1. Climate Variability, Predictability, and Change: *An Introduction*

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Introduction

CLIMATE SCIENCE

For about the last three decades scientists from a variety of related disciplines have applied three-dimensional, time-dependent models of fluid flow to study the atmosphere on time scales of minutes to a few days and spatial scales of meters to a few thousand kilometers. About two decades ago atmospheric modelers began routine simulations of the global circulation using three-dimensional grids on time scales beyond one year, and hence launched the science of climate modeling. Addition of this new tool to the list of methods used by those studying climate called for a new field of study now known as climate science. Evolution of this sub-discipline has resulted in unprecedented opportunities to simulate climates that evolve concurrently with changes in atmospheric greenhouse gases—a major driver of future climates—in a physically consistent way. The prospect of future anthropogenically induced changes to global and regional climate of magnitudes to have measurable impact has brought new urgency to the study of climate. Concurrently, population growth and economic development have created new dependencies and risks relating to possible changes in means and extremes of climate from conditions observed during the instrumental record. Because of this, the future of climate science is now more than ever tied to the future of climate-sensitive societal activities. Herein we summarize the state of climate science research in the Midwestern USA.

GLOBAL CLIMATE CHANGE: AN OVERVIEW

The 2007 report from the Intergovernmental Panel on Climate Change contained the most unequivocal statements regarding global climate change of any such report issued to date (IPCC 2007). Their major findings include the following:

- We have "*very high confidence* that the global average net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 [+0.6 to +2.4] W^{m}−2"
- "Warming of the climate system is unequivocal. Palaeoclimatic information supports the interpretation that the warmth of the last half

century is unusual in at least the previous 1,300 years."

- "At continental, regional and ocean basin scales, numerous long-term changes in climate have been observed." Although the committee also note, "Some aspects of climate have not been observed to change."
- "Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations."
- "For the next two decades, a warming of about 0.2°C per decade is projected for a range of SRES emission scenarios. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected. . . . Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would *very likely* be larger than those observed during the 20th century."
- "There is now higher confidence in projected patterns of warming and other regional-scale features, including changes in wind patterns, precipitation and some aspects of extremes."

For the majority of scientists the conclusion is clear. The global climate system has evolved, and continues to evolve, principally (though not exclusively) due to human activities. We are at a nexus, where unequivocal evidence exists for anthropogenic forcing of climate change, and unprecedented international efforts are being engaged in mitigation of, and adaptation to, climate change. A critical component of these efforts is focused on improved quantification of how changes in global climate have been manifest regionally and how future changes may be manifest at the regional/local scale. In this volume we present examples of these analyses.

PURPOSE OF THIS VOLUME

Herein we focus on climate variability, predictability, and change in the Midwestern USA (figure 1.1) and provide detailed assessments of past climate variability and possible future states. The contributions presented derive from a workshop held in October 2007 at Indiana University, which brought together climate scientists from across the Midwest to document the state of the art regarding the predictability, variability, and possible changes in the Midwestern climate, to identify remaining gaps in our knowledge, and to articulate possible strategies to address those gaps.

The climate system operates across a wide spectrum of time scales, from "short-term" climate variability that might reasonably be characterized using measures of inter-

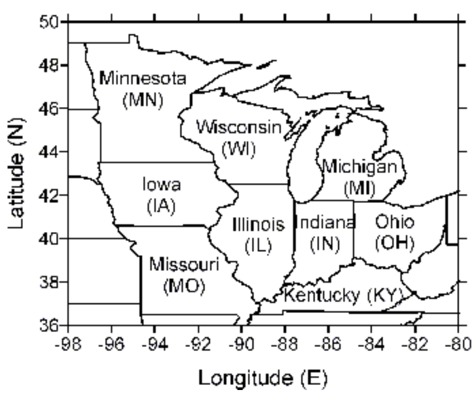

Figure 1.1. A map showing the Midwestern region and identifying the states that compose the Midwest.

annual to inter-decadal variability and that may or may not be predictable depending on the source, to longer-term evolution of the mean climate state and/or variability therein. We focus on a variety of parameters in the past and current climate over the Midwestern USA in order to quantify the historical climate and provide an assessment of variability, and assess the likelihood of change in the mean and variability of the climate over the past one hundred years and the coming one hundred years respectively. In doing so we are limiting our analysis and presentation to essentially the period for which observational records exist and for which simulations from multiple coupled Atmosphere-Ocean General Circulation Models (AOGCMs) are deemed to exhibit skill and are readily available (IPCC 2007).

"Climate change" refers to a shift in mean climate conditions in a specific region, whereas "climate variability" refers to temporal fluctuations around the mean. A further focus of this volume is on a key question in climate science: whether a change in the mean is always associated with a change in the variability (e.g., variance) of a given climate parameter, and indeed whether an increase in the mean de facto results in an increase in the variability around that mean and hence a change in climate extremes.

The Midwestern USA

Differing definitions of the Midwestern USA are present in the literature. We focus predominantly on the upper eight states shown in figure 1.1 and thus use a definition coincident with the definition of the Midwest used in the National Climate Assessment program (Easterling and Karl 2000). However, some chapters also include data from Kentucky and hence expand the definition to nine states (listed in alphabetical order: Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin). These nine Midwestern states comprise approximately 21% of the nation's population and economic activity (the cumulative state domestic product is approximately 21% of the gross domestic product for 2004) (table 1.1).

Farming, manufacturing, and forestry characterize the Midwest. Of these, agricultural activity dominates land use, with up to 89% of the land area of the states being used for agricultural purposes (table 1.1). As a result the Midwest produces most of the nation's corn and soybeans. Climate variability and extreme weather play a key role in dictating crop yields. For example, the region, like much of the Great Plains, experienced greatly depressed crop yields during the droughts of the 1930s. By some estimates yields of wheat and maize in the Great Plains were 50% lower during the 1930s than in the prior decade (Rosenzweig and Hillel 2008). Outbreaks of pests and disease are also critically linked to meteorology and climate. For example, the epidemic of southern leaf blight fungus of maize (*Helminthosporium maydis*) that affected the central United States during 1970–1971 led to a 15% reduction in national maize production and $1.09 billion in economic losses, and was spread from Mississippi into the Midwest by winds associated with tropical storm activity in the Gulf of Mexico (Rosenzweig and Hillel 2008). Equally, changes in land use and land cover associated with agricultural activities have led to changed surface energy and moisture budgets and thus changes in boundary layer properties and local to regional thermal and moisture regimes (Cotton and Pielke 2007).

The Great Lakes, which form the world's largest freshwater lake system, serve as recreational centers and a transportation link via the St. Lawrence Seaway to the Atlantic Ocean. Additionally, the Midwest is traversed by the Mississippi and Ohio rivers. Changes in hydrologic regimes may influence river discharge and lake levels and hence have a profound effect on natural and agro-ecosystems, tourism, and commerce. Equally, over the entire nation, the United States of America uses more than 500 billion liters of freshwater per day, with over 40% going to cooling power plants and approximately the same amount being used for irrigation. Changes in hydrologic regimes (e.g., the amount and/or timing of precipitation; see chapter 9) may increase pressure on water supplies even in regions that historically have not exhibited water scarcity. The severity of this problem with respect to electricity production is exemplified by the drought in France during 2003 that caused loss of 15% of the nuclear electricity generation for five weeks due to reductions in the

Table 1.1. Descriptive statistics for each Midwestern state, along with estimates of their greenhouse gas (GHG) emissions

	Area of state (sq. miles)	Population in 2006	Gross state product (2004)	Land in farms in 2002	1990 Total GHG emissions (MMTCE)	Fraction of GHG from Energy/ Agriculture	2000*/2002** Total GHG emissions (MMTCE)
Illinois	55,583	12,831,970	478,966 (4.5)	27.3 (77)	66.1	86/3	
Indiana	35,867	6,313,520	208,834 (1.9)	15 (66)	61.3	93/3	
Iowa	55,869	2,982,085	100,853 (0.9)	31.7 (89)	17	72/18	32.8*
Kentucky	39,728	4,206,074	125,021 (1.2)	13.8 (54)	35.4	84/3	
Michigan	56,803	10,095,643	344,954 (3.2)	10.1 (28)	57.4	NA	62.59**
Minnesota	79,610	5,167,101	206,216 (1.9)	27.5 (54)	22.5	85/10	
Missouri	68,885	5,842,713	186,018 (1.7)	30.0 (68)	29.3	86/8	
Ohio	40,948	11,478,006	385,373 (3.6)	14.6 (58)	88.9	85/2	
Wisconsin	54,310	5,556,506	193,900 (1.8)	15.7 (45)	27.1	87/9	

Population estimates from the Census Bureau http://quickfacts.census.gov/qfd/states/.
GHG inventory data available from http://www.epa.gov/climatechange/emissions/state_ghginventories.html.

Gross state product is in millions of chained 2000 dollars (data from Werneke and DeBrandt [2006]). Number in parentheses is percent of U.S. gross domestic product.

Land in farms is given in millions of acres (data from Werneke and DeBrandt [2006]). Number in parentheses is percent of total state land that is agricultural.
The GHG inventory methodology changed between the 1990 inventories and the subsequent inventories shown in this table. Of the Midwestern states, only Iowa and Michigan have updated their inventories since 1990.

availability of water for cooling purposes (Hightower and Pierce 2008).

The Midwest is also home to a number of important metropolitan centers, including Chicago, Detroit, Indianapolis, and Columbus, which rank as the third, eleventh, twelfth, and fifteenth most populous urban areas in the United States. There is considerable evidence that these, and other, urban areas cause substantial changes in precipitation and severe weather regimes due to enhanced emission of cloud condensation nuclei (CCN), changes in surface roughness and low-level convergence, and addition of heat and moisture (see chapters 19, 20, and 22 herein and Cotton and Pielke 2007). Additionally, increasing urbanization in the region may increase the vulnerability of the populace to climate change via increased exposure to climate risk such as unhealthful temperatures (resulting from the urban heat-island effect; Schoof, Pryor, and Robeson 2007).

Climate Variability, Predictability, and Change in the Midwestern USA

GLOBAL AND CONTINENTAL CONTEXT

Climate change over the Midwestern USA is best interpreted in the spatial context of global and continental tendencies. Annual minimum and maximum temperatures for the continental United States are shown in figure 1.2. For the Midwest, the most notable feature is the north-south temperature gradient, which is due primarily to low temperatures to the north in winter (see chapter 2). Global projections of climate change imply larger temperature increases over the poles than over the equator, which would suggest that isotherms will migrate northward, with northern isotherms moving farther than southern isotherms over the Midwest. This seems to be generally true for the annual mean but not uniformly so for all seasons (see chapter 2) or for daily maximum and minimum temperatures (e.g., the warming hole discussed in chapter 3). Observations of mean U.S. temperature since 1975 show a notable warming trend (~1.1°C over 32 years) (NOAA 2008) that is consistent with temperature increases over other large land masses at mid to high latitudes in the Northern Hemisphere. Mid-continent areas are warming more than coastal areas, and winters have been warming more than summers. Globally, daily minimum temperatures increased more than daily maximum temperatures until about the mid 1980s. Since that time, global daily maximum and minimum temperatures have been rising at about the same rate (IPCC 2007). While the northern hemisphere land masses warmed by approximately 0.3°C per decade between 1979 and 2005, averaged over the entire Midwestern USA the warming rate was 0.5°C per decade, with most of this change being contributed from increases in fall and winter (see chapters 2 and 7). Nighttime temperatures in the Midwest are rising more than daytime temperatures, thereby leading to a reduced diurnal temperature range, unlike the global diurnal temperature range, which has been constant in recent years.

The historical climatological pattern for U.S. precipitation (figure 1.3) has high annual amounts in the eastern half of the United States and low values in the west (excepting coastal Washington and Oregon), with superposed highest regional

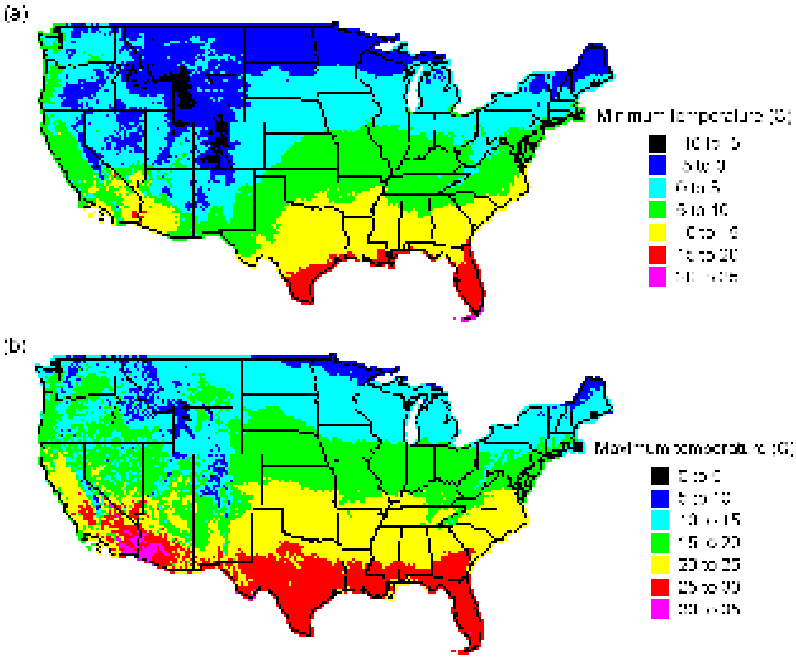

Figure 1.2. Climatological normals (1971–2000) for (a) annual minimum temperature (°C) and (b) annual maximum temperature (°C) over the contiguous U.S., computed using data from the PRISM Group, Oregon State University, http://www.prismclimate.org.

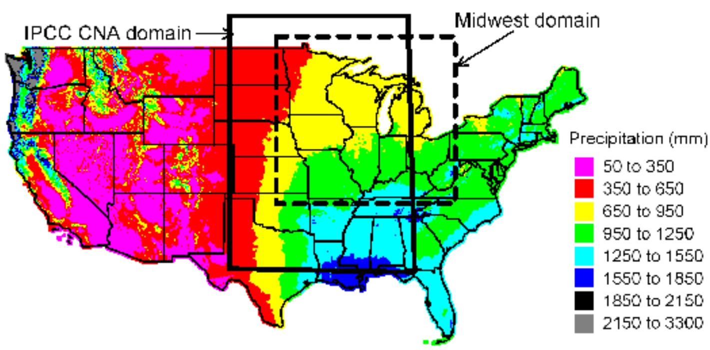

Figure 1.3. Annual average precipitation for 1971–2000 over the contiguous United States, computed using data from the PRISM Group, Oregon State University, http://www.prismclimate.org. Also shown is the Midwest domain used herein and the central North American region described in the Fourth Assessment Report of the IPCC.

precipitation in the southeast quarter and less but still high amounts in the northeast. This overall pattern puts the Midwest in the unique location of having a large climatological east-west gradient on its western boundary (separating the semi-arid or steppe climate to the west from the temperate continental climate over the Midwest) and north-south gradient throughout (separating the subtropical humid climate to the south from the temperate continental Midwest, see chapter 9). Future changes in precipitation, in contrast to temperature, are not likely to consist of a simple shift of current patterns. As discussed herein, changes in U.S. precipitation to date are more complex and show regionally specific behaviors and high variability. The United States has generally experienced a trend of increasing precipitation in the latter half of the twentieth century, but due to the high variability trend detection is very challenging (see chapters 9 and 12).

CLIMATE OF THE MIDWESTERN USA

As described in several of the chapters contained in this volume, the Midwestern USA has a strongly continental climate, though hot summers are mitigated in part by the presence of the Great Lakes (see chapter 21). Only the southwest portion of the region exhibits mean daytime maximum temperatures in excess of 32°C (approximately 90°F) (Burt 2004). The region experiences relatively cold winters (again mitigated in part by the Great Lakes) that result in mean daily minimum temperatures in January of below -18°C (approximately 0°F) in the northwest of the region (Minnesota and parts of Wisconsin, see chapter 7). Large diurnal variations in temperature are occasionally experienced. On 11 November 1911, Kansas City, Missouri, had a maximum temperature of 76°F and a minimum temperature of 11°F. The continental climate results in a relatively high energy demand, as evidenced in the climatological mean heating and cooling

Table 1.2. 1971–2000 Mean heating degree days (HDD) and cooling degree days (CDD) in each calendar month in the four most populous cities in the Midwest and the two largest cities in the U.S. (New York and Los Angeles)

		J	F	M	A	M	J	J	A	S	O	N	D	Ann
Chicago	HDD	1333	1075	858	513	232	49	6	9	112	401	759	1151	6498
CDD	0	0	1	9	48	159	279	233	91	10	0	0	830	
Detroit	HDD	1270	1074	886	527	219	41	5	12	121	426	742	1099	6422
CDD	0	0	0	6	42	145	254	208	75	6	0	0	736	
Indianapolis	HDD	1192	957	724	394	141	16	2	4	77	335	659	1020	5521
CDD	0	0	2	10	69	221	331	272	122	14	1	0	1042	
Columbus	HDD	1154	940	731	415	152	27	3	7	80	347	654	982	5492
CDD	0	0	2	9	61	198	305	254	109	12	1	0	951	
New York	HDD	1015	869	731	433	182	21	6	4	43	264	532	847	4947
CDD	0	0	0	2	31	151	326	300	125	13	1	0	949	
Los Angeles	HDD	252	205	200	141	78	19	1	0	2	21	121	234	1274
CDD	4	6	6	15	19	58	135	175	154	81	22	4	679	

Note*: Heating degree day (HDD) and cooling degree day (CDD) are quantitative indices that reflect the demand for energy needed to heat or cool buildings. A base of 65ºF is used in computing HDD and CDD.*
Source*: Data taken from http://cdo.ncdc.noaa.gov/cgi-bin/climatenormals/climatenormals.pl.*

Table 1.3. Summary of extreme weather impacts on the Midwestern states

	Flood damage (1955–1999) average/year (million 1999 $US)	Tornado damage (1950–2006) (million 2006 $US)	Lightning fatalities (1959–1994)
Illinois	218.7	1754	85
Indiana	113.4	3951	74
Iowa	312.9	1709	65
Kentucky	118.8	1015	82
Michigan	35.56	1641	89
Minnesota	144.9	2285	53
Missouri	272.2	1975	79
Ohio	102.4	2149	115
Wisconsin	60.87	936	47

Source: *Data taken from http://www.sip.ucar.edu/sourcebook/.*

degree days for the four largest cities (table 1.2). In contrast to the huge seasonality in thermal regimes, much of the Midwest exhibits only moderate seasonality of precipitation receipt, with generally wetter spring and summer and low precipitation totals in fall and winter (see chapters 9 and 12). Precipitation climates are strongly influenced by the presence of the Great Lakes, and there is evidence for a large increase in lake-effect snowfall in the region of the Great Lakes since 1951, due in part to reduced ice cover since the early 1980s (Burnett et al. 2003; see also chapter 21).

As described in more detail in chapters 19–22, the region experiences a range of climate hazards (Burt 2004; Schmidlin and Schmidlin 1996; Visher 1944; Gallus, Snook, and Johnson 2008). Between 1959 and 1994, 689 people died as a result of lightning strikes, and economic losses due to tornado damage over the last fifty-six years exceed $17 billion (see table 1.3). The region's inhabitants are accustomed to major disruptions of transportation, agricultural, and industrial activities due to weather-related phenomena such as episodic flooding associated with prolonged and/or intense precipitation (see chapters 13 and 19). For example, one of the worst floods in United States history occurred in 1993 (June to August), with Illinois, Iowa, Missouri, and Wisconsin experiencing either record or near-record flooding (Bell and Janowiak 1995). Another devastating flood occurred in Ohio in March 1913, which resulted in 467 deaths and $147 million in damage (LaPenta et al. 1995). Equally, several weeks of heavy precipitation across the Midwest culminated in June 2008 in extensive flooding. As of June 20, 2008, twenty levees along the Mississippi River had been breached. Some parts of the Midwest also experience a high frequency of snowfall. For example, the western portion of the Michigan Peninsula experiences lake-effect snow and in individual years can have snow accumulations of over 2500 mm.

The Midwest has also experienced periods of intense and prolonged drought. The three-year drought of the late 1980s (1987–1989) covered 36% of the United States at its peak, but was focused on the north-central and Midwestern states. Particularly the summer of 1988 was characterized by both elevated temperatures and suppressed precipitation across much of the contiguous United States. On the basis of area-averaged temperature departures, the summer (June–August) of that year was the third warmest summer since 1931 for the country as a whole, and precipitation during June of that year was in the lowest 10th percentile of observed values across much of the Midwest (Ropelewski 1988). This drought was predicted, though the severity and extent were underestimated (Namais 1991). According to some estimates the 1980s' drought was the most expensive natural disaster of any kind to affect the United States. Combining losses in energy, water, ecosystems, and agriculture, the total cost was approximately $39 billion (Riebsame, Changnon, and Karl 1991).

The Midwestern USA is characterized by frequent passages of synoptic systems, and the seasonality of the climate is strongly influenced by the position and intensity of the polar jet stream (see chapters 17 and 18). Inter-annual and intra-annual variations in the intensity and tracking of synoptic scale systems and several surface parameters (e.g., temperature and precipitation) are explicable, at least in part, by a number of teleconnection indices—most notably the North Atlantic Oscillation (NAO), the Pacific–North American (PNA) index, and indices of the El Niño Southern Oscillation (ENSO) (Gershunov 1998; Leathers and Palecki 1992; Leathers, Yarnall, and Palecki 1991; Rosenzweig and Hillel 2008; Schoof 2004; Schoof and Pryor 2006). In accord with the dependence of thermal and hydrologic regimes on these indices, agricultural output is also linked to these hemispheric scale oscillations. Gross Domestic Product (GDP) during 1998 from agriculture in the United States was approximately $198 billion. The net effect of a strong El Niño was to suppress that by nearly $5 billion, while a strong La Niña depressed it by nearly $3 billion (Rosenzweig and Hillel 2008). Although the impacts on agro-ecosystems are not wholly repeatable, predictable, or consistently negative, during the strong El Niño of 1982–1983 the Midwest/Great Plains experienced hot and dry conditions resulting in soybean reductions associated with approximately $3.4 billion in losses, and maize production losses of approximately $5.5 billion (Rosenzweig and Hillel 2008). Given the tremendous importance of these teleconnections to the agricultural and other industries, over the last decade the National Atmospheric and Oceanic Administration (NOAA) has invested resources in developing seasonal forecasts of both the teleconnection indices and the related regional climate impacts (Hartmann et al. 2002; Rosenzweig and Hillel 2008). The importance of these teleconnections to the climate of the Midwestern USA also means that, as described in chapters 3 and 17, accurate portrayal of these teleconnections is a critical component of developing accurate climate projections derived using AOGCMs.

Climate Model Projections of Future Trends over the Midwestern USA from the IPCC AR4

The Midwest climate is dominated by the influence of mid-latitude cyclones. In future climate scenarios, AOGCMs generally indicate a slight poleward shift in storm tracks, an increase in the number of strong cyclones but a reduction in medium-strength cyclones. Atmospheric moisture transport and convergence are projected to increase, resulting in a widespread increase in annual precipitation over the northern half of the eastern United States, mostly due to increases of 5–20% in winter precipitation.

All global climate models reporting results for the IPCC AR4 produce global increases in surface air temperature for all future greenhouse gas emissions scenarios, and the projected increase in global mean temperature varies only modestly for different emissions scenarios for the first half of the twenty-first century. The mean of several global models for the A1B scenario (a mid-range emissions scenario) is about 0.28°C per decade increase in temperature (assuming a linear trend) over the twenty-first century. Summarizing from the AR4, all of North America is very likely to experience a continuation of the warming observed over the past twenty-five years, with magnitude that is likely to exceed the global average. In northern regions, warming is likely to be largest in winter. The lowest winter temperatures are likely to increase more than the average winter temperature in northern North America. Summer daily minimum temperatures are likely to increase more than the mean in the Midwest, although there is less certainty about daily maximum temperatures in summer. Annual precipitation is likely to increase in the north with most of the increase coming in winter and spring but decreases in summer. The length of the snow season and annual snow depth are very likely to decrease (although total cold-season precipitation might not decrease since more might fall as rain).

The AR4 does not specifically look at the region we define as the Midwestern USA (dashed box in figure 1.3). However, the report does include a focus on a region labeled Central North America (CNA) (solid black box in figure 1.3), the results for which are shown in table 1.4. CNA encompasses a large portion of the southern United States, which will reduce confidence that table 1.4 is applicable to the Midwest. However, some general model results can be used to improve applicability of table 1.4 to the Midwest. For instance, the northeastern United States is likely to experience a larger increase in precipitation than the southeastern United States in this future climate. Also, the warming is likely to be higher in the northern half than the southern half of the CNA box, particularly in winter. This suggests that true numbers for the Midwest (except the number of years to attain significance) would be slightly larger than entries in table 1.4 for both temperature and precipitation. This would tend to weaken

Table 1.4. Distribution of model responses (50% being mean of all models) from a set of 21 AOGCMs for Central North America (CNA) for changes in temperature (°C) and precipitation (%) between the 1980–1999 period and the 2080–2099 period for the A1B emission scenario. T(yr) indicates the time in years for the response to reach the 95% significance level (assuming linear changes over the 100-year period). This region has precipitation increasing for all sub-categories of the middle half of the distribution for March-April-May. Frequencies (%) of extreme warm, wet, or dry seasons, averaged over all models, are shown only when 14 of 21 models agree on increase (bold and underline) or decrease. Table adapted from results presented in IPCC (2007).

	Temperature response						Precipitation response						Extreme season (%)		
Season	Min	25	50	75	Max	T(yr)	Min	25	50	75	Max	T(yr)	Warm	Wet	Dry
DJF	2.0	2.9	3.5	4.2	6.1	30	-18	0	5	8	14		71	**7**	
MAM	1.9	2.8	3.3	3.9	5.7	25	-17	2	7	12	17	>100	81	**19**	4
JJA	2.4	3.1	4.1	5.1	6.4	20	-31	-15	-3	4	20	>100	93		15
SON	2.4	3.0	3.5	4.6	5.8	20	-17	-4	4	11	24		91	**11**	
Annual	2.3	3.0	3.5	4.4	5.8	15	-16	-3	3	7	15		98		

the north-south precipitation gradient over the Midwest (figure 1.3). The median annual temperature increase for CNA is 3.5°C (table 1.4). By the reasoning in the previous paragraph we might expect the Midwest to experience temperature increases of more than 0.36°C per decade, with the increase over this value coming from the fall and winter months. Similarly, the increases in winter and spring precipitation likely to occur in the northern regions of CNA would likely increase the annual increase in the Midwest above the CNA-mean of 3%.

The western United States, particularly the southwestern United States, is projected by AR4 models to have notable decreases in annual precipitation with multi-year or even multi-decadal periods of continuous drought. This, coupled with precipitation increases to the east, would suggest a larger east-west gradient along the western border of the Midwestern USA. It also is plausible that the pattern of dryness to the west periodically could encroach on the Midwest from the west and create higher inter-annual variability of precipitation in this region.

Risk-management decisions and other applications involving climate information for the Midwest would benefit substantially from having future climate projections that were developed for a region smaller than the CNA. Climate scenarios for regions smaller than the CNA are now being developed as described in multiple chapters within this volume. The projections of changes in climate of the Midwestern USA for the next few decades being produced under activities such as the North American Regional Climate Change Assessment Program (NARCCAP) will provide the complement to observed trends of the past thirty years to deliver the best available guidance on future trends of climate for use in studying the impacts of climate change and for developing climate risk assessment tools.

Regional Contribution to, and Response to, Anthropogenic Climate Change

As described above, the Midwestern USA has relatively high energy demands. and the nine Midwestern states shown in table 1.1 produced nearly one-third of the national greenhouse gas emissions (as measured in units of metric ton of carbon equivalents) in 1990, the last year for which data are uniformly available for all states.

Concerned with rising demand for energy and energy prices and increasing dependence on imported energy, in combination with increased recognition of the need to address climate change while sustaining and enhancing economic growth and job creation, in late 2007 ten Midwestern leaders (Governor Jim Doyle of Wisconsin, Governor Tim Pawlenty of Minnesota, Governor Rod Blagojevich of Illinois, Governor Mitch Daniels of Indiana, Governor Chester J. Culver of Iowa, Governor Jennifer Granholm of Michigan, Governor Kathleen Sebelius of Kansas, Governor Ted Strickland of Ohio, Governor M. Michael Rounds of South Dakota, and Premier Gary Doer of Manitoba) signed the Midwestern Regional Greenhouse Gas Reduction Accord. Indiana, Ohio, and South Dakota signed the agreement as observers to participate in the formation of the regional cap-and-trade system.

The stated goal for the Midwestern

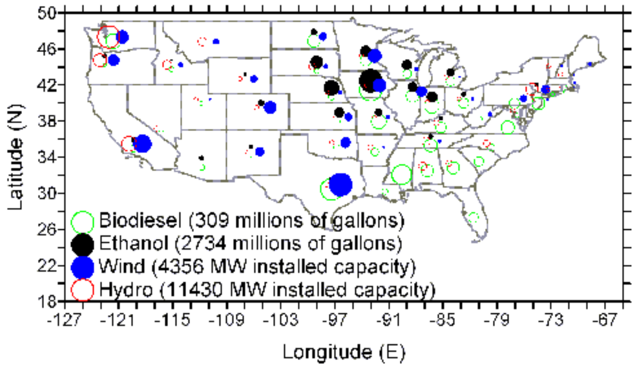

Figure 1.4. A map showing installed capacity for renewable energy supplies in 2007 for each state from: biodiesel (data from http://www.biodiesel.org/), ethanol (data from http://www.ethanol.org/), wind power installations (data from http://www.awea.org/), and hydroelectricity (data http://www.hydro.org/). The state data are plotted around the geographic center of population but are slightly offset to improve legibility. The colors used for each source are given in the legend along with the highest value for any state. The area of the circles scales linearly with the installed capacity.

Regional Greenhouse Gas Reduction Accord is to develop "a regional strategy to achieve energy security and reduce greenhouse gas emissions that cause global warming." The accord will:

- Establish greenhouse gas reduction targets and timeframes consistent with MGA (Midwest Governors Association) member states' targets;
- Develop a market-based and multi-sector cap-and-trade mechanism to help achieve those reduction targets;
- Establish a system to enable tracking, management, and crediting for entities that reduce greenhouse gas emissions; and
- Develop and implement additional steps as needed to achieve the reduction targets, such as a low-carbon fuel standards and regional incentives and funding mechanisms. http://www.midwesterngovernors.org/

The Midwestern USA depends heavily on electricity from traditional coal-fired plants and on largely imported petroleum for agricultural, transportation, and industrial sectors. However, as identified by the governors, the Midwest also poses some characteristics that may be useful in measures to mitigate climate change by reducing carbon dioxide emissions. These include:

- Existing and growing wind energy developments, due to the moderately good wind resource (see chapters 15 and 16).
- Substantial existing, and potential for expanded, biofuel production (figure 1.4).

However, these activities, while reasonable components of mitigation strategies, are themselves vulnerable to a changing climate. Hence, questions can be raised regarding whether the climate change commitment we have already undertaken, and that we have yet to make, altered the feasibility of both traditional and renewable energy sources?

Regional Sensitivity to Climate Variability and Change

In the context of climate variability, predictability, and change, the Midwest is unique with respect to:

(1) Potential importance in current policy measures to reduce climate change. For example, U.S. ethanol production climbed to almost 5 billion gallons in 2006, up nearly 1 billion gallons from 2005, and production is slated to exceed 10 billion gallons by 2009 (Westcott 2007). According to U.S. Department of Agriculture Statistics, in 2005/2006 14% of corn grown in the United States went into ethanol production, and that fraction is projected to increase (Westcott 2007). As described above (figure 1.4), the Midwestern states contain a very large fraction of current ethanol production capacity. With the bio-economy gaining momentum, additional stress will be placed on agricultural yields in the region (McNew and Griffith 2005; Wang, Saricks, and Wu 1999), which in turn exhibit climate sensitivity (see, for example, discussions in chapters 4 and 7). The demand for increased and inter-annually consistent agricultural production in the Midwest may change the resilience of the Midwest to changes in the mean climate state and variability therein. It may also increase the need for accurate long-range forecasts, the pay-offs for accurate forecasts, and the costs associated with inaccurate forecasts (Changnon 2002).

(2) The sign/magnitude of recent climate change/evolution. For example, parts of the Midwest have experienced cooling temperatures over the last century in contrast to the global mean, and there is a well-documented warming hole over the southwestern portions of the Midwest (Pan et al. 2004) (see also chapter 3 of this volume). Understanding of the mechanisms, and consequently improved simulations, of the warming hole will improve confidence in climate projections.

(3) The ability of coupled AOGCMs to simulate current and possible future climate states. For example; AOGCM simulations over the central/Midwestern USA exhibit much greater divergence than over many parts of the world (see, for example, chapters 6 and 8). This divergence includes teleconnections with sea-surface temperatures in the central and south Pacific (Joseph and Nigam 2006). Resolving reasons for the model divergence will greatly enhance the capabilities of AOGCMs.

(4) The frequency and consequences of extreme events. Insurance losses from weather-related risk (Kunreuther and Michel-Kerjan 2007) and many of the hazardous weather events occur within the Midwest (Kunkel, Pielke, and Changnon 1999) (table 1.3). For example, Hurricane Katrina excepted, the major extreme weather-related economic losses within the United States over the last decades have been focused on the Midwest (see chapter 20). Such events are extremely important to the regional economy, but changes in the frequency of inherently rare events are difficult to quantify in the historical records and very challenging to simulate in the context of climate change.

Synthesis of Midwestern USA Analysis in the 2000 Climate Change Impacts Assessment

In the Climate Change Impacts on the United States assessment published in 2000 (Easterling and Karl 2000) the following were identified as "key issues" in the Midwestern USA:

(1) Reduction in lake and river levels. During the twentieth century, rapid lake-level fluctuations of 1 to 1.5 m were observed in Lake Michigan (Polderman and Pryor 2004). Significant drops in the level of the Great Lakes during the late 1990s affected tourism and shipping industries and forced local communities to undertake expensive dredging operations, but also permitted reestablishment of diverse wetlands and expanded fish spawning grounds. Conversely, abnormally high lake levels pose a risk to sensitive shoreline environments by increasing their susceptibility to erosion from higher wave energy during strong storms (Meadows et al. 1997). Recent research reports that Lake Superior, the world's largest lake, experienced record low water levels in 2007 (Holden 2007) and that Lakes Huron and Michigan were also at near-record lows in that year (Sellinger et al. 2008). While these recent declines do not prove a climate link, changing precipitation regimes and/or evapo-transpiration may influence both lake and river levels (see chapter 10).

(2) Health and quality of life in urban areas. Major regional heat waves in the Midwest during both 1980 and 1995 (Changnon, Kunkel, and Reinke 1996) have focused concern on heat-related mortality and morbidity, particularly in light of high regional relative humidity, which tends to exacerbate heat stress (see chapter 5). There is also concern that climate change may cause enhancement of air pollutant concentrations (Leung and Gustafson 2005; Mickley et al. 2004) in a region where several major urban areas already exceed the National Ambient Air Quality Standards (Pryor and Spaulding 2009), or assist the spread of infectious diseases into the region (Ebi et al. 2006).

(3) Agricultural shifts. Inter-annual variability in agricultural production over the past decades in the United States is closely linked to climate variability. For example, the drought of 1988 was accompanied by estimated economic losses of $56 billion. The floods of 1993 in the Mississippi River Basin caused over $23 billion in agricultural losses (Rosenzweig et al. 2000). Changes in the timing/amount of precipitation may alter the need for irrigation, or, under scenarios of intensification of extreme precipitation events, prompt increased soil erosion. Equally, changes in climate parameters may alter the introduction and spread of plant pathogens (Pan et al. 2006). Primary weather-related impacts on Midwest agriculture are dependent on precipitation and/or temperatures during key phenological stages during the spring and summer months for crops such as maize and soybeans and, to a lesser extent, during winter and fall months for crops such as winter wheat. The primary limitation on yields appears to be water stress caused by anomalously low or high precipitation (Wu, Hubbard, and Wilhite 2004). These yield limitations can be enhanced by anomalously warm or cool temperatures, especially when drought conditions lead to low precipitation combined with high temperatures (Hubbard and Wu 2005).

(4) Changes in semi-natural (uncultivated) and natural ecosystems.

> Phenological changes in native and perennial plant species have been observed in response to changes in thermal regimes (Walther et al. 2002). In at least one study terrestrial equilibrium net primary production (NPP) over parts of the Midwestern USA exhibited a high degree of climate sensitivity (Moldenhauer and Ludeke 2002). As discussed in chapter 4, significant changes in frost-free season length have been observed across the Midwest, and may continue in the current century. Changes in thermal regimes have already been observed to be associated with changes in plant hardiness across the Midwest (chapter 7).

While the state of our knowledge regarding climate variability, predictability, and change has evolved since 2000, these four key vulnerabilities remain. Although regional sensitivity to climate change is often framed in terms of vulnerability, at least in terms of the latter two points raised above, climate evolution may also be associated with new opportunities. Global climate change and variability will result in both "winners" and "losers" (O'Brien and Leichenko 2003). It may be that the Midwestern USA will experience a mixture of these effects, depending on the socioeconomic or environmental sector under consideration.

Structure and Content of This Book

While the impacts of climate change act as motivation for much of the research presented in this volume, we focus solely upon the physical climate and structure the chapters along four thematic lines:

- Thermal regimes
- Hydrologic regimes
- Atmospheric circulation and flow regimes
- Climate hazards.

Each section is preceded by an overview or synthesis chapter designed to familiarize the reader with the topic under study and highlight results of both prior research and the presentations contained in this volume. The individual chapters present unique research focused on a variety of aspects of the physical climate of the Midwest, designed to quantify the current climate in which we live, past climate evolution, and possible future climate states. We conclude the volume with a chapter (number 23) that describes some ongoing efforts to improve our understanding of climate variability, change, and predictability along with recommendations for possible additional research avenues that could or should be pursued.

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