the *Base Period;* more generally, a *bivariate normal distribution* which approximates the variability of *annual crop weather* in the recent past. S-2:2,3; **1-6; A-2**

s_T = standard deviation of *annual temperature* in the *Base Period* (the recent past); one of the *BND parameters.*

s_P = standard deviation of *annual precipitation* in the *Base Period;* one of the *BND parameters.*

r = the correlation coefficient for *annual temperature* and *annual precipitation* in the *Base Period;* one of the *BND parameters.*

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BND(ΔT, ΔP) = probability of the joint occurrence of ΔT and ΔP after a *climate change;* more generally, a *bivariate normal distribution* which is assumed to describe the variability of *annual crop weather* in a particular climate state. S-2:3; **1-10; A-2**

Y = a *relative annual yield,* usually normalized.

Y(ΔT, ΔP) = the *relative annual yield* associated with ΔT and ΔP; more generally, the *annual-yield function* of a *key crop.* S-2:2; **1-5, 1-8; 5-3** thru **5-6**

Y = the expected (or average) value of a distribution of *relative annual yields; expected yield,* usually normalized.

Y(ΔT, ΔP) = the *expected yield* associated with ΔT and ΔP; more generally, the *expected-yield function* of a *key crop.* S-2 3,5; **1-11, 1-13; 6-2** thru **6-5**

BND. *Bivariate normal distribution;* a *BND matrix.*

CV. Coefficient of variability.

NRCV. *Normalized relative coefficient of variability.*

TERMS

absolute yields (contrasted with relative yields). S-10:12; **1-14; 4-6; 5-9**

Agriculture Panel. A panel of 35 experts (see Acknowledgments) recruited for *Task II* to project the effects of technology on yield trends (**B-1, B-2, B-3**) and estimate the *annual-yield functions* (**D-1, D-2**).

annual crop weather. The values of ΔT and ΔP affecting one year's stand of a *key crop.* See also *bivariate normal distribution.* S-2:2; 1-5:21

annual precipitation (ΔP). A differential measure of *crop-year precipitation;* one of the random variables that determines the annual yield of a *key crop.* See also *bivariate normal distribution.* 1-5:21; **5-2**

annual temperature (ΔT). A differential measure of one year's *heading-period temperature;* one of the random variables that determines the annual yield of a *key crop.* See also *bivariate normal distribution.* 1-5:21; **5-2**

annual-yield function. An explicit rule, matrix, or figure, etc., that assigns a *relative annual yield* to a specific occurrence of *annual crop weather; rela-*

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relative yields (contrasted with absolute yields). S-10:12; **1-14; 4-6; 5-9**

renormalized (annual) yield. Annual yield reckoned as a decimal fraction of the *expected yield* projected for an assumed climate state (1976 technology is understood). **4-4**

response surface. The representation of a function as a surface over the plane of its two independent variables.

semiquartile range. The distance between the 25th and 75th percentiles of a distribution. 4-5:109

sensitivity. Four kinds of "sensitivity" are examined in the report. (1) The relative influences of ΔT and ΔP on the year-to-year variability of yields: S-9:11; **5-7.** (2) The sensitivity of the relative-yield distributions to the *BND paramaters:* S-9:11; **5-10, 5-11; D-3, D-4.** (3) The effects of 10% changes in precipitation compared with the effects of the *expected zonal climate changes:* S-9:11. (4) The sensitivity of the *expected yields* in the *climate-crop scenarios* to the *expected zonal climate changes:* see *climatic uncertainty.*

skewness. The third moment of a distribution divided by the cube of the standard deviation. 1-5:22

standard-deviation response surface. A graph of the standard deviation of *relative annual yields* as a function of the *climate-change variables* $\Delta \bar{T}$ and $\Delta \bar{P}$, derived from an *Expected-Yield Summary Table.* S-2:3,5; 1-11:38; **6-4, 6-5**

task; *Tasks I, II, III, IV.* The sequential phases of the climate impact assessment. S-1:1

technology component of crop yields. The contribution of technology to yields, as distinct from the contributions of weather and climate. More specifically, the estimated crop-yield effects of technological change; the *technology projections* for 2000 AD. S-1:2; **S-5**

technology projections. The *Agriculture Panel's* projections of the effects of technological change (absent climatic change) on yield trends to the year 2000; see also "methodology (1)" and "uncertainty about the *technology projections.*" Discussion of the projections: **S-5, S-7, S-8; Chap II; 4-5, 4-6, 4-8; B-3; E-4.** Graphical representations: **1-4; B-1, B-2.**

technology yields. 4-5:109

temperature. See ΔT and $\Delta \bar{T}$, also "sensitivity."

LMED

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