Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

GLOBAL CLIMATIC CHANGE EFFECTS ON IRRIGATION REQUIREMENTS FOR THE CENTRAL GREAT PLAINS

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INTRODUCTION

Change is inevitable, but variability is certain in weather, especially in the Great Plains. The Great Plains is considered the U.S. bread basket and certainly is critically important to national and even world agricultural productivity. The Great Plains agricultural crop productivity is dependent upon water, both from precipitation and groundwater. Groundwater from the vast Ogallala Aquifer in the Central Plains is predicted to continue to decline as long as irrigation remains viable considering escalating energy costs and farm production costs (seed, fertilizer, equipment, etc.). Water right transfers from agriculture to urban and industrial requirements will further exacerbate this inevitable resource strain. Labor or farm skills for the rapidly escalating advances in agricultural technology may become a limiting factor in the future, too. Weather directly affects the water requirements of crops and thus their irrigation requirement.

Climate change is controversial, as to warming or cooling and especially the cause, but the world data on increased atmospheric carbon dioxide (CO_2) and green house gases (GHGs) is incontrovertible. The impact of rising CO_2 is generally considered ‘positive’ in terms of photosynthesis and its effects on plant control of transpiration through stomatal regulation. GHGs likely impact only atmospheric solar transmittance both for short-wave (mainly by water vapor and ozone) and long-wave radiation (mainly by carbon dioxide, nitrous oxide, and methane). Many believe that GHGs contribute to the earth temperature rise from the so called ‘green house effect,’ but many leading scientists also believe that any warming cycle is potentially derived from plasma bursts or “sun spot activity’ on the sun and part of longer-term historical weather trends (many centuries).

CLIMATE FORECASTS

Climate or weather is a stochastic process that has a predictable component and a random component. The normal random part of climate and weather makes the discernment of any 'change' in climate difficult. El Niño-Southern Oscillation phenomena have been demonstrated to influences weather in many parts of the world. The El Niño-Southern Oscillation (ENSO) is characterized by its extremes -- El Niño is the warming cycle of the eastern tropical Pacific Ocean and La Niña is the cooling cycle. Figure 1 illustrates the most recent sea surface temperature (SST) anomalies in the tropical Ocean (Australian continent is visible in the lower left and the Mexico and Central America locations are in the upper right). The National Center for Environmental Prediction (NCEP) of the NOAA/National Weather Service predicts (Jan. 15, 2009 predictions) due to the La Niña conditions of SST that developed in December 2008 that the Central Plains air temperature in May-June-July 2009 will be above 'normal' in most of the Southern Great Plains and Southwestern U.S. (Fig. 2) and that the rainfall will be near normal (50:50 chance of being 'normal' (Fig. 3). This is useful information for 2009 crop management strategic planning (crop species selection, crop hybrid selection, irrigation planning, and even commodity hedging for crop sales or the futures market). They illustrate near-term weather predictions useful in irrigation management. These NOAA predictions are updated monthly, so anyone can keep current on the near-term weather predictions. The NCEP has shorter-term and longer-term predictions on their web site located at [http://www.cpc.ncep.noaa.gov/products/predictions//multi_season/13_seasonal_outlooks/color/churchill.php]. Figures 2 and 3 are U.S. examples showing interesting forecasts for the Central Great Plains for the 2009 summer.

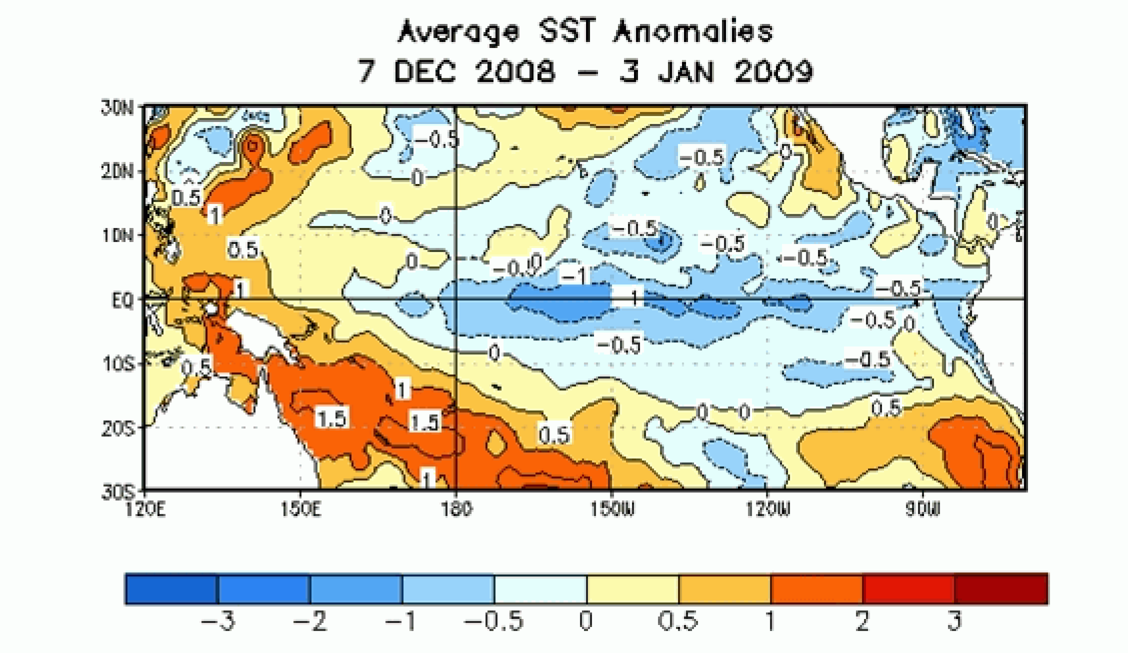

Figure 1. Average sea surface temperature (SST) anomalies (°C) for the four-week period 7 Dec. 2008 to 3 Jan. 2009. Anomalies are computed with respect to the 1971-2000 base period weekly means (Xue et al., 2003). From http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/ensodisc.html (viewed on 22 Jan. 2009).

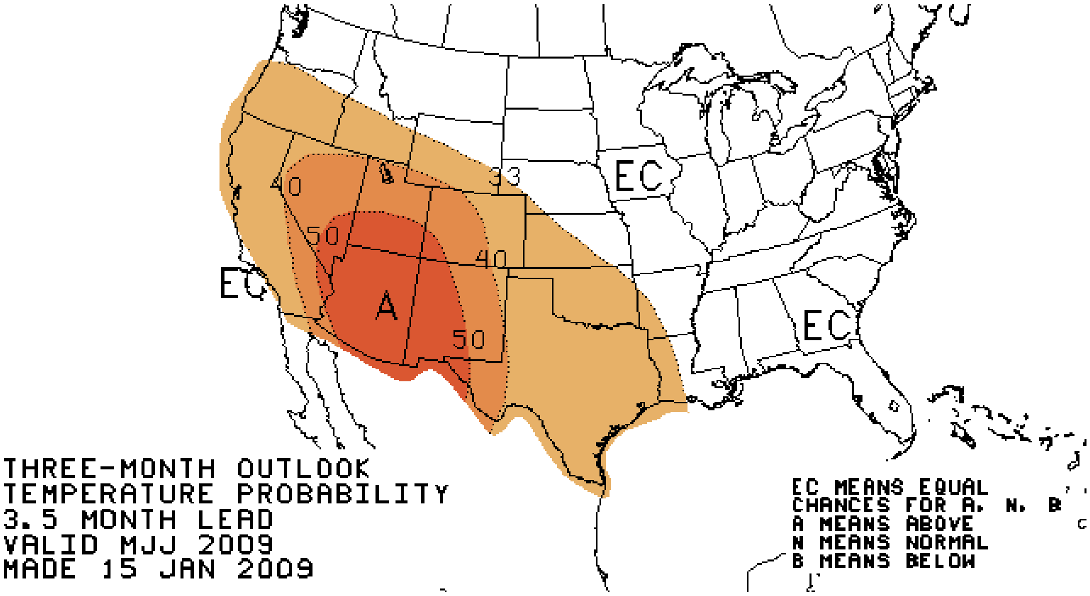

Figure 2. NOAA National Center for Environmental Predictions for May-June-July 2009 temperature from January 15, 2009 predictions using the ENSO SST using procedures from Saha et al. (2006).

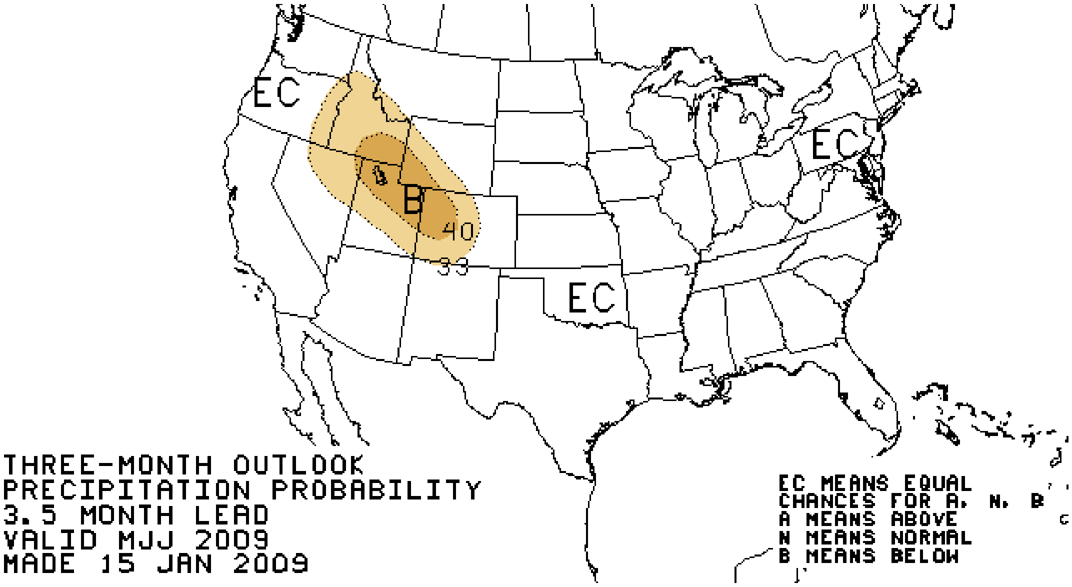

Figure 3. NOAA National Center for Environmental Predictions for May-June-July 2009 precipitation from January 15, 2009 predictions based on the ENSO SST using procedures from Saha et al. (2006).

CLIMATE CHANGE AND VARIABILITY

Increasing concentrations of GHGs in the earth's boundary layer make the earth's atmosphere opaque to long-wave radiation preventing long-wave radiation from escaping through the atmosphere. The trapped long-wave radiation in the earth's atmosphere is believed to alter the earth's radiation energy balance and thereby increasing the surface temperature. GHGs include carbon dioxide, water vapor, methane, nitrous oxide, chlorofluorocarbons, and other gases. Carbon dioxide (CO_2) concentration in the atmosphere has increased since the industrial revolution from the burning of carbon-based fuels (wood, coal, petroleum, etc.). Neftel et al. (1985) estimated that the preindustrial global atmospheric CO_2 concentration was in the range of 265-290 ppm (volume based) based on ice core samples from the Siple Station (West Antarctica). The longest CO_2 records are from the Mauna Loa Observatory, Hawaii (Fig. 4) from NOAA and the Scripps Institution of Oceanography, University of California, San Diego. Carbon dioxide concentrations have increased from 315 ppm in 1958 to 385 ppm in 2008. This increase in atmospheric CO_2 is generally attributed to deforestation and the burning of fossil fuels such as fuel oil, natural gas, and coal. The atmospheric CO_2 concentrations are expected to double from the preindustrial concentrations at some point in the 21st century (Ramírez and Finnerty, 1996). The annual mean CO_2 concentration growth rate has approximately doubled from 1 ppm yr^{-1} in the 1950s to about 2 ppm yr^{-1} since 2000.

Water vapor is also a GHG that is highly variable both spatially and temporally. Atmospheric water vapor is the result of evaporation from lakes, rivers, and oceans and evapotranspiration (ET) from land surfaces. 'Green house' warming should result in an increase in evaporation and ET because of increased surface temperature. However, the increased atmospheric water vapor will likely increase cloudiness. Exact prediction of cloudiness at a specific location is imprecise due to local elevation, position (latitude and longitude), and global winds. Increased clouds in some areas may increase the likelihood of convective and/or influence orographic precipitation. The clouds also reflect direct solar irradiance and scatter short-wave irradiance (diffuse solar radiation) reaching the earth's surface. Most expect at many global locations that net radiation, one of the most important surface energy balance parameters determining crop water use rates, will possibly be reduced with a feed-back effect to reduce 'green house' warming.

Ramírez and Finnerty (1996) reviewed the large uncertainties in the global 'green house' warming hypothesis. To summarize their review, they cited research results based on data from remote sensing during the 1979 to 1988 years that showed no obvious trend in atmospheric temperature over the 10-yr period; some statistical evidence that supported a 0.4°C decrease in temperature

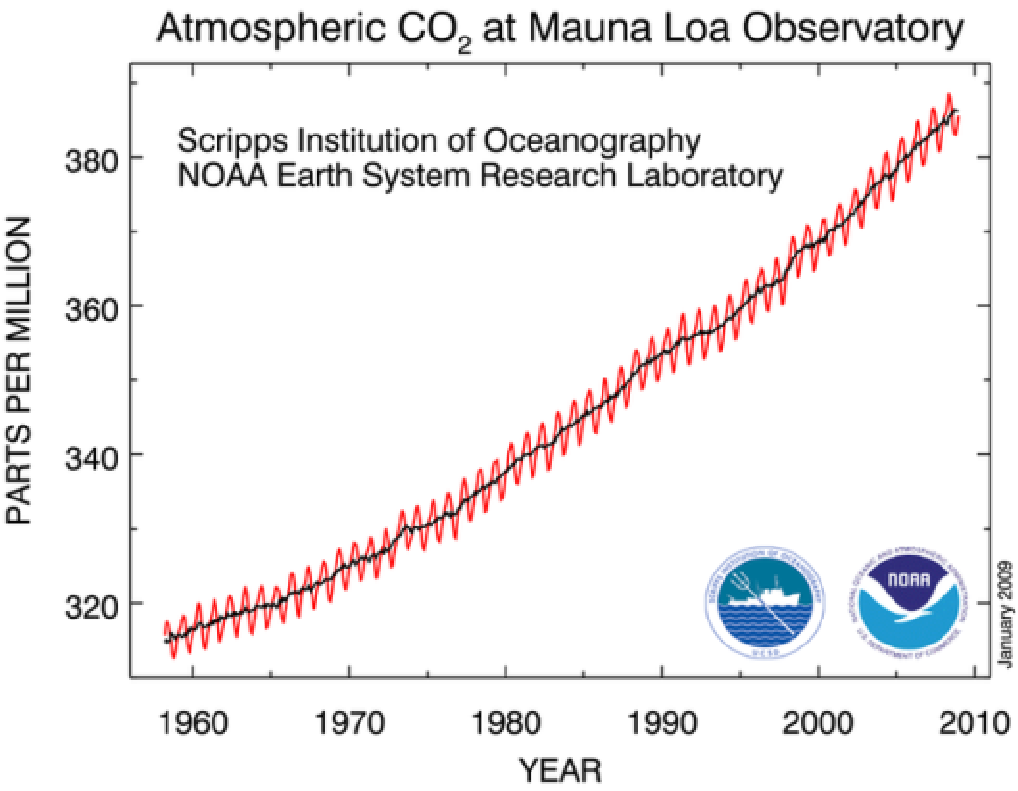

Figure 4. Volumetric CO_2 records from the Mauna Loa Observatory, HI from NOAA and the Scripps Institution of Oceanography, University of California, San Diego. The red (or gray in B&W) lines are the monthly mean data and the black (or darker in B&W) line is the annualized data. [Source: Dr. Pieter Tans, NOAA/ESRL (http://www.esrl.noaa.gov/gmd/ccgg/trends/), viewed Jan. 23, 2009].

for the northern hemisphere from the years 1940-1980; a global temperature rise less than 0.4°C from 1880 to 1970; and according to the statistical analysis of climate records and from an analysis of global climate records from land and the oceans around the world, a temperature increase over the past 90 years that was in the range of 0.4-0.6 °C. Singer and Avery (2007) cited studies from 450 peer-reviewed authors and co-authors that found reason to doubt the 'global warming hypothesis'. Avery (2008) indicated that these concerns did not mean that fossil fuels use and other GHG sources shouldn't be reduced (Wang, 2008), but that additional engineering solutions including greater efficiency in transportation, energy efficient buildings, and greater planning for droughts and shifting patterns in water availability should be included.

CO_2 and Plant Response to Climate Change

Rising atmospheric CO_2 has been called 'atmospheric fertilization' because greater concentrations in CO_2 will lead to greater rates in photosynthesis.

Bisgrove and Hadley (2002) provide a useful review of global warming on plant responses. Because rising CO_2 and a possible temperature increase and possible decrease in precipitation could dramatically alter future climatological records, the increased frequency of extreme weather events (droughts, floods, colder winters, extreme heat waves, etc.) is widely speculated but nearly impossible to quantify. Global climate change will impact other factors of irrigated agriculture, too, like weeds (both species and their growth rates) and diseases.

Current carbon dioxide concentrations limit plant photosynthesis based upon the following photosynthesis equation:

$$\begin{aligned} &\mathbf{6\ CO_2\ (carbon\ dioxide) + 6\ H_2O\ (water) \longrightarrow} \\ &\mathbf{(with\ energy\ from\ sunlight) \longrightarrow} \\ &\mathbf{C_6H_{12}O_6\ (glucose,\ a\ carbohydrate) + 6\ O_2\ (oxygen)} \end{aligned} \qquad \ldots[1]$$

Green house growers of horticultural crops have raised the concentration of CO_2 in the enclosed greenhouses to increase crop growth and yield for many years. Research has shown that doubling of CO_2 concentrations will lead to approximately a 40-50% increase in the growth of plants (Kimball et al., 1983; Poorter, 1993). Kimball (1983) reported that doubling CO_2 concentrations increased biomass productivity on average by 33% in vegetal species studied with a decrease in evapotranspiration. Poorter's (1993) review reported that herbaceous crop plants produced more biomass than herbaceous wild species (58% vs. 35%), and potentially fast growing wild species had greater biomass than slow growing species (54% vs. 23%). In addition, he found that leguminous species capable of symbiosis with nitrogen fixing organisms had larger responses to CO_2 compared with other species. Poorter (1993) also indicated that there was a tendency for herbaceous dicotyledons (broadleaved plants) to show a larger response than monocotyledons like grasses. Plants, however, adapt to elevated CO_2 concentrations, and the long-term exposure to elevated CO_2 is much less than short-term elevated CO_2 exposure. In addition, it has been reported that some species in an elevated CO_2 environment have a lower stomata density. Nonetheless, the effect of increased CO_2 remains a significant factor in increasing photosynthesis and increasing water use efficiency.

Carbon dioxide concentration is a main mechanism that plants use to regulate the respiration rate and the rate of absorption of CO_2 for photosynthesis by changing the stomatal resistance. An increase in atmospheric CO_2 will increases the leaf's internal CO_2 absorption rate mainly for C3 species. The plant will respond by increasing its stomatal resistance (a partial closing of the stomate pore), which reduces the CO_2 absorption rate to maintain a desired internal substomatal CO_2 concentration. Kimball and Idso (1983) reported stomata responded to increased CO_2 by regulating photosynthesis in more than 50 species. Transpiration is reduced by this increased stomatal resistance and leaf temperature is increased (Morison, 1987). An increase in stomatal resistance will reduce the plant transpiration rate, thereby increasing the plant water use efficiency (assimilation per unit transpiration). Most agricultural plants are categorized by their photosynthetic mechanisms that control the chemical processes in their glucose manufacture from CO_2 and H_2O (water) [eqn. 1] as C3 and C4 species because of their photosynthetic pathways [for a more thorough review of the impacts of elevated CO_2 and temperature on photosynthesis see Sage (2002) and Ainsworth and Rogers (2007)]. Other plants are called CAM that stands for Crassulacean Acid Metabolism after the plant family in which it was first found (*Crassulaceae*) and because the CO_2 is stored in the form of an acid before use in photosynthesis. CAM species are mainly succulents such as cactuses and agaves. Common C3 species include wheat, cotton, soybean, and most legumes like alfalfa while common C4 crop species include sorghum, corn, and sugarcane. Some grass species are either C3 or C4 types. C3 plants fix atmospheric CO_2 directly onto 5 carbon sugar RuBP (ribulose bisphosphate) and thus into glucose. C4 plants first fix atmospheric CO_2 into 4-carbon acids in the mesophyll of the leaf and decarboxylate the 4-carbon acids in the bundle sheath cells where the CO_2 is then fixed by RuBP carboxylase (all of this takes place during the day). CAM plants first fix atmospheric CO_2 into malic acid and other 4C-acids at night. During the day, malic acid is decarboxylated and the CO_2 released is then fixed by rubisco (all of this takes place in the same cell). Generally, the C4 photosynthetic pathway is considered more water efficient than C3 species. However, C3 species typically are more sensitive to elevated CO_2 (Rosenberg et al., 1988). The carbon-fixing efficacy of Rubisco depends on the ratio of CO_2:O_2. For C3 plants, this is closely coupled to ambient conditions, and efficacy is approximately 2/3 while for C4 plants, the CO_2:O_2 ratio is much greater and carboxylation efficacy is nearly 100% (Ainsworth and Rogers, 2007). Therefore, increased CO_2 in air should directly increase assimilation for plants with C3 physiology. For C4 plants, the elevated CO_2 effects are indirect due to increased stomatal resistance and reduced transpiration.

EFFECTS OF CLIMATE ON IRRIGATION REQUIREMENT

Two main modes have been used to estimate long-term climate change on crop water requirements and irrigation requirement. The earlier and simpler ones used were sensitivity analyses of regular ET equations and/or crop simulation models to estimated climate scenarios based on projections of weather scenarios (Rosenberg, 1981). Several examples are illustrated: Warrick (1984) used 1930s weather data with a statistical yield model that showed a 50% wheat yield decline in the Great Plains; Terjung et al. (1984) used a yield model with four climate scenarios for air temperature, solar irradiance, and precipitation to find that ET and total applied irrigation were sensitive to the climatic scenarios and locations used; Liverman et al. (1986) reported lower dryland yields under cloudy, hot, and dry climates; and Rosenzweig (1985) suggested that in the Southern Great Plains spring wheat varieties might be required to replace winter wheat cultivars due to colder winter temperatures with a doubling of CO_2.

Most recent efforts have used general circulation models (GCMs) from various global climate research efforts (Rosenzweig, 1990). Many GCM models have been developed (see Hansen et al., 1983; Smith and Tripak, 1989; and Manabe and Wetherald, 1987 for explanations and examples). The Intergovernmental Panel on Climate Change (IPCC; see http://www.ipcc.ch/) that was established in 1988 has attempted to serve as the 'clearing house' and 'repository' to provide reports at regular intervals that can become standard works of reference to be widely used by policymakers, experts and students. Houghton et al. (2001) is an example. The 4th Climate Change 2007 Synthesis Report was just released in 2008 (see the IPCC web site above).

Most recent attempts to investigate climate change on irrigation have used GCMs as a climate basis (Allen et al., 1991; Ramírez and Finnerty, 1996; Peterson and Keller, 1990; Rosenzweig, 1990; Smith et al., 2005; Rosenberg et al., 1999; Brumbelow and Georgakakos, 2001; Thompson et al., 2005; and Reilly et al., 2003). Many GCMs were simulations under 2 X CO_2 concentrations that result in global temperature increases of 2-5°C, with regional temperature changes from -3°C to +10°C. Precipitation fluctuates in the range of -20% to +20% from current regional averages (Peterson and Keller, 1990). GCMs generally are limited in resolution to a 0.5° x 0.5° grid. The 'predicted' weather represents that whole grid. They simplify the spatial and temporal scales of global fluid dynamics as well as the complex physics that drive the exchanges of water, heat, and energy between the earth's atmosphere, oceans, and continental land masses on those grids; however, in most cases GCMs still require near 'super' computers to make all the complex computations necessary. Hence, they are typically operated at major universities and/or governmental agencies. GCMs' spatial scales are considered too large to accurately capture smaller scale terrain and other heterogeneities on the local and regional climate scale. Different GCMs use different modeling strategies and often produce different model climates. Therefore, there is a rather large uncertainty associated with the predicted potential climate changes. Two widely used GCMs are the BMRC (Australian Bureau of Meteorology Research Center) (McAveney et al., 1991) and the UIUC (University of Illinois at Urbana Champaign (Schlesinger, 1997). Table 1 illustrates the GCM simulation climate scenarios used by Smith et al. (2005) in their series of papers by the two above GCMs. The BMRC model temperatures changes were slightly larger than the 'global' scenarios while the precipitation was reduced over the U.S. For the UIUC model without sulfates, the temperatures matched the 'global' scenarios well, but the precipitation was increased considerably compared with the BMRC model. For the UIUC + Sulfates model runs, the simulated temperatures were lower than the BMRC scenarios and the precipitation increased as a mean over the conterminous U.S. Figure 5 shows the predicted annual mean temperatures for the conterminous U.S. from Smith et al. (2005). The Australian model (BMRC) predicts a slightly warmer Central Great Plains for the +1°C GMT scenario and a smaller temperature change for the western parts of the Central Great Plains, except the eastern portions and the southern parts (Texas, Oklahoma). It predicts a significantly drier trend (Fig. 6) for the Central Great Plains region for both scenarios. The Univ. of Illinois model without sulfates (UIUC) predicted a warmer Central Great Plains for both scenarios and an increased precipitation in the Central Great Plains. When sulfates were included in the UIUC model, it predicted a more modest temperature change with only a small precipitation increase for the +2.5°C scenario.

Table 1. Annual mean change in temperature and precipitation over the conterminous United States by the GCM climate change scenarios (scaled to the 1960 to 1989 historical climate data). Source: Smith et al. (2005).

GCM	GMT[1]	Temp. Change (°C)	Precip Change (mm)
BMRC	1.0	1.5	-39
	2.5	3.6	-98
UIUC	1.0	0.9	98
	2.5	2.3	245
UIUC + Sulfates	1.0	0.4	132
	2.5	1.6	287

[1] GMT is global mean temperature

Climate change (changes in temperature and/or precipitation regimes) would likely lead growers to change crops, cultivars, and management practices, including irrigation, to mitigate any adverse effects or to take advantage of more favorable conditions. Peterson and Keller (1990) suggested that higher temperatures and reduced precipitation could increase crop water demand in some areas and prompt the development of irrigation in regions previously devoted to dryland or rainfed cropping. They reported that the percentage of cropland irrigated in the western U.S. increased when global mean temperature (GMT) exceeded 3°C and a decline in production resulted from inadequate water for irrigation. Tung and Douglas (1998) found in a study of crop response to GCM projected climate change with double atmospheric CO_2 concentrations that the higher ET effects outweighed the effects of CO_2 fertilization in some areas of the U.S., and they suggested that irrigation could mitigate effects of climate change.

In another simulation study of CO_2 induced climatic changes, Allen et al. (1991) reported higher ET demand and irrigation water requirement for alfalfa, but decreases for winter wheat and corn, although the GFDL (Geophysical Fluid Dynamics Laboratory) model had increased corn irrigation requirement (Fig. 7b), in the Great Plains due to higher temperatures and changes in precipitation patterns (Fig. 7). Allen et al. (1991) used CGMs from Princeton Univ. (GDFL, Geophysical Fluid Dynamics Laboratory) and the GISS (Goddard Institute for Space Studies) (Hansen et al., 1984).

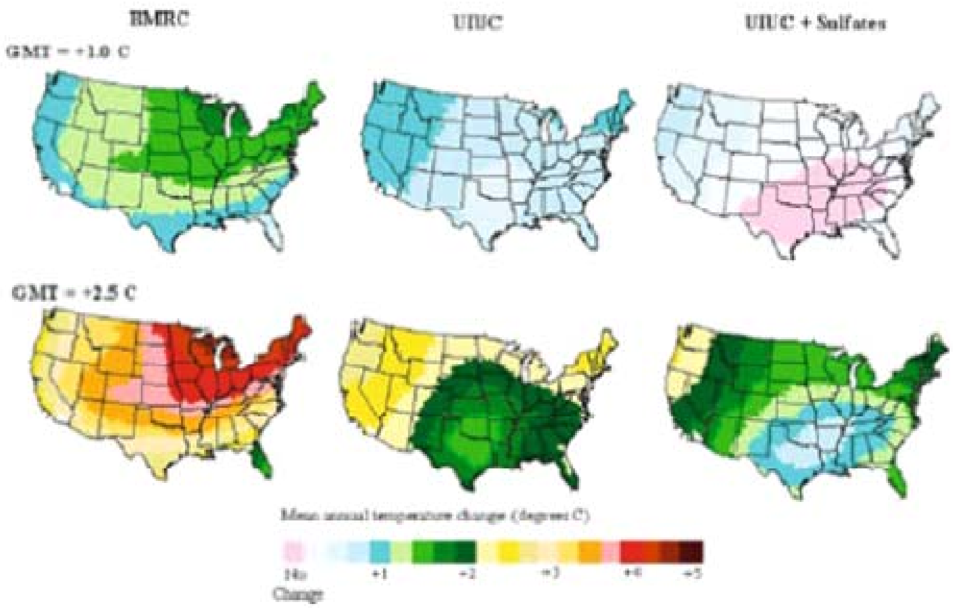

Figure 5. Annual mean temperature change from baseline for three GCMs for two global mean temperature scenarios. Source: Smith et al. (2005). Note: 5°C change = 9°F change.

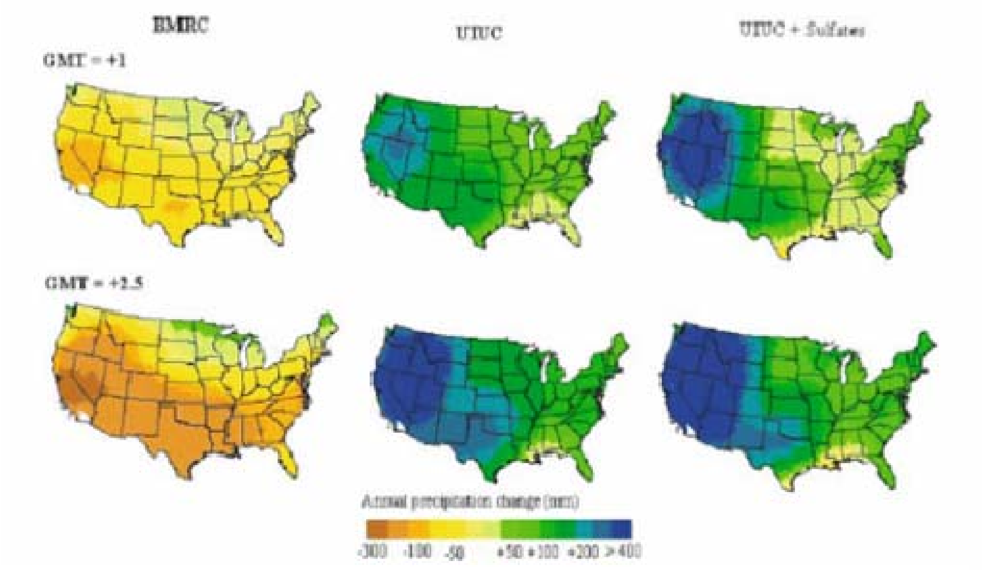

Figure 6. Annual precipitation change from baseline for three GCMs for two global mean temperature scenarios. Source: Smith et al. (2005). Note: 200 mm change = 7.88 in. change.

Brumbelow and Georgakakos (2001) used GCMs from the Canadian Centre for Climate Modeling and Analysis Global Coupled Model 1 (CGCM1) and some from the UK Meteorological Office Hadley Climate Model version 2 (HadCM2) together with crop simulation models and USDA soils data (STATSGO) (NRCS, 1994) to estimate climate change impacts on crop productivity and irrigation in the conterminous U.S. They are one of the few simulation studies that validated model outputs with U.S. county yield data for a 19-yr calibration period. Table 2 summarizes their mean irrigation requirement changes in four Great Plains regions and for three crops. Figure 8 illustrates their predicted change in corn yield and irrigation requirement for the conterminous U.S. The predicted mean change in irrigation requirement in most of the Central Great Plains had a ‘neutral’ change (-10 to 10 mm). The western portions of the Central Great Plains had a more pronounced decrease in irrigation requirements from -40 to -11 mm. Predicted irrigated corn yields decreased 600 to 1,200 kg ha^{-1} (~10 to 20 bu ac^{-1}).

Table 2. Regional mean changes in irrigation requirement in mm and % change (in parenthesis) for three crops in the Great Plains. Source: adapted from Brumbelow and Georgakakos (2001).

Region	Soybean	Winter Wheat	Corn
Northwestern GP	na[1]	-25.9 (-39%)	-15.1 (-75%)
Northeastern GP	2.5 (31%)	-16.0 (-49%)	-0.8 (-100%)[2]
Southwestern GP	30.6 (86%)	28.1 (22%)	-15.7 (50%)
Southeastern GP	23.9 (156%)	16.1 (56%)	-4.0 (43%)

[1] ’na’ region was not simulated.

[2] Percent appears large due to the small value of the ‘baseline’ irrigation requirement (< 10 mm).

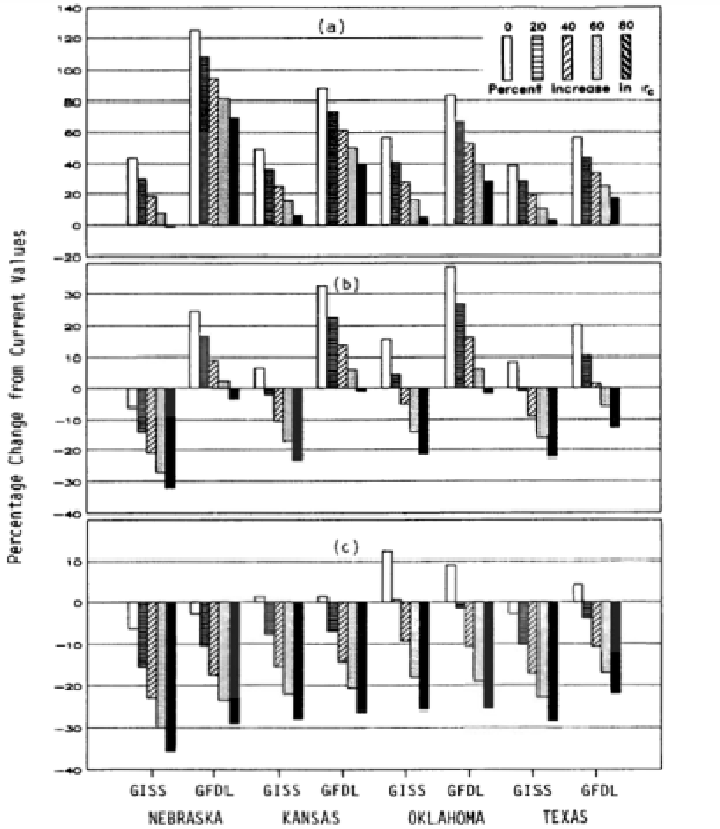

Figure 7. Projected percent change in seasonal irrigation requirement from ‘baseline’ (current values) for four Great Plains states for five levels of simulated increase in bulk stomatal resistance from increased CO_2 for (a) alfalfa [top]; (b) corn [center]; and (c) winter wheat [bottom]. Source: Allen et al. (1991).

Strzepek et al. (1999) modeled water supply and demand for irrigation in the U.S. Corn Belt with climate change using a suite of GCM-derived scenarios of climate change. They found that producers

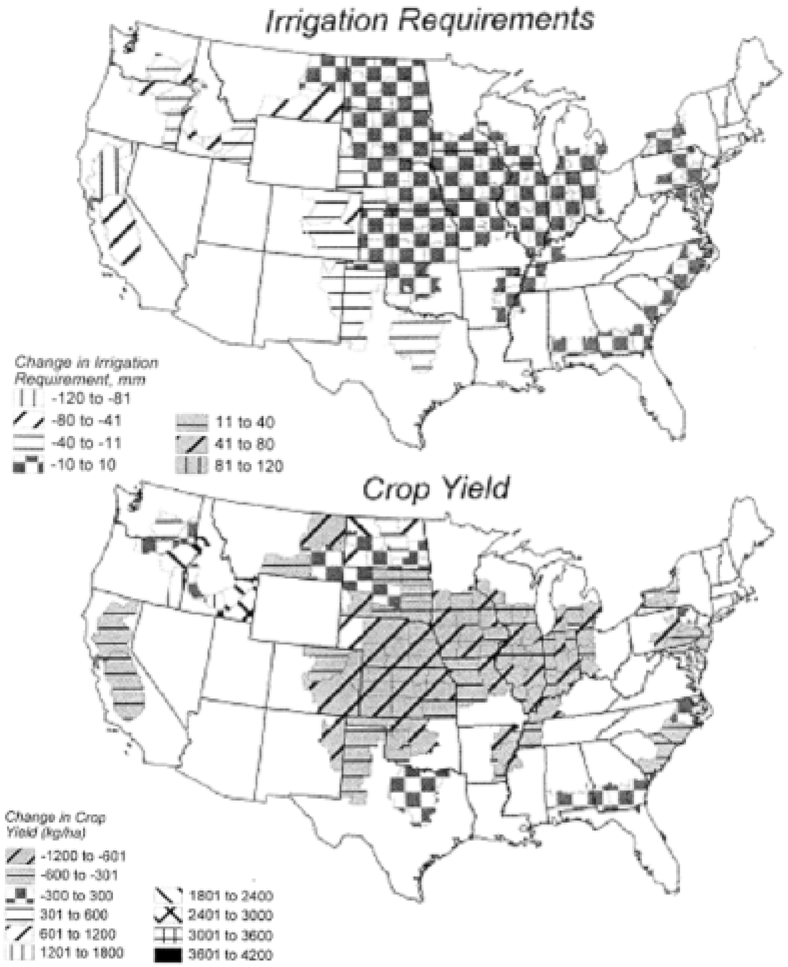

Figure 8. Changes in mean corn irrigation requirements (top) and crop yield (bottom). Source: adapted from Brumbelow and Georgakakos (2001).

would benefit from utilizing irrigation, but they also indicated a concern in the spring for excessive soil water perhaps requiring more subsurface drainage. In the near term, they suggested that the relative abundance of water for U.S. agriculture can be maintained. They suggested that progressively greater changes in agricultural production and practices from climate change impacts were expected by 2050 and beyond in agreement with Reilly et al. (2001).

SUMMARY

Accurately predicting global climatic change impacts on the Great Plains remains largely uncertain. Nevertheless, future environments in the Central Great Plains will have elevated CO_2 and GHGs in the atmosphere that will impact the surface energy balance, photosynthesis, water use efficiency, cloudiness, and precipitation, and likely extreme weather phenomena. These all have some degree of uncertainty and probably more variability than past climatic patterns. Most reports indicate few impacts immediately; however, in the out-years (~>2050) we should begin seeing significant shifts in weather in the Great Plains. Some will be ‘positive’ (growers need to be prepared to utilize) while others might be more ‘adverse’ (growers will need to make strategic decisions to minimize impacts). Undoubtedly, some changes in Great Plains agriculture will be necessitated, e.g., crop hybrid changes, crop species adjustments, crop management, etc., and irrigation will continue to be a significant factor, especially in the Central Great Plains, for mitigating global climate change impacts and providing national food security.

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