CLIMATE CHANGE IMPACTS FOR THE CONTERMINOUS USA: AN INTEGRATED ASSESSMENT

PART 1. SCENARIOS AND CONTEXT

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Abstract. As carbon dioxide and other greenhouse gases accumulate in the atmosphere and contribute to rising global temperatures, it is important to examine how derivative changes in climate may affect natural and managed ecosystems. In this series of papers, we study the impacts of climate change on agriculture, water resources and natural ecosystems in the conterminous United States using twelve scenarios derived from General Circulation Model (GCM) projections to drive biophysical impact models. These scenarios are described in this paper. The scenarios are first put into the context of recent work on climate-change by the IPCC for the 21st century and span two levels of global-mean temperature change and three sets of spatial patterns of change derived from GCM results. In addition, the effect of either the presence or absence of a CO_2 "fertilization effect" on vegetation is examined by using two levels of atmospheric CO_2 concentration as a proxy variable. Results from three GCM experiments were used to produce different regional patterns of climate change. The three regional patterns for the conterminous United States range from: an increase in temperature above the global-mean level along with a significant decline in precipitation; temperature increases in line with the global-mean with an average increase in precipitation; and, with a sulfate aerosol effect added to in the same model, temperature increases that are lower than the global-mean. The resulting set of scenarios span a wide range of potential climate changes and allows examination of the relative importance of global-mean temperature change, regional climate patterns, aerosol cooling, and CO_2 fertilization effects.

1. Introduction

Atmospheric concentrations of carbon dioxide and other heat-trapping gases have been increasing over the past century, enhancing the atmosphere's natural greenhouse effect. This increase is thought to be the major cause of the measured increase in surface temperatures over the last 50 yr (Mitchell et al., 2002). Further climate changes over this century are nearly certain, although of uncertain magnitude.

While global-mean temperatures are a useful measure of the overall magnitude of possible anthropogenic influence, it is regional climate changes that will produce

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impacts on both human and natural systems. Further, it is not necessarily average changes but changes in seasonality, variability and extremes that will be more disruptive. Changes in climate will translate to changes in other important natural processes, notably the hydrologic cycle. In addition to climate changes, increasing atmospheric carbon dioxide concentrations ([CO_2]) will likely affect plant growth and water balance.

This series of papers presents a coordinated set of climate impact studies that examine the responses of agriculture, water resources, and natural ecosystems to a set of climate change scenarios. The biophysical models used are the EPIC model for agriculture (Williams, 1995), the HUMUS model for water resources (Arnold et al., 1999), and the BIOME3 model for natural ecosystems (Haxeltine and Prentice, 1996). These are fully described and validated in Parts 2 and 6.

Using a range of future climate scenarios, we simulated the impacts on dryland agriculture (Part 3) and on water resources (Part 4). Next, we examined the degree of change of water demand by irrigated crops, the amount of water available to meet that demand, and how total potential crop production in the United States might be affected (Part 5). We then assessed, under the same climate scenarios, the possible magnitude of changes in natural ecosystems (Part 6). The series ends with an economic analysis of the impacts of the various climate change scenarios on agriculture and water resources (Part 7). In this, the first of the papers, we present the climate change scenarios used for these analyses, discuss the changes projected over the United States and provide some context for the sectoral impact studies.

2. Climate Change Scenario Descriptions

A set of climate scenarios projecting how temperature and precipitation will change due to anthropogenic influences is one of the fundamental inputs needed for biophysical impact models. These models also require future CO_2 concentrations to evaluate the impact of CO_2-fertilization on vegetation. The magnitude of these changes is not known, however, due to uncertainties in both the climate response to anthropogenic influences and the extent of future emissions of greenhouse gases. Thus, we conduct our analyses over a matrix of scenarios that covers a wide range of possible future climatic conditions in order to examine the range of possible impacts.

The impact models used in this study require inputs of climate parameters such as temperature and precipitation; for this reason the scenario descriptions also focus on physical rather than socio-economic parameters. This is not to say that socio-economic factors are irrelevant to impacts analysis. Different assumptions for driving forces such as population levels and income, for example, can lead to drastically different demands for agricultural goods, which would imply quite different implications for climate impacts on agriculture. In this analysis socio-economic effects and physical changes are separated. We first calculate impacts such as agricultural productivity changes for a matrix of physical climate change scenarios. The last paper (Sands and Edmonds, 2004) in this series then conducts an analysis that examines the impact of these physical changes in a larger socio-economic context using an integrated assessment model.

Ideally, an end-to-end analysis would include all of these factors simultaneously, considering a self-consistent set of impact inputs from global-mean-climate changes, rates of climate change, carbon dioxide concentrations, regional climate changes, and regional (and global) socio-economic factors. Developing such a study would likely require a spatially disaggregated representation of driving forces such as population, income, and other social-economic indicators. Just as the uncertainty in climate changes increases with decreasing spatial scale the same is also true for socio-economic driving forces, even if larger-scale values are taken as given. Such an end-to-end analysis would provide useful insights and self-consistent results, but would be one of a wide range of possible results given the uncertainty in each of the factors in the causal chain.

The present study is, instead, structured to examine a range of possible outcomes in a conceptually (and computationally) straightforward framework. We, therefore, will proceed below to examine the variables that define the inputs needed for each of these analyses. Each scenario consists of the following three sets of input data: (1) a specification the magnitude of future anthropogenic climate change in terms of global-mean temperature change, (2) the strength of the effect of increasing CO_2 concentrations on plant processes, and (3) the spatial pattern of these changes in temperature and precipitation as simulated by GCM models. No changes in climate variability are considered: the absolute values of inter-annual changes are assumed to be identical to those in the 30-yr reference period (see below). Each of these variables is discussed below. The result is a grid of twelve climate change scenarios along with a baseline case of no further climate changes (Table I).

2.1. GLOBAL-MEAN TEMPERATURE CHANGE

The global-mean temperature change due to anthropogenic influences is the most widely used measure of the magnitude of future climate change. There are two primary determinants of the overall level of future climate changes, the level of greenhouse gas emissions, including the influence of aerosols, and the *climate sensitivity* (see below). Neither the future emission levels nor the climate sensitivity are known, which means that there is a wide range of possible changes in global-mean temperature.

For this study two values of global-mean temperature (GMT) change are used: $+1\,^{\circ}$C and $+2.5\,^{\circ}$C . The temperature changes here, and henceforth, are relative to a 1990 base year.[1] As with most climate impact analyses, this one was done with a discrete set of input parameters. In all likelihood, future climate changes will not

TABLE I

Scenario matrix: A baseline climate plus 12 combinations of climate model, global-mean temperature projection, sulfate aerosols and CO_2 fertilization effects

GCM	GMT (°C)	CO_2 concentration (ppmv)
Baseline		365
BMRC	1	365
		560
	2.5	365
		560
UIUC	1	365
		560
	2.5	365
		560
UIUC + Sulfates	1	365
		560
	2.5	365
		560

Note. The CO_2 concentration levels are meant as proxies for the strength of the fertilization effect and not as specific concentration levels associated with the given temperature change values (Section 6).

be stationary but will change over time, so that any specific set of parameters will occur only once (or perhaps not at all).

2.1.1. *SRES Context*

To put these changes into context, first consider the simplified range of future changes given in Figure 1, which shows the global-mean changes projected for six illustrative emission scenarios from the IPCC Special Report on Emission Scenarios (SRES) using a central value for the climate sensitivity (Cubasch et al., 2002). The SRES scenarios cover a wide range of driving forces, which result in a range of emissions. As demonstrated in Figure 1, these emissions result in a range of future climate changes (although note that different sets of driving forces can result in similar emissions; Nakicenovic and Swart, 2000). We see that a global-mean temperature change of 1 °C occurs in these scenarios as a transient point, which is exceeded in all of these cases. The case for a 2.5 °C change is less certain. Both in scenarios with high emissions or with elevated climate sensitivity (not shown), this level of climate change can be exceeded. There are also scenarios in which this level of climate change is not reached.

The picture given in Figure 1 is, however, incomplete. The range of future climate changes is determined by emissions, the behavior of the climate system, and the behavior of gas cycles. Uncertainty in all of these contributes to the spread in

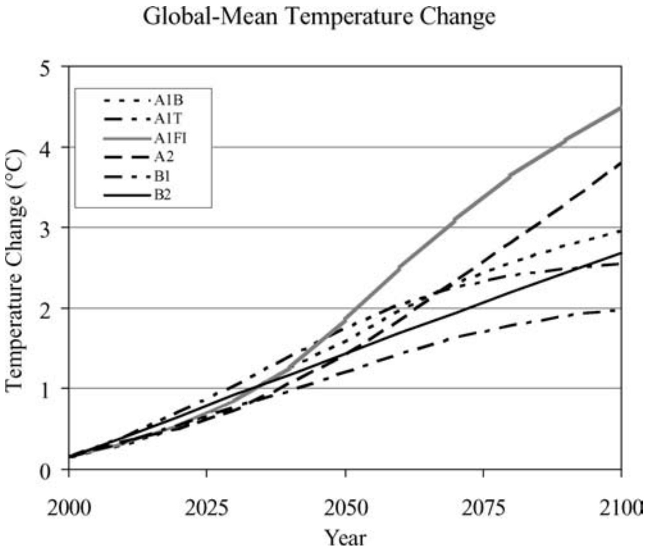

Figure 1. Global-mean temperature change, relative to 1990, under six different scenarios for future emissions under the assumption of a climate sensitivity of 2.5 °C. These six emissions scenarios span a range of future assumptions for global socio-economic development in the absence of climate policy (Nakicenovic and Swart, 2000). See Cubasch et al. (2002) for details of the temperature change calculations.

possible future climate change (Wigley and Raper, 2001). A particularly important parameter is the climate sensitivity, which is an aggregate measure of how much the climate will respond to changes in radiative balance, such as those caused by changes in greenhouse gas concentrations. The climate sensitivity is conventionally given as the equilibrium global-mean warming associated with a doubling of carbon dioxide concentrations.

2.1.2. *Probabilities and Scenarios*

In order to present a fuller picture considering variation in multiple parameters we will turn to probabilistic estimates of future temperature change, using the results from the analysis of Wigley and Raper (2001). In using these results we wish to put the discrete scenarios used in this study into some context. Any probabilistic calculation is, however, itself subject to uncertainty and we will discuss below how the uncertainties in these calculations affect our interpretation in the context of the present work.

Figure 2 shows one estimate of the probability of exceeding a 1 °C and 2.5 °C increase in global-mean temperature over the next 100-yr assuming that no climate mitigation policies are implemented (Wigley and Raper; 2001). Intermediate date and probability figures are purposely not given in this figure to emphasize that we are not attempting to assign a specific probability to our impacts scenarios but to provide context to the scenarios.

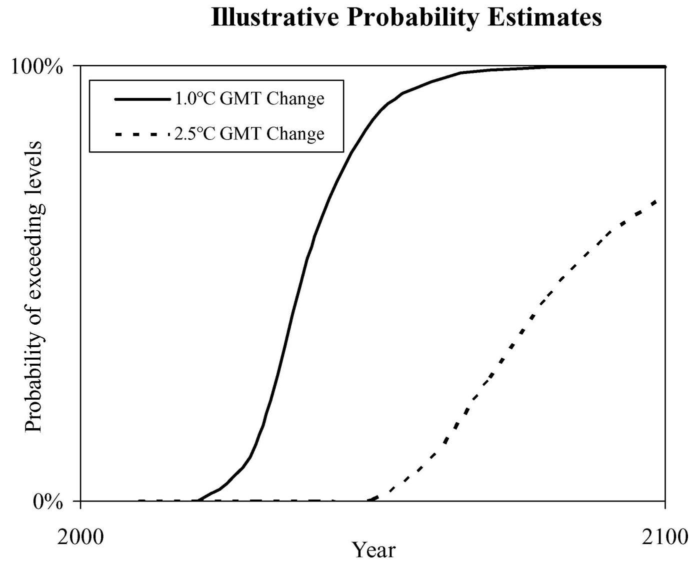

Figure 2. Estimates of the probability of exceeding two specified levels of global-mean temperature change, relative to 1990, as calculated by Wigley and Raper (2001). These estimates take into account range of possible future emissions and climate parameters.

The probabilistic calculations presented here are based on two sets of assumptions. The primary set of assumptions is about the distribution of input parameter values. The second set of assumptions concern the behavior of the climate system. The latter are embodied in the simple climate model used to translate input parameter values into climate outputs. The model used (MAGICC) has been shown capable of re-producing the global-mean outputs of most general circulation models. With the exception of possible discontinuities in the behavior of the climate system, we conclude that the uncertainties in this calculation lie primarily with the assumptions about the distribution of input parameter values.[2]

The principal input parameters that determine future climate change are emissions of greenhouse gases and aerosols and the value of the climate sensitivity. Here, we assume that each of the emissions scenarios are equally likely and that all values of the climate sensitivity over the range of 1.5–4.5 °C per CO_2 doubling, as assumed by the IPCC, are equally likely as well (a range in gas-cycle parameters is also considered). The shape of the distribution for climate sensitivity does not have a large effect on the outcome since most realizations will use values near the center of the distribution (Wigley and Raper, 2001).

The range of parameters used is based largely on results from both physical-science models (for values of the climate sensitivity) and socio-economic models (for emissions scenarios). While model results are often constrained by observational or historical data, it is clear that there is much about both the climate system and socio-economic systems that is not well understood. While we believe the parameter ranges are a reasonable representation of our current understanding of these systems, future estimates could turn out to be significantly different than those estimated here. This is an important, and almost impossible to quantify, source of uncertainty, as has been recognized for other systems where modeling has been used to predict the future of poorly understood systems (Sarewitz et al., 2000).

A particular point of contention exists regarding the assignment of probabilities to emissions scenarios. While the properties of a physical systems can be subject to a formal statistical analysis, projections of the state of socio-economic systems 100 years in the future is arguably more problematic. Many of the critical links between socio-economic systems are not understood well enough to allow straightforward incorporation into a quantitative model. Furthermore, future socio-economic developments are not independent variables, but are subject to policy decisions made today and in the future. Recognizing these difficulties, Wigley and Raper (2001) choose to make all of the SRES scenarios equally likely. In constructing these scenarios, the SRES writing team did not assign a probability to any of the scenarios or scenario families, stating that "the distribution of the scenarios provides a useful context for understanding the relative position of a scenario but does not represent the likelihood of its occurrence." These considerations will be noted as we proceed with interpretation of probabilistic results.

2.1.3. *Probabilistic Context*

With these points on the probabilistic interpretation of scenarios in mind, we now turn to the specific scenarios used in this study. Consider now the probability of exceeding a 1 °C increase in global-mean temperature relative to 1990 as shown in Figure 2. The probability of exceeding a 1 °C global-mean temperature change by the middle of the century is very high. At this point the influence of the emissions scenario of global-mean temperature change is relatively small (Figure 1). Therefore, the probabilities up to mid-century are influenced largely by the values of climate parameters, in particular the climate sensitivity. We conclude that, given our current understanding of the climate system, that a 1 °C change in global-mean temperature is nearly certain to occur by the end of the century and probably will occur by mid-century. While policy scenarios may reduce emissions, such reductions will have limited impact on climate change for some time due to both the thermal inertia in the climate system (Dai et al., 2000) and interactions between greenhouse gas and sulfur dioxide emissions (Smith et al, 2004). Note also that the lower range of the SRES emissions scenarios result in carbon dioxide concentrations by 2100 that are nearly stable at around 550 ppmv, a commonly analyzed policy target. Therefore, even under many climate change mitigation policy scenarios, global-mean temperature is likely to exceed 1 °C by 2050. In the long term, the impacts under this scenario are likely to be underestimates of eventual climate impacts by the end of the century.

For the 2.5 °C set of impacts scenarios, we can conclude that there is low chance of a 2.5 °C increase in global-mean temperature, relative to 1990, by 2050.[3] Again, by 2050, the influence of the emissions scenario assumptions is relatively small and the results are primarily driven by climate system and aerosol forcing assumptions. Therefore, the 2.5 °C set of impact scenarios are focused on the second half of the century if not later. After 2050 the conclusions that can be drawn from the probabilistic analysis are less well defined. Due to the longer time horizon, most of the assumptions made for this calculation have a larger impact on results in 2100 as compared to 2050 including issues of how to probabilistically represent emissions scenarios. The calculation of Wigley and Raper (2001) results in a 70% probability of a global-mean temperature change that exceeds 2.5 °C by 2100 with no climate policies in place. Therefore, we can conclude that a level of climate change of 2.5 °C is feasible, but that this is by no means certain to occur nor is this an upper bound to possible changes by 2100.

In summary, the 1 °C impact scenarios provide a conservative lower bound for the future impacts of climate change. Impacts at this level are likely to be exceeded by the middle of the century. The 2.5 °C impact scenarios simulate a level of climate impacts that may be felt at some point in the latter half of this century. Global temperatures might not reach this level, or could exceed this level, depending on climate sensitivity, future socio-economic developments, and the presence of climate policy actions.

2.2. CARBON DIOXIDE FERTILIZATION EFFECT

The primary driving force of the climate changes presented above is the increasing concentration of carbon dioxide in the atmosphere. In addition to the effect of any changes in climate on plant growth, changes in the atmospheric concentration of CO_2 ($[CO_2]$) will also affect plants directly. In experiments in controlled environments (Kimball, 1983; Rogers et al., 1996) and in field studies using free-air carbon dioxide enrichment (FACE) facilities (Mauney et al., 1994; Kimball et al., 1995), a CO_2 ‘fertilization effect’ has been observed; agricultural crops grown at higher $[CO_2]$ experience increased growth rates, improved water use efficiency, and higher yields (Makino and Mae, 1999; Allen et al., 1998; Maroco et al., 1999). Plants respond to increasing CO_2 concentrations with increased rates of photosynthesis and with increased stomatal resistance that reduces transpiration, hence conserving water and reducing water stress.

While the presence of these CO_2 “fertilization” effects are well documented, there is considerable uncertainty regarding how accurately and consistently these effects can be applied to long-term simulations of crop growth over large areas (Bowes, 1993; Makino and Mae, 1999) and how these effects extend to unmanaged ecosystems (Drake et al., 1996; Oechel et al., 1994; Oren et al., 2001). These uncertainties are discussed in detail in the subsequent papers on the EPIC model. We consider these uncertainties by reporting results for the two levels of CO_2 concentration used in the impact studies reported here. The first, a level of 365 ppmv, essentially the current concentration,[4] is used to represent the notion that the direct effects of 'fertilization' do not manifest themselves or are insignificant. This is, therefore, a lower bound case for CO_2 fertilization effects. A higher $[CO_2]$ – 560 ppmv – was also used in the analysis. Given that CO_2 fertilization effects tend to saturate with increases in concentration, the use of this concentration level, along with central assumptions about the physiological response of plants to $[CO_2]$ represent a reasonably strong CO_2 fertilization effect. Under a wide range of assumptions about the carbon cycle, a $[CO_2]$ level of 500 ppmv is reached or exceeded by most of the SRES scenarios by the end of the century (Prentice et al., 2002). A number of scenarios, depending again on carbon-cycle assumptions, can exceed this level by 2050.

The uncertainty in the climate sensitivity, in particular, means that there is no unique figure for the amount of temperature change that could be considered consistent with a specific CO_2 concentration level. The matrix of climate scenarios considered for the impact analyses thus is not intended to literally pair a specific CO_2 concentration level with specific levels of climate change. Instead, we are considering two simplified cases: no CO_2 fertilization effect and a moderate to strong CO_2 fertilization effect as bounding cases.

In summary, combining the two climate change (temperature change) levels and the two chosen CO_2 concentration levels gives four scenarios. While we do not expect there to be no effects due to CO_2 fertilization, these effects may be significantly limited in the real world as compared to an idealized model. The 365 ppmv – "no fertilization effect" – scenarios provide a certain lower bound for fertilization effects.

The combination of 1 °C and 560 ppmv is unlikely in the 'real-world'. Temperature changes that would accompany this concentration level are likely to be significantly higher that 1 °C . This scenario represents, then, a modest amount of climate change coupled with a strong CO_2 fertilization effect and sets a lower bound for the transient effects that could occur between about 2030 and 2050 (Figures 1 and 2).

The fourth combination of 2.5 °C and 560 ppmv is physically realizable and not improbable. It is possible that CO_2 fertilization effects could exceed the level assumed here. It is also probable that saturation effects and other limiting factors will be important given both the significant levels of CO_2 fertilization and climate change assumed. We consider this combination to be a reasonable point estimate of climate change with possible ameliorating effects of CO_2 fertilization, as could occur towards the end of this century.

2.3. THE SPATIAL PATTERN OF CLIMATE CHANGE

Global-mean temperature change, while useful as a measure of overall strength of greenhouse warming, is not the most relevant measure for impact analysis, which requires information on regional and local changes in climate. Relevant variables include precipitation, temperature, and changes in the variability and extremes in these quantities. Regional climate changes are estimated by a variety of methods including historical analogy, general circulation models (GCMs), and GCMs coupled with various downscaling techniques.

Our method here is to use historical climate data, coupled with GCM results. Rather than using GCM results directly, we use the pattern scaling method embodied in the SCENGEN system of Hulme et al. (1995) to produce regional climate change patterns. In this method, each GCM is considered to have a characteristic climate sensitivity and climate response pattern, although the latter can change with different assumptions about aerosol effects. Since neither the true response pattern nor the climate sensitivity are known, this method allows a wide range of possible climate responses to be generated.

A historical climate data series from 1960 to 1989 was used to establish a baseline climate data set for the EPIC, HUMUS and BIOME3 simulations (Arnold et al., 1999). The GCMs provided data on the monthly change in daily mean temperature and precipitation. Baseline daily climate data were then adjusted with the GCM-generated changes.

To provide the widest range of possible future climate scenarios, two GCMs were chosen for their divergent projections of future climate over the continental United States. This allows the analysis to consider the widest range of potential future conditions and place theoretical bounds on the degree and direction of change most likely to occur. The models are from the Australian Bureau of Meteorology Research Center (BMRC) (McAveney et al., 1991) and the University of Illinois at Urbana Champagne (UIUC) (Schlesinger, 1997). The UIUC GCM was also run with the inclusion of sulfate aerosol effects (UIUC + Sulfate), providing a third set of climate change projections. The pattern of climate change from these three models, each at two levels of global-mean temperature and two levels of [CO_2] gives 12 climate change scenarios to be evaluated, as shown in Table I.

The spatial patterns of temperature and precipitation change for the BMRC scenarios are identical for the 1 °C and 2.5 °C scenarios; only the magnitudes of the changes are different. The same is true for the UIUC scenarios (without sulfate aerosols). This is because, for forcing components where the pattern of forcing remains constant over time, the climate change response pattern is assumed also to remain constant with time. The situation is different for the UIUC + Sulfate aerosol scenarios. Since the pattern of forcing from sulfate aerosols varies with time, the resulting pattern of climate change will also vary with time. For this scenario a SCENGEN run with IS92a forcing assumptions was used to derive the climate change patterns. The 1 °C and 2.5 °C scenarios were produced when the global-mean temperature change in the IS92a scenario reached these points. This results in climate change patterns that are different for the 1 °C and 2.5 °C scenarios. A quantitative discussion of the climate change patterns as given by the three GCM results follows.

3. Geographic Patterns of Climate Change

3.1. ANNUAL TEMPERATURE AND PRECIPITATION CHANGES

The annual temperature and precipitation change, averaged over the conterminous United States, is given in Table II. All three model results project an increase in the annual-mean temperature of the conterminous United States, although the magnitude of the increase (relative to the global-mean) differs with each model.

Temperature change in the United States is greater than the global average value for the BMRC model, about equal to the global average in the UIUC model, and less than the global average in the UIUC + Sulfates model run.

The simulation results for precipitation also differ, with the UIUC model showing increasing precipitation over most of the conterminous United States and the BMRC showing substantial drying. Precipitation decreases in BMRC, increases in the UIUC model run and increases even more in the UIUC + Sulfates model run.

The average results given in Table II are only a general indication of the regional effect of climate change. Regional patterns in these changes over the U.S. drive the ecosystem models used in this analysis. The pattern of changes for each of these three models is discussed below.

3.1.1. *BMRC*

Temperature increase under BMRC is moderate in the southern states, along the West Coast and in the more northerly portions of the Great Plains and Northeast (Figure 3). The Great Lakes region shows the greatest increase in temperature. The range of increase here for a global-mean temperature (GMT) = +1 °C is from 1 to 2 °C and for GMT = +2.5 °C the range is from 2.5 °C to 5 °C above baseline. In the BMRC scenarios precipitation declined nationwide under GMT of +1 °C and +2.5 °C (Figure 4). Drying is most extreme in the south and southwestern parts of the country and up the West Coast. The exception is the northern part of the country

TABLE II
Average annual change in temperature and precipitation over the conterminous United States given by the GCM climate change scenarios, as scaled for use in this study

GCM	GMT (°C)	Temperature change(°C)	Precipitation change (mm)
BMRC	1	1.5	−39
	2.5	3.6	−98
UIUC	1	0.9	98
	2.5	2.3	245
UIUC + Sulfates	1	0.4	132
	2.5	1.6	287

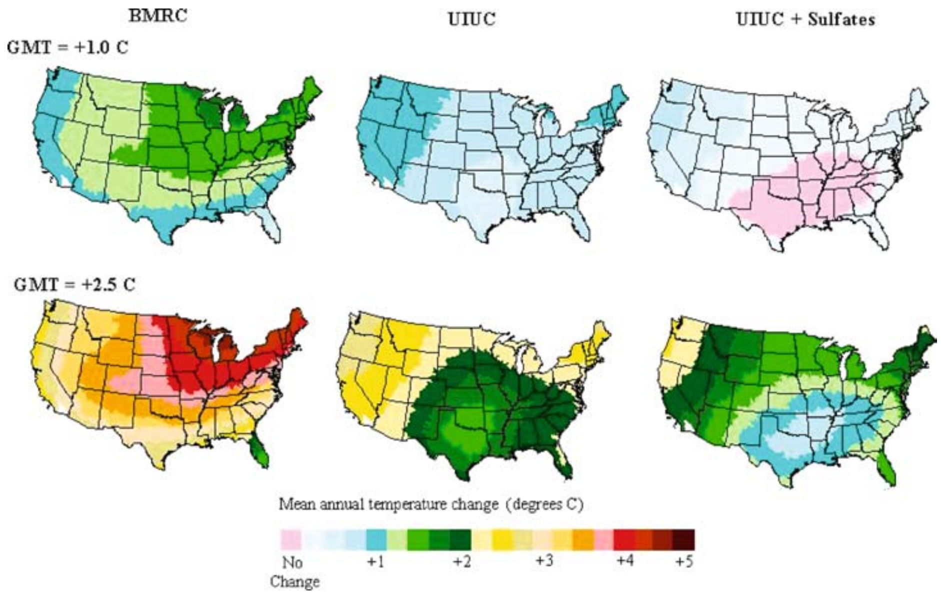

Figure 3. Mean annual temperature change from baseline for the three GCMs at two global-mean temperature change levels.

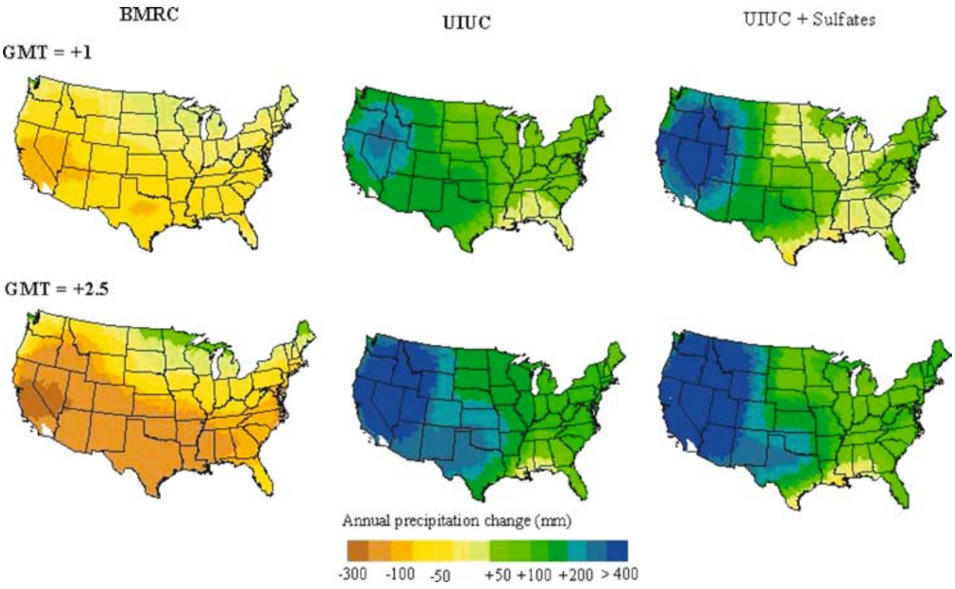

Figure 4. Annual precipitation change from baseline for the 3 GCMs at two levels of global-mean temperature change.

where drying is moderate. Some precipitation increases are projected, notably in the Great Lakes region and the Northeast. The increase of GMT to +2.5 °C intensifies both the drying in the Southwest and West Coast and the increase in precipitation in the Northeast and Great Lakes states.

3.1.2. *UIUC*

Warming under UIUC is moderate, ranging from 0.5 °C to 1.5 °C above baseline when GMT = +1 °C and from 1.5 °C to 3 °C when GMT= +2.5 °C (Figure 3). Warming is weakest in the south central part of the country and strongest in the Northeast and Northwest. UIUC projects increased precipitation across most of the country (Figure 4). Some slight drying is shown on the Gulf Coast, but moderate to large increases in precipitation occur over the rest of the country. The Western half of the country receives more of an increase than the East. At GMT = +2.5 °C, precipitation increases further across the country, and the drying along the Gulf Coast is moderated.

3.1.3. *UIUC + Sulfates*

Temperature and precipitation changes are affected by the inclusion of the sulfate aerosol effect in the UIUC model (Figure 3). Temperature increases are least under this scenario, ranging from 0 °C to 1 °C with GMT = +1 °C and from 1 °C to 3 °C when GMT = +2.5 °C . The regional distribution of temperature change is similar to that under UIUC without sulfate. Precipitation declines in some regions with the addition of sulfates to the UIUC model, but increases in others (Figure 4). Precipitation increases were least in the southern Gulf Coast states and through the Ohio Valley and parts of the Midwest. Precipitation increases in the Northeast, unchanged from UIUC, and increases to a greater extent over much of the western half of the country.

3.2. SEASONAL CHANGE IN TEMPERATURE AND PRECIPITATION

Projected climate changes will not be uniform throughout the year. How air temperature increases seasonally will determine crop growth and hydrologic response. Higher summer temperatures could induce more severe and protracted temperature stress in crops as well as increased rates of evapotranspiration, reducing crop water use efficiency[5] and runoff. Temperature increases in the spring and fall would lengthen the crop growing season but also shorten the time to maturity, thereby lowering yields. A longer growing season may also favor introduction of new species or cultivars and enable use of management practices not previously possible.

Seasonal differences in the patterns of temperature change are reported for seven of the eighteen major U.S. water resource regions in Table III. Under BMRC, the temperature increase is greatest in winter for the Ohio, Upper Mississippi, Arkansas and Texas Gulf regions and least in the spring. For the Missouri, South Atlantic, and Pacific Northwest regions, the increase is greatest in the summer and the least in fall. Temperature change under UIUC is greatest in summer and least in winter in these regions. The temperature increase in summer is 0.5 °C greater than the average annual increase. Under UIUC + Sulfate, a distinct change occurs where the Ohio, Upper Mississippi and Arkansas-White-Red regions register a slight cooling in

TABLE III
Mean daily temperature change (°C) in 7 major water resource regions

Scenario	3. S. Atl.-Gulf	5. Ohio	7. U. Miss	10. Missouri	11. Arkansas	12. TX Gulf	17. Pacific NW
Winter							
BMRC +1	1.14	1.94	2.10	1.63	1.59	1.24	1.33
BMRC +2.5	2.87	4.83	5.22	4.08	3.95	3.09	3.32
UIUC +1	0.66	0.55	0.69	0.80	0.38	0.49	1.08
UIUC +2.5	1.64	1.34	1.68	1.99	0.93	1.24	2.71
UIUC Sulfate +1	−0.06	−0.52	−0.56	−0.10	−0.48	−0.21	0.63
UIUC Sulfate +2.5	0.59	−0.14	−0.05	0.76	−0.26	0.25	2.11
Spring							
BMRC +1	1.21	1.44	1.56	1.38	1.61	1.52	1.10
BMRC +2.5	3.03	3.62	3.90	3.43	4.01	3.80	2.74
UIUC +1	0.83	0.80	0.69	0.73	0.57	0.53	1.08
UIUC +2.5	2.09	2.02	1.72	1.83	1.43	1.35	2.71
UIUC Sulfate +1	0.19	0.16	0.08	0.21	−0.16	−0.21	0.86
UIUC Sulfate +2.5	1.17	1.12	0.91	1.10	0.42	0.29	2.41
Summer							
BMRC +1	1.21	1.58	1.59	1.70	1.47	1.05	1.46
BMRC +2.5	3.03	3.94	3.95	4.24	3.68	2.64	3.65
UIUC +1	0.95	1.04	1.20	1.28	1.06	0.95	1.40
UIUC +2.5	2.37	2.61	2.99	3.19	2.62	2.37	3.48
UIUC Sulfate +1	0.40	0.63	1.10	1.19	0.65	0.54	1.33
UIUC Sulfate +2.5	1.57	2.09	2.96	3.17	2.10	1.80	3.46
Fall							
BMRC +1	1.05	1.47	1.58	1.33	1.30	1.14	1.05
BMRC +2.5	2.64	3.67	3.95	3.34	3.26	2.85	2.62
UIUC +1	1.04	1.04	0.89	0.79	0.89	0.85	0.89
UIUC +2.5	2.58	2.60	2.19	1.99	2.22	2.11	2.26
UIUC Sulfate +1	0.59	0.68	0.69	0.43	0.77	0.62	0.25
UIUC Sulfate +2.5	1.94	2.11	1.97	1.49	2.06	1.79	1.33

winter and spring. The greatest increases in temperature occur in the summer and fall in these regions.

The seasonal distribution of precipitation is also very important in the growth and management of crops. Higher spring and summer precipitation would lower demand for irrigation. In many regions, reduced fall and winter precipitation would reduce the reserves of water in snowpack and, ultimately, the water level in reservoirs, diminishing the supplies for irrigation, navigation, hydropower, fisheries and wildlife. A large increase in the winter and spring could increase the frequency of damaging floods and lower crop production because of water-logging, impediments to tillage, soil erosion, loss of nutrients by leaching and so on.

The seasonal distribution of precipitation is also different from the annual change in the seven regions represented in Table IV. Under BMRC, the largest percentage

TABLE IV

Seasonal precipitation (mm) at baseline and percentage change in precipitation under the climate change scenarios in 7 major water resource regions (MWRR)

Scenario	3. S. Atl.-Gulf	5. Ohio	7. U. Miss	10. Missouri	11. Arkansas	12. TX Gulf	17. Pacific NW
Winter							
Baseline (mm)	321	236	106	51	125	155	320
BMRC +1 (%)	−10	5	7	2	−13	−23	1
BMRC +2.5 (%)	−25	12	18	4	−32	−57	3
UIUC +1 (%)	0	11	18	13	24	22	4
UIUC +2.5 (%)	0	29	44	32	59	56	9
UIUC Sul +1 (%)	−3	25	24	11	15	5	13
UIUC Sul +2.5 (%)	−8	45	51	26	43	28	24
Spring							
Baseline (mm)	335	310	230	161	241	226	188
BMRC +1 (%)	−6	−7	5	6	−7	−10	−5
BMRC +2.5 (%)	−15	−16	13	14	−17	−24	−13
UIUC +1 (%)	−14	3	10	7	−2	−4	9
UIUC +2.5 (%)	−35	8	24	19	−5	−9	23
UIUC Sul +1 (%)	−32	0	6	1	−26	−30	8
UIUC Sul +2.5 (%)	−62	3	19	8	−43	−51	20
Summer							
Baseline (mm)	413	313	301	192	237	224	93
BMRC +1 (%)	−18	−12	−14	−20	−22	−20	−30
BMRC +2.5 (%)	−45	−30	−34	−50	−56	−51	−74
UIUC +1 (%)	7	0	7	46	51	36	150
UIUC +2.5 (%)	18	0	17	114	128	91	375
UIUC Sul +1 (%)	22	−9	−5	63	64	45	260
UIUC Sul +2.5 (%)	41	−15	−4	134	144	101	534
Fall							
Baseline (mm)	282	265	219	116	208	250	210
BMRC +1 (%)	−4	−7	−5	−8	−18	−18	5
BMRC +2.5 (%)	−11	−18	−14	−21	−46	−45	14
UIUC +1 (%)	28	20	18	37	37	34	53
UIUC +2.5 (%)	71	51	46	92	92	86	133
UIUC Sul +1 (%)	29	9	−4	23	25	29	91
UIUC Sul +2.5 (%)	71	32	8	66	72	76	184

declines in precipitation occur during summer in most regions. The Upper Mississippi and Missouri regions show increased precipitation during the winter and spring months. The Pacific Northwest and Ohio regions also show small increases in winter precipitation. Percentage precipitation increases are greatest in the summer and fall under the UIUC scenarios. Precipitation is decreased in the South Atlantic, Arkansas and Texas Gulf regions during the spring. Under UIUC + Sulfate, the decrease in spring precipitation in these regions is intensified. The South Atlantic region also shows a decline in winter precipitation. Summer precipitation declines slightly in the Ohio and Upper Mississippi regions, while the remaining regions experience their greatest increases in this season. Increases in the Ohio and the Upper Mississippi are greatest in winter.

4. Summary and Conclusions

Here we have presented the general methodology used in this study and the motivation behind it. In the papers that follow we first analyze the validity of the impact assessment models, EPIC and HUMUS, and conclude that they can reproduce historical conditions of crop yield and streamflow with a level of confidence sufficient for the geographical coverage and scale of this study. We then present the results of these model simulations for a wide range of possible climate changes. Using two GCMs, we explore a range of possible changes in climate that could occur based on differences in the degree of warming, the influence of sulfates, and the potency of the CO_2-fertilization effect.

Climate change over the conterminous United States, as given by the GCM results, are scaled to match two levels of global-mean temperature increase: 1 °C and 2.5 °C . By this procedure we span a range in uncertainty of the overall magnitude of future climate change. While the uncertainty in future climate change is difficult to access quantitatively, analysis indicates that the 1 °C increase in global-mean temperature is nearly certain to be exceeded within the next half century (Figure 2). Therefore, the range of impacts found for this set of scenarios (see Table I) are those likely to occur, even in the event that policies to control climate change are implemented. The likelihood of our scenarios that assume a 2.5 °C global-mean temperature change is more difficult to assess. This level of climate change could well be exceeded within this century, particularly in the case with no policy actions. It is also possible that this level might not be reached, but the impacts on crops, water resources and unmanaged ecosystems identified under these scenarios certainly cannot be considered as upper bounds on the possible impacts of climate change.

The different climate change models used to represent a range in how global changes would be translated into regional changes that affect agricultural and natural systems. The BMRC and UIUC projections of climate change over the United States differ both with respect to the degree of warming and the sign and amount of precipitation change. We will show that the choice of regional climate pattern has a substantial effect on impacts.

Simulations in the papers that follow consider two levels of atmospheric [CO_2]. We note that the impact of CO_2 on ecosystem function, especially on the water use efficiency and carbon uptake of plants, is not yet fully understood at the landscape scale. Therefore, the simulations are run both assuming that the effect of CO_2 will not change ($CO_2 = 365$ ppmv) and that CO_2 will influence ecosystems based on the parameters in the impact models ($CO_2 = 560$ ppmv) at double the pre-industrial concentration. Thus, the results presented represent a range of global and regional climate change plus a range in CO_2 fertilization effects.

The impacts calculations presented in the following paper concentrate on what can be termed physical impacts – changes in crop productivity and ecosystem composition for example. The combination of a range in assumptions (Table I) for global climate change, regional changes, and CO_2 fertilization effects results in a wide range in physical impacts. The actual range of possible impacts, however, is likely even larger. The calculations here, for example, assume that the absolute value of climate variability over a 30-yr time period is scaled simply from that in the base year. Changes in climate variability in the future could have significant impacts and this adds additional uncertainty to impacts results. Finally, changes in socio-economic driving forces such as population, technology and income levels are co-determinants of impacts. Here, we have concentrated on the physical impacts, where we demonstrate a very large uncertainty range. Inclusion of socio-economic interactions would be particularly challenging in a factorial design as presented here, but would add further to the range in impact outcomes.

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Notes

[1] The impact analyses were performed relative to a baseline climatology for 1960–1989. To be fully consistent, a small additional increment of anthropogenic temperature should be added to the SRES temperature change values presented here. For simplicity, since these calculations are used only for context, this has not been done.

[2] The probabilistic calculations did not include the possibility of some large, non-linear change in the climate system. The probability of such a change is difficult to estimate, since this may be

caused by behavior that is currently not well understood or modeled. It is generally thought that the probability of such a "state change" would increase with increasing global-mean temperature change.

[3] Even given the previous caveat about "state changes" in the climate system, the basic physics of the ocean's thermal inertia is robust and will not significantly change this conclusion. At later times, however, such state changes could significantly change the results.

[4] The atmospheric concentration of CO_2 in 2000 was 371 ppmv.

[5] Total biomass (or harvested) yield per unit of water consumed.

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