Vol. 56: 61–79, 2013
doi: 10.3354/cr01143

CLIMATE RESEARCH
Clim Res

Published February 21

High-resolution projections of climate-related risks for the Midwestern USA

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ABSTRACT: We use output from a suite of Regional Climate Models (RCMs) applied under the North American Regional Climate Change Assessment Program (NARCCAP) to quantify possible changes in metrics of climate impacts in the Midwest for the middle 21st century (2041–2062). RCM simulations of the historical period indicate a large positive bias in growing season length, but generally good agreement with observationally derived estimates of metrics such as the mean summertime maximum and apparent temperatures and number of cooling degree days. There is a tendency towards intensification of thermal extremes by 2041–2062 that is equal to or exceeds the bias in the ensemble mean during the historical period (1979–2000). For example, the number of days in the Chicago region each year with temperatures in excess of 32.2°C (90°F) is doubled by the mid-century. The ensemble average estimates for 1979–2000 from the RCMs is negatively biased in terms of annual, spring and summer precipitation (the wettest pentad) and mean dry day duration, but is positively biased in terms of total precipitation accumulated on the 10 wettest days of the year. The RCM simulations indicate an increased likelihood of extreme hydroclimate events that again are equal to or exceed the historical biases. For example, the wettest pentad and total accumulation on the top 10 wettest days of the year are projected to increase by ~10%. Preliminary results for icing and extreme wind events indicate no change in the magnitude of extreme wind events, and perhaps slight reductions in icing risk.

KEY WORDS: NARCCAP · Dynamical downscaling · Climate hazards · Extreme events

1. INTRODUCTION

Risks and opportunities associated with climate change and variability will be realized at local and regional scales. Thus there is an increasing need for climate projections to be cast in the context of current risk within a given region and for impact-sector specific indices to be derived. We describe major vulnerabilities to climate variability and change for the Midwest as manifest in the recent historical record and provide projections of key impact metrics for the middle of the current century. We focus on the middle 21st century because it is sufficiently near-at-hand to have relevance for regional sectoral planning, but is sufficiently 'far-ahead' to allow fairly robust identification of a climate change signature rather than being dominated by climate variability.

We adopt an inclusive definition of the Midwest, which contains the states of Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin and use a domain that extends 36–49° N and 103–80° W (see Fig. 1). These states have a total land area of ~505 million acres (~22% of the US total), a combined population of ~71 million people (~23% of the US total), and a gross domestic product (GDP) of ~3 trillion dollars (~22% of the US total) (Pryor & Barthelmie 2013a).

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2. KEY CLIMATE VULNERABILITIES

2.1. Agriculture

The 357 million acres of farmland within the Midwest comprises ~39% of the US total (US Department of Agriculture [USDA], www.usda.gov). Annual corn yields in the Midwest exceed 10 billion bushels (90% of US yields as a percentage of US$ receipt) and the region yields ~3 billion bushels of soybeans (83% of the US$ receipts) (data for 2008–2010 from www.usda.gov). These yields are not only critical to domestic consumption, but also to global food provision. Twenty-percent of US grown corn is exported, and the US accounts for ~60 and 40% of global corn and soybean exports, respectively (Hayes 2013). Midwestern yields of these 2 key crops, along with others, have exhibited fairly consistent increases (i.e. yields have increased 3 to 5-fold) over the last century primarily as a result of technological innovation (Niyogi & Mishra 2013). However, inter-annual variability of crop yields remains strongly linked to climate variability (Mishra & Cherkauer 2010). Crop harvested yields as an estimate of cropland net primary productivity (NPP) in Iowa varies between years by a factor of 2, with the years of lowest NPP being 1983 (which had an unusually wet spring), 1988 (a drought year), and 1993 (affected by flooding) (Prince et al. 2001). Extreme heat — particularly if coupled with extreme humidity — is also linked to negative impacts on livestock operations due both to physiological stress (similar to that experienced by humans) and spread of some diseases (Thornton 2010).

Extreme hydroclimate events have been responsible for major historical agricultural yield deficits in the Midwest. Flooding during 1993 led to damage of over 40 000 km^2 of crops and over $3 billion in agricultural losses (Rosenzweig et al. 2001). Drought also accounted for ~30% of insured crop losses in the Midwest between 1989 and 2009 (Hayes 2013). The drought of 2002 (which was not limited to, but covered much of the Midwest), resulted in ~$2.5 billion in crop insurance indemnity payments, and a $9.5 billion drop in US net farm income (Hayes 2013). Extreme precipitation during spring can lead to water-logging of soils that either delay planting, reduce available soil nitrogen and/or delay in-season fertilization, all of which can reduce yields (Balkcom et al. 2003). Further, corn uses more water during flowering than at other times of the year. In the 40 d surrounding corn anthesis (i.e. flowering) if the rainfall is <44 mm for each 8 d period, yields decrease by 1.2 to 3.2% per 1°C (1.8°F) increase, but when temperatures exceed 35°C (95°F), yields decline by 9% for each reduction in precipitation of 25.4 mm (Hatfield 2010). Thus optimal water management is critical. A large fraction of agricultural land, particularly in the eastern Midwest, is subject to tile drainage (e.g. according to some estimates, 50% of land in Indiana is tile-drained; Cuadra & Vidon 2011). Irrigation use across the Midwest is highest in Nebraska (where >75% of land is irrigated), and lowest in Ohio and Kentucky (Gollehon & Quinby 2006), and despite the relatively abundant precipitation, USDA data indicate yield benefits. For example, corn yields in Nebraska in 2007 were 50% higher on irrigated land, and even in Indiana irrigation increased corn yields by >10% (data from the USDA 2008 Farm and Ranch Irrigation Survey [FRIS], www.agcensus.usda.gov/Publications/2007/Online_Highlights/Fact_Sheets/Practices/fris.pdf). Thus, irrigation use is expanding, although the degree to which this increased water use can be sustained is uncertain in light of growing water demands from other sectors (Dominguez-Faus et al. 2009). For example, groundwater serving 8.2 million people in the Chicago-Milwaukee area is declining at a rate of ~5 m yr^{-1} (www.sandia.gov/energy-water/docs/121-RptToCongress-EWwEIAcomments-FINAL.pdf).

2.2. Human health

Extreme heat events increased in frequency over the eastern USA between 1949 and 1995 and not only affected ecosystem health and productivity, but caused over 3442 deaths between 1999 and 2003 (Luber & McGeehin 2008). The 1995 heat wave was associated with record breaking electricity demand (Hayhoe et al. 2010a), nearly 800 deaths (Hayhoe et al. 2010b), 1072 excess hospital admissions (Semenza et al. 1999), and >3000 excess emergency room visits (Vavrus & Van Dorn 2010) in Chicago alone. In response some Midwestern cities have implemented heat/health watch warning systems (Ebi et al. 2004, Kalkstein et al. 2009) and engaged in actions designed to mitigate heat vulnerability and/or mitigate the intensity of the urban heat island (Yang et al. 2008, Krayenhoff & Voogt 2010). There is some evidence that human heat stress may be amplified by elevated humidity (Semenza et al. 1996), and dew point temperatures across the region have increased (Rogers et al. 2007, Schoof 2013). Thus heat stress may have increased even in the absence of substantial changes in daily maximum temperature.

2.3. Transportation and infrastructure

The Midwest is home to major transportation linkages. Chicago O'Hare airport ranked 2nd in the nation in terms of passenger embarkations (nearly 31 million) in 2009, while Minneapolis was ranked 15th and Detroit ranked 17th (data from the Federal Aviation Authority [FAA], www.faa.gov). Severe weather events affect both the capacity and efficiency of air transport due to disruptions such as delays and flight cancellations or rerouting and increased financial and environmental costs due in part to increased fuel usage (Pejovic et al. 2009). During 1977–1979, 85% of flight arrival and departure delays at Chicago O'Hare were associated with adverse weather (heavy rain, thunderstorms, low cloud ceilings, reduced visibility, high winds, snow or ice) (Changnon 1996). More recent data from Chicago O'Hare also indicate adverse weather accounted for 55% of both delayed operations and total delay times during May 2011 to April 2012 (data from www.faa.gov).

Adverse weather also accounts for 15% of all highway delays, with heavy precipitation responsible for ~70% of the weather-related delays, and snow and high winds being the 2nd and 3rd most important causes (US Department of Transportation 2007). During 1977 to 1979 traffic accidents in the metropolitan Chicago area were increased by almost a factor of 3 for days with precipitation >5 cm (Changnon 1996). Nationally, the annual cost of weather-related delays to trucking companies is $2.2 to $3.5 billion (US Department of Transportation 2007). Highways I-290, I-90 and I-94 around Chicago had the highest freight congestion rankings in the USA in 2009, while I-70 and I-64 in St. Louis, Missouri ranked 6th for congestion; thus, it seems likely that a substantial fraction of these national economic losses derive from activities in the Midwest.

Recent flood events have affected multiple economic sectors within the Midwest. Flooding in the Midwest is most common in spring and summer. For example, in Iowa 90% of all floods occur between March and August. Early season (e.g. March) floods often derive from heavy rain falling onto snow, or soils saturated by snow melt, while late spring and summer floods most typically rise from sustained heavy precipitation (as in 2008) (Mutel 2010). Heavy rainfall over parts of the Midwest (e.g. nearly 50% of mean annual total accumulation in eastern Iowa fell between 21 May and 13 June 2008) resulted in major flooding lasting over 24 d in early summer 2008 over parts of Iowa, southern Wisconsin and central Indiana, and caused total economic losses of $15 billion (including $8 billion in agricultural losses) (Budikova et al. 2010). These floods also caused major transportation disruptions, including $154 million of losses to Illinois railroads (Changnon 2009).

Extreme precipitation events in the Midwest have also been associated with failures of urban infrastructure such as overflow of combined storm water and sewage systems (CSO) resulting in degradation of water quality in the Great Lakes and major rivers (Patz et al. 2008, Goulding et al. 2010). Chicago has experienced both CSO and flash floods due to intense rainfall events (Changnon 1999). For example, the 40 cm of precipitation that fell over parts of the city during a single 24 h period on 17–18 July 1996 caused flood damage to the city that cost $645 million to repair (Changnon 1999).

2.4. Energy

The Midwestern economy is energy-intensive. In 2008–2009 the only Midwestern state that had an energy intensity index (i.e. energy use per unit of GDP) below the national average of 7385 kJ [7000 BTU] per $1 GDP was Illinois (Pryor & Barthelmie 2013a). The Midwest has electricity generation capacity of >250 000 MW (nearly one-quarter of the total national capacity; Joskow 2006), and both the generation and distribution systems are vulnerable to climate variability and change.

The efficiency of thermal power plants (ratio of electricity produced to energy in fuel burned) is reduced under higher ambient air temperatures (Gotham et al. 2012). Additionally, thermoelectric power is the major user of fresh water in the Midwest (e.g. between 61% [Minnesota] and 82% [Illinois]) in all states except South Dakota, Nebraska and Kansas where irrigation is the largest user of freshwater withdrawals (Kenny et al. 2009). Many Midwest thermoelectric facilities draw cooling water from rivers (not lakes) and about one-third of the region's electricity is generated from units relying on once-through cooling (rather than the more water-efficient wet recirculating cooling) (Gotham et al. 2013). Thus the availability and temperature of cooling water can have a significant impact on generation (Feeley et al. 2008), in part due to the need to curtail operation due to water quality regulations regarding the maximum allowable temperature for return water (as regulated under Section 316 of the Clean Water Act).

Generally, the Midwest experiences more heating degree days than cooling degree days (CDD) (Pryor & Barthelmie 2013a), though due to the energy supply mixture, electricity demand is maximized in the summer (Gotham et al. 2013). The transmission of electricity across most of the Midwest is governed by the Midwest Independent Systems Operator (MISO) that includes parts of the Canadian province Manitoba, parts of Ohio, South Dakota, Montana and Missouri, plus the majority or all of North Dakota, Minnesota, Wisconsin, Iowa, Illinois, Indiana and Michigan. The net load in 2010 on MISO was 585 274 000 MWh, with highest demand and largest ratios of peak hourly demand to average electricity load (of up to 1.6) during the summer (www.eia.gov/cneaf/electricity/page/eia411/eia411.html). Given ~12% of total electricity consumption in the US is used for cooling (22% of the residential total, and 12% of the commercial sector), if projected tendencies towards increased frequency of very high temperatures are realized, there may be an increase in both base load during the summer and amplification of peak summer demand due to increased electricity consumption for cooling. This scenario was realized in the MISO network during the summer heat wave of 2006 when the peak demand during 31 July reached 116 000 MW (i.e. ~85% of the total generating capacity during summer 2006—of 137 232 MW) (www.ferc.gov/market-oversight/mkt-electric/midwest.asp#dem).

Elevated temperatures not only influence demand and generation, but also distribution of electricity. On 14 August 2003 electricity supply to over 40 million people was disrupted. A major cause was that 'one power plant in Ohio had shut down, elevated power loads overheated high-voltage lines, which sagged into trees and short-circuited. Like toppling dominoes, the failures cascaded through the electrical grid, knocking 265 power plants offline and darkening 24 000 square kilometers' (Grant et al. 2006, p. 78). Thermal limits on power system components are more restrictive on hot days (potentially requiring derating) (Beard et al. 2010), and transmission failures or curtailment to ensure compliance with allowable conductor temperature in order to prevent excessive sagging may increase if temperatures rise.

Over 95% of the 322 868 km (200 000 miles) of the national electric power transmission cable is over ground (Abel 2009), and in the Midwest an even smaller fraction is buried (<1%). Under extreme ice accumulations the resulting loads (particularly when icing is associated with high winds) can lead to failure of support structures and interruption to electricity transmission (Riddex & Dellgar 2001, Jones et al. 2004). An analysis of large-scale failures of the electricity distribution network over North America indicated 31.4% were associated with extreme wind or rain events, and 11% were attributable to ice accumulation (Hines et al. 2009). In addition to the impact on electricity distribution, in the early 1990s, ice storms caused an average of 10 fatalities, 528 injuries, and economic losses of $380 million each year in the contiguous USA (Irland 2000). As well as the threat extreme wind events present to the energy sector, they were also responsible for 42 fatalities across the USA, property damage of over $1.2 billion and crop damage estimated at $179 million in 2008 (costs normalized to 2010 dollars, data from Pryor & Barthelmie 2013b).

3. DATA AND METHODOLOGY

High-resolution climate simulations analyzed herein derive from the North American Regional Climate Change Assessment Program (NARCCAP) Regional Climate Model (RCM) suite (Mearns et al. 2012). NARCCAP used a range of coupled Atmosphere-Ocean General Circulation Models (AOGCMs) and multiple RCMs in a sparse matrix sampling scheme under the A2 SRES (emission scenario) to systematically investigate downscaling uncertainties (Mearns et al. 2012). The RCMs were run at a resolution of ~50 × 50 km, and the air temperature, specific humidity, precipitation and wind components at 10 m used here were archived at a temporal resolution of 3 h. We analyze output from 1979–2000 to describe the historical period and 2041–2062 to describe conditions for the middle of the current century. The RCMs employed (and the AOGCMs used to supply the lateral boundary conditions) are CRCM (CCCMa CGCM3.1, CCSM3), HadRM3 (HadCM3), MM5I (CCSM), RegCM3 (CCCMa CGCM3.1, GFDL CM2.0) and WRFG (CCCMa CGCM3.1, CCSM3). Each metric presented is computed on the native grid of each RCM. However, because the grids of each model differ slightly, in both analyses of the ensemble mean changes across all 8 model simulations and tests of the consistency in the sign of differences in the future versus historical period, the spatial fields of each metric from each model are averaged onto a common 1 × 1° grid.

We also present output from 10 AOGCMs that are part of the CMIP-3 data archive (BCCR BCM2.0, CCCMa CGCM3.1, CNRM CM3, CSIRO Mk3.0, GFDL CM2.0, GISS Model E Russell, IPSL CM4, MIUB ECHO G, MPI ECHAM5, and MRI CGCM2.3.2a) (Meehl et al. 2007) to provide a context for the high-resolution projections. The AOGCM simulations are driven by the B1, A1B and A2 SRES (listed from low to high radiative forcing) and are presented for 2046–2065 and 2081–2100. This generation of AOGCMs provides consistency with those used as lateral boundaries for the NARCCAP RCMs.

Historical data are also presented to quantify how key metrics of climate impacts have changed in the past and to evaluate the skill of historical simulations from the RCMs. This comparison is conducted primarily for spatially averaged values of the metrics, without correction for the inhomogeneous station distribution. The observational air temperature data used derive from over 100 stations in the NCDC Global Summary of the Day (GSOD) data set and the CRUTEM3 data set, which is a homogenized data set with spatial resolution of 5 × 5° (Brohan et al. 2006). The precipitation data used derive from *in situ* observations at 522 stations collated by the Illinois State Water Survey and used previously by Pryor et al. (2009b).

Based on key regional vulnerabilities, we identified a number of key indices for use in assessing possible climate change impacts on specific socioeconomic sectors within the Midwest (Table 1). Those for the thermal regime are (1) growing season length (based on a temperature threshold of 4°C), (2) mean summer (June to August; JJA) maximum air temperature, (3) number of days with temperatures >32.2°C (90°F), (4) mean apparent temperature (a heat index which combines the effect of temperature and humidity) during JJA, and (5) number of CDD computed using a threshold of 18.3°C (65°F). Given the sensitivity of the metrics to data quality (e.g. instrumentation sensitivity, siting and shielding), historical trends from *in situ* data are computed for 1974 to 2010 using the median of pairwise slopes regression technique (Lanzante 1996) and are deemed statistically significant if the p-value is <0.1.

Annual precipitation ranges from a low of ~500 mm in the west of the study domain to >1400 mm in the east, but throughout much of the domain 40% of annual total precipitation derives from the top 10 wettest days (Pryor et al. 2009a). Changes in the hydroclimate are thus described using the following indices: total precipitation accumulated during (1) spring (March to May; MAM) and (2) summer, (3) sum of precipitation received on the top 10 wettest days of the year, (4) wettest pentad (running 5 d period), and (5) mean duration of consecutive dry days (also referred to as 'dry spells', Christensen et al. 2007). Due to the acknowledged bias in climate models (e.g. they generate drizzle too frequently, Sun et al. 2006) a threshold of 1.3 mm is used to define a rain day. We do not consider extreme precipitation associated with long return periods because of previous findings that have indicated a systematic underestimation of very low probability (e.g. 100 yr return period) high magnitude events in the NARCCAP RCMs (Mishra et al. 2012). To provide consistency with an earlier study (Pryor et al. 2009b), historical trends from *in situ* records are computed for the period 1901–2000, and trend magnitudes and significance are quantified using bootstrapping and a 90% confidence level.

We also consider 2 aspects of climate hazards: extreme wind speeds and icing probability. These types of events are extremely challenging to simulate in the current and future climate. RCMs applied with their current formulations and at the resolution used in NARCCAP are not able to represent all of the phenomena responsible for extreme wind speeds in the region. Nevertheless, extreme winds associated with

Table 1. Major climate metrics used herein presented by impact sector. Metrics in normal typeface: maps are presented; metrics in *italics*: discussed in text for specific locations but maps are not presented

Sector	Temperature	Precipitation	Climate hazards
Agricultural	Growing season duration	Spring total	
	Number of days $T > 32.2$°C[a]	Summer total	
	Mean summertime maximum temperature	Dry duration	
Human health	Number of days $T > 32.2$°C[a]	Spring total	
	Mean summertime apparent temperature	Wettest pentad	
	Mean summertime maximum temperature	Top 10 wettest days	
	Frequency of 7 consecutive days with T > 32.2°C[a]	*Daily total >6.4 cm*	
Infrastructure/ transportation		Wettest pentad	20 yr wind speed
		Top 10 wettest days	Icing probability
		Daily total >5 cm	
		Daily total >6.4 cm	
Energy	Cooling Degree Days (CDD)	Summer total	20 yr wind speed
	Number of days > 32.2°C[a]	Dry duration	Icing probability
	Mean summertime maximum temperature		

[a](90°F)

synoptic scale phenomena (i.e. a scale presented in the RCM simulations) comprise 70% of damaging wind events in the Midwest (Changnon 2009); hence, extreme wind speeds are characterized here using the 20 yr return period wind speed computed using the method of moments approach (Pryor et al. 2012). Icing is a complex phenomenon (Fikke et al. 2007). The probability index used here is predicated on the assumption that icing is initiated when the simulated surface air temperature in a given RCM grid cell is below freezing ($T < 0°C$) and the relative humidity (computed based on the modeled specific humidity) is ≥95%. Accumulated ice is assumed to persist as long as $T < 0°C$ (Clausen et al. 2007). Given the paucity of *in situ* data for these events, no observational records are presented and no evaluation of the high-resolution projections is made.

4. CLIMATE CHANGE IN THE MIDWEST

4.1. Representation of historical climate normals

There remain large uncertainties in making high-resolution climate projections for a given future time window (Castro et al. 2005, Hawkins & Sutton 2009, Mearns et al. 2012). These include, but are not limited to uncertainties that derive from natural variability of the climate system due to processes that are not fully represented within the climate models, in the quantity and timing of emissions of radiatively active gases and aerosols (and thus the amount and spatial patterns of human forcing of the climate system), in the integrated response of the climate system to the forcing (including biogeochemical feedbacks), due to unresolved or untreated components of the climate system (e.g. the warming hole over the southern portion of the study domain is causally linked, at least in part, to changes in land use and irrigation that are not captured in the models).

To assess the relative skill of the RCMs in simulating the climate metrics used herein, values derived from the RCM output were compared to those from *in situ* observations during 1979 to 2000. Since all of the observing stations are located within the US, the RCM output was screened to exclude parts of the domain located in Canada.

The ensemble average growing season length from the RCMs is positively biased relative to the observations (by ~30 d) during 1979 to 2000. This is due in part to large overestimation of the growing season duration in the CRCM and MM5I simulations conducted within CCSM with lesser (but still substantial) positive bias in RCM3-GFDL and HadRM3-HadCM3 simulations. Results for the other metrics of the thermal climate exhibit a higher degree of accord with the observations. The mean summertime maximum temperature from the observations is ~29°C, while the ensemble average from the RCMs is 26°C and the mean summertime apparent temperature is almost 30°C in the observations but only 27°C in the RCM ensemble. This bias is absent from the mean number of CDD (992 in the observations and 995 in the model ensemble), and is highly variable across the model suite members. In contrast to the other metrics of extreme temperature, the spatially averaged mean number of days with maximum temperatures in excess of 32.2°C is 24 in the observations and 30 in the ensemble average of the RCM, in part due to a very high number of occurrences of temperatures above this threshold in the CRCM-CCSM simulation.

The ensemble mean annual total precipitation is negatively biased in the RCM (the RCM ensemble mean is 781 mm, while the spatial average of the observations is 853 mm). The dry bias is largest for the WRFG simulations with both the CGCM and CCSM lateral boundary conditions, but only simulations with RegCM3 yield annual total values above the observational mean. The dry biases in annual total precipitation derive largely from the spring and summer seasons. The observed spatially averaged mean total precipitation in spring and summer is 242 and 296 mm, respectively, while the RCM ensemble mean values are 180 and 260 mm. The negative bias in summertime precipitation is consistent with comparisons of the NARCCAP RCMs when run within NCEP-reanalysis lateral boundary conditions (as presented in Mearns et al. 2012), and as in those comparisons, the RegCM3 simulations actually overestimate summertime precipitation relative to the observations. Total accumulation on the top 10 wettest days of the year is positively biased (by almost 20%) in the ensemble RCM average (the ensemble average is almost 470 mm, while the average of the observations is 380 mm), while the wettest pentad is lower in the ensemble mean (78 mm from the RCM and 101 mm in the observations), and indeed all RCM simulations generate wettest pentad values below that derived from the observations. Mean dry day duration is negatively biased in the ensemble mean spatially averaged RCM output (4 d versus >5.5 d in the observations), and in all individual RCM simulations. The synthesis of RCM performance is thus in accord with prior research that has indicated generally negative bias in simulation of extreme events (Mishra et al. 2012) and too frequent occurrence of light precipitation (Dai 2011).

4.2. Historical tendencies and future projections

According to the CRUTEM3 data set, annual mean temperature increased by ~0.06°C per decade during 1900–2010 (Fig. 1), increasing to 0.12°C per decade during 1950–2010, and 0.26°C per decade in 1979–2010 (i.e. the period after the major "regime shift" in atmospheric and oceanic conditions over the North Pacific during the winter of 1976–1977, Hare & Mantua 2000). The estimate of temperature change over the domain for 1900–2010 is thus of slightly lower magnitude than estimates of 0.072 to 0.089°C per decade for the entire Northern Hemisphere land mass for 1902–2005 (Trenberth et al. 2007). This is in part due to the presence of a 'warming-hole' centered along the Iowa-Nebraska-South Dakota border (Pan et al. 2004). The warming trend is of largest magnitude during winter and at night leading to a reduction in the diurnal temperature range (Vose et al. 2005). Based on the CRUTEM3 data, the rate of change of mean temperature in January (1950 to 2010) is ~0.24°C decade^{-1}, while for July it is ~0.06°C decade^{-1}. These observations are consistent with increased greenhouse gas (GHG) concentrations, but have been amplified by changing land use, increased use of irrigation and thus changing soil moisture (Kalnay & Cai 2003). The resultant changes in partitioning of the surface energy balance due to irrigation have also been causally implicated in the 'warming hole' in the southwest of the Midwest (Pan et al. 2009).

Ensemble mean regional projected temperatures based on output from the ten CMIP-3 AOGCMs indicate further increases of 2.2 to 2.9°C over the study domain by the middle of the 21st century (where the range covers the mean value for 3 emission scenarios: B1, A1B, A2) (Fig. 1). The ensemble mean temperature anomaly at the end of the 21st century is 2.1 to 3.2°C above the 1961–1990 mean for the B1 scenario, while for the A1B scenario it is 2.9 to 4.3°C, and for the A2 scenario 2.8 to 4.7°C (Fig. 1). The ensemble mean air temperature in 2041–2062 from the 8 NARCCAP RCM simulations under the A2 scenario is also 2.9°C higher than in 1979–2000 when spatially averaged across the domain (Fig. 1). All RCMs indicate spatially averaged increases in mean air temperature of 2.4 to 3.4°C, and all grid cells from the RCM simulations exhibit higher temperatures in the future period (2041–2062) with ensemble mean changes in the range of 0.86 to 4.2°C above those from 1979–2000. The range of projected temperature anomalies from the RCMs is thus smaller than those from the AOGCMs, but all RCM simulations fall within the range from the AOGCMs (Fig. 1).

Consistent with phenological changes that indicate a lengthening of the growing season over the contiguous US (Jeong et al. 2011), *in situ* data records from across the Midwest generally indicate a tendency towards increased growing season length over the latter portion of the 20th century (Fig. 2a). Continuation of this tendency is projected in the ensemble average ratio of growing season length (2041–2062:1979–2000) from the NARCCAP RCMs. This ratio is 1.0 to 1.4 across the entire domain with a spatially averaged mean ratio of 1.16. This ratio equates to an average increase in the duration of the growing season by 2041–2062 of ~3 wk. Further, at least 6 of the 8 RCM simulations indicate longer mean growing season length in the future period for all grid cells (Fig. 2a). This is consistent with a model analysis by Christiansen et al. (2011) that used the Precipitation-Runoff Modeling System and temperature and precipitation output from 5 AOGCMs for 4 watersheds in the Midwest, and found increases in growing season length by the end of the current century of 27 to 39 d under the A2 SRES. An increase in frost-free season length of ~2 wk by mid-century (2046–2065) and >4 wk by 2081–2100 was also projected in transient 21st century AOGCM simulations downscaled using a statistical approach (Schoof 2009).

The NARCCAP RCM simulations also indicate increased mean daily maximum air temperature (T_{max}) during the summer (Fig. 2b). The range of ratios across the domain is 1.0 to 1.3, while the mean ratio is 1.16. Thus the spatially averaged mean daily maximum air temperature during the summer 2041–2062 is projected to be ~16% (4°C) higher than during 1979–2000. Only a small minority of station records indicate significant changes in mean summertime T_{max} over the period 1974–2010, and those that do generally indicate declines (Fig. 2b). This may reflect the short data record used relative to the high interannual variability of summertime T_{max} or issues pertaining to changes in the surface energy balance and heat partitioning due to increased irrigation use (as implicated in the regional 'warming hole').

Both indices of human heat stress considered here indicate a tendency towards higher values in the future (Fig. 2c,d). Historical data exhibit fewer significant tendencies and the trends are much less consistent in terms of the sign of change. As with the analysis of mean T_{max}, the majority of stations exhibit no significant historical tendency, possibly due to challenges in trend detection in a highly variable time series and categorical metrics such as the number of days with $T > 32.2$°C. Conversely, the ensemble average change from the RCM shows a high degree of

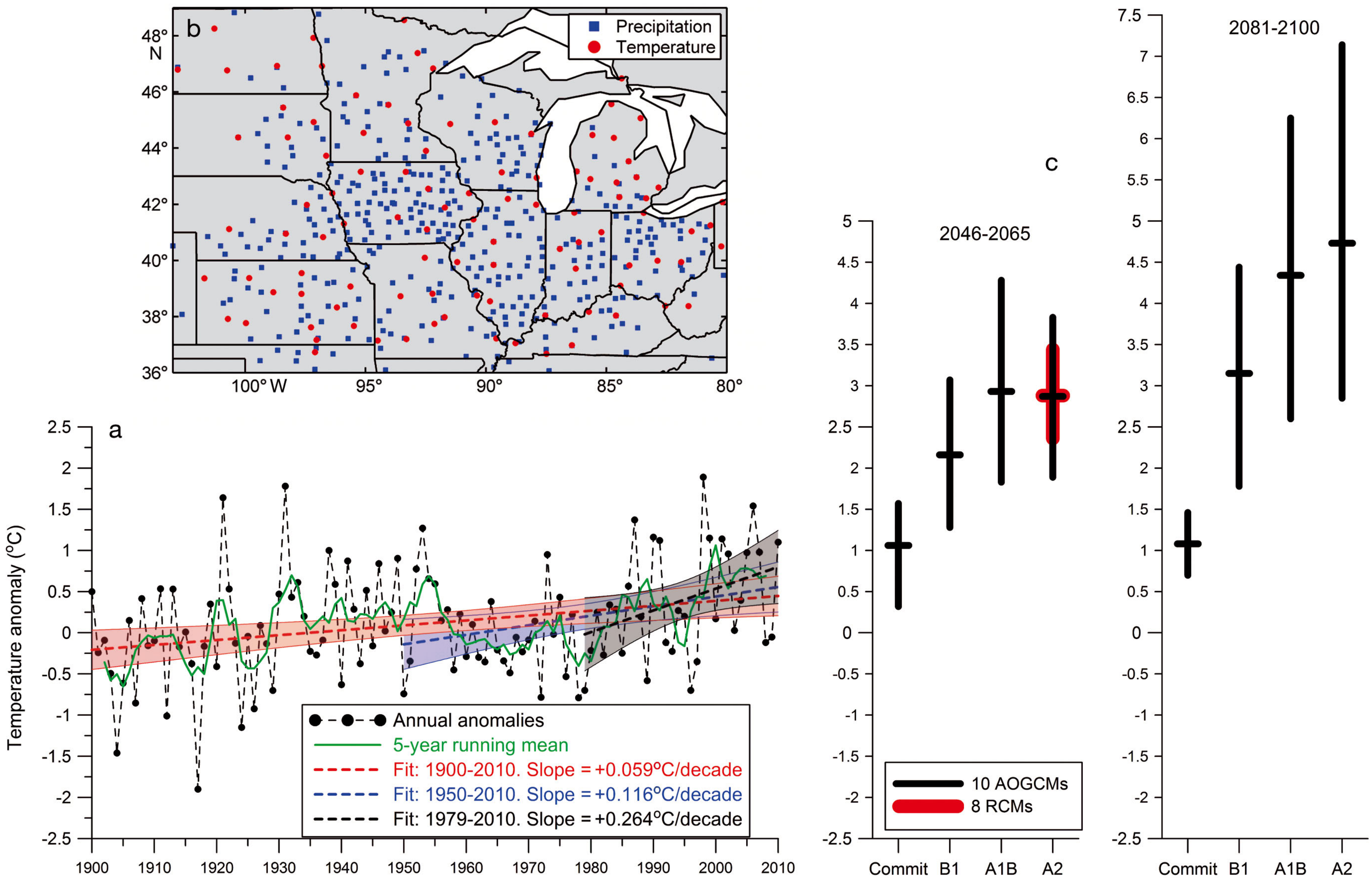

Fig. 1. (a) Annual anomalies (relative to 1961–1990) in air temperatures from the CRUTEM3 data set for the region 36–49° N, 103–80° W (domain shown in panel [b]). Linear trends (and 95% CI) for 1900–2010, 1950–2010 and 1979–2010. (b) Stations from which *in situ* data are presented. (c) Ensemble mean and range of anomalies for 2046–2065 and 2081–2100 (relative to 1961–1990) from 10 AOGCMs for 4 emission scenarios (committed climate change scenario and the B1, A1B and A2 SRES). Range shown: spatially averaged temperature changes from the 10 individual AOGCMs. In red: temperature anomaly and range for the 8 NARCCAP RCM simulations for 2041–2062 relative to 1979–2000 for A2 SRES

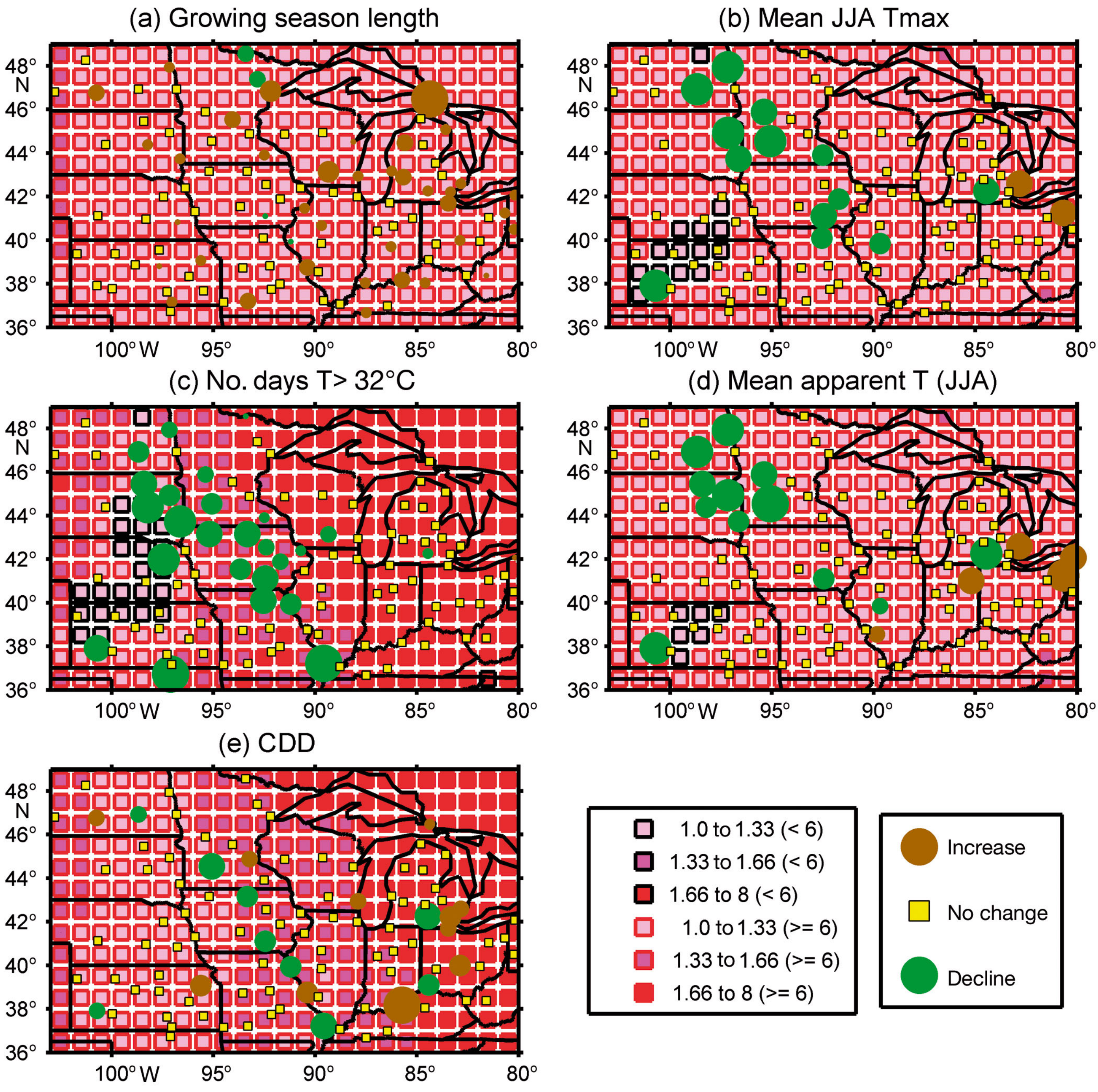

Fig. 2. Historical tendencies from observations (1974–2010) and the ratio in climate projections for 2041–2062 relative to 1979–2000 for 5 key thermal metrics: (a) growing season length, (b) mean maximum summer (JJA) temperature, (c) number of days with air temperatures >32.2°C (90°F), (d) mean summertime apparent temperature, and (e) number of cooling degree days (CDD). Background: Midwest region and outlines of the states. Key box: ratios (future:past) based on output from 8 AOGCM-RCM combinations. Grid cell outlines: degree of agreement between the ratios from 8 RCMs. Black: <6 of the simulations agree with the sign of change as manifest in the ensemble average; Red: ≥6 of the simulations indicate increases. Interior of grid boxes: magnitude of ensemble mean ratio: increase in color intensity = increased magnitude ratios. Dots: sign and magnitude of trends observed at individual stations, increased diameter with trend magnitude. Brown dot: changes that show statistically significant increases (at 90% confidence level). Green dot: statistically significant declines. Yellow squares: stations with no significant changes observed. Dots the size of dots in key = maximum trend value for that statistic. Units (and maximum value of trend magnitude) in each frame: (a) d decade^{-1} (25), (b)°C decade^{-1} (7), (c) d decade^{-1} (8), (b)°C decade^{-1} (7), and (e) number decade^{-1} (140)

spatial consistency, with much of the eastern Midwest exhibiting twice as many days above this threshold than are evident in the historical period (Fig. 2c). In each set of RCM simulations the number of grid cells in which this threshold ($T > 32.2$°C) was surpassed >5 times during each 22 yr period increased by >45% from 1979–2000 to 2041–2062. Indeed, the spatially averaged mean ratio in the number of days with $T > 32.2$°C is 2.2 (future projection:contemporary period). This is on the low end of results from prior statistical downscaling analysis for Chicago, which projected increases in the number of days above this threshold for 2070–2099 that equate to ratios of 2 to 4 (where the range represents the variation from a lower to higher emission scenario than used in the NARCCAP simulations) (Hayhoe et al. 2010a). As described above, the historical tendencies towards a decrease in the number of days with $T > 32.2$°C in the west of the domain may be linked to increased use of irrigation and thus changes in the surface energy balance. The large magnitude of change in the occurrence of $T > 32.2$°C in the east in RCM simulations for 2041–2062 appears to be linked, at least in part, to simulated decreases in soil moisture during the summer. Changes in mean apparent temperature in the ensemble average of the RCM simulations are of lesser magnitude than for $T > 32.2$°C, but again all grid cells exhibit ensemble average ratios >1.0 (the spatial average ratio is 1.16, indicating an increase of 4.5°C), and at least 6 of the 8 RCM simulations exhibit higher values in the future period over the entire domain (Fig. 2d). The pattern of increases in the number of CDD in the RCM projections mirrors that of the number of days with $T > 32.2$°C, while historical data from the station observations indicate that the spatially averaged mean tendency in CDD across the Midwest is slightly positive, but the majority of stations exhibit no significant change over the data period (Fig. 2e).

Instrumental records of precipitation exhibit very high inter-annual variability, but 24% of stations across the Midwest experienced increased annual total precipitation for 1901–2000, with a substantial fraction of that trend deriving from intensification of high-magnitude events (Fig. 3c,d) (Pryor et al. 2009c). Concomitant with the intensification of extreme precipitation events, there has been a shift towards a greater fraction of the total annual precipitation occurring during the spring (Pryor & Schoof 2008) (Fig. 3a). Continuation of the historical tendency towards increased annual total and spring total precipitation is indicated by the ensemble average ratio of projections for the mid-century from the 8 RCMs (Fig. 3a). The domain average ensemble mean ratio of annual total precipitation is 1.04, indicating spatially averaged precipitation is ~4% higher in the future period. Historical trends over the eastern portion of the region equate to a ~1% change per decade (Pryor et al. 2009c), and thus, if extrapolated into the future, are consistent with the change indicated by the RCM ensemble. This finding is in accord with results from a statistical downscaling analysis for the Great Lakes region (specifically Michigan and Illinois), which found that annual precipitation was generally higher at the end of the 21st century (by up to 20%) relative to the end of the 20th century (Hayhoe et al. 2010c). Total precipitation in spring and summer shows very different trajectories across the 2 seasons. The spatially averaged ratio in spring accumulation is 1.09, indicating 9% higher springtime precipitation on average in the future period. Conversely, in accord with prior research using a different model suite (Seneviratne et al. 2002), the NARCCAP RCMs indicate a tendency towards declining summer precipitation (with a domain averaged ensemble mean decline of ~8%), which is a reversal of the historical trends (Fig. 3b). The historical trend towards slight wetting of the summer or no change (as at the majority of stations) is consistent with analyses of the Palmer Drought Severity Index (PDSI) over the historical period (1950-2008), which have also indicated no evidence of drying in the historical record (Dai 2011). The average duration of the number of days without precipitation has also shown declining tendencies in the historical record (Fig. 3e). This may be due in part to increased local water availability due to irrigation (DeAngelis et al. 2010) or issues pertaining to changes in the detection of light rain events (Groisman & Knight 2008). Output from the NARCCAP RCM suite for 2041–2062 indicate a longer duration of sequences of dry days in the future period than during 1979–2000 (the spatially averaged mean ratio is 1.05), which is consistent with the projected reduction of summertime precipitation. Although the RCM exhibit high negative bias in the historical period, the high degree of consistency in mean dry duration across the individual models (>80% of grid cells exhibiting ratios >1 in ≥6 of 8 RCM simulations; Fig. 3e) may be indicative of a climate change signal.

Results for 2 metrics of intense precipitation indicate historical tendencies towards intensification and higher values in 2041–2062. The ensemble mean tendency in precipitation receipt on the top 10 wettest days of the year indicates that, averaged over the entire domain, the future period (2041–2062) is char-

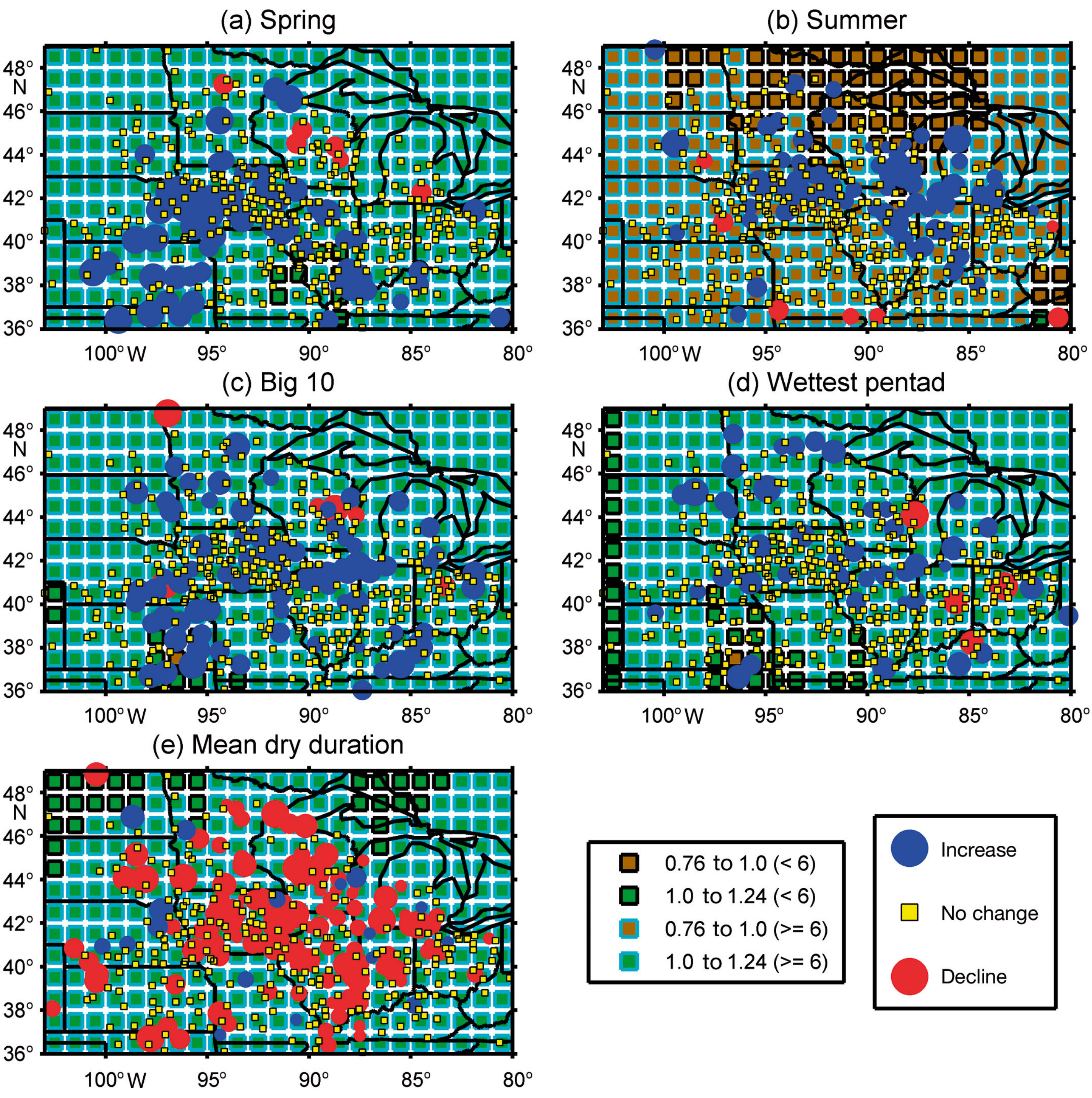

Fig. 3. Historical tendencies from observations (1901–2000) and ratio in climate projections for 2041–2062 relative to 1979–2000 for 4 key hydroclimatic metrics: (a) spring precipitation, (b) summer precipitation, (c) total accumulation on the top 10 wettest days of the year, (d) total accumulation on the wettest pentad (5 d running period) and (e) mean duration without precipitation (number of dry days in a sequence). Background: outlines of the states. Key box: ratios (future:past) based on output from 8 AOGCM-RCM combinations. Grid cell outlines: degree of agreement between the ratios from 8 RCMs. Black: <6 RCMs agree with the sign of change as manifest in the ensemble average. Cyan: ≥6 of the simulations indicate increases. Interior of grid boxes: magnitude of ensemble mean ratio. Dots: sign and magnitude of trends at individual stations (increased diameter shows increasing trend magnitude). Red dot: changes that show statistically significant decreases (at 90% confidence level). Blue dot: statistically significant increases. Yellow squares: stations with no significant changes observed. Historical temporal trends are expressed in % decade^{-1}. Largest value of trend magnitude in each frame: (a, b) 5, (c, d, e) 4

acterized by 10% (nearly 50 mm) higher values than during 1979–2000 (Fig. 3c). Estimates for the wettest pentad also indicate 9% higher values on average during 2041–2062 (Fig. 3d). Tendencies toward increases in high magnitude precipitation events accompanied by positive tendencies in indicators of summer drought were also observed in prior statistical downscaling (Schoof et al. 2010). Further, analyses of climate projections from 4 AOGCM using a SWAT model also found water yields and soil moisture in the Upper Mississippi Basin increased in spring (2071–2100 relative to 1961–1990), while water availability and soil moisture decreased in summer (Wu et al. 2012). An additional study of the PDSI in 2030–2039, 2060–2069 and 2090–2099 using a 22 model ensemble also indicated a possible drying trend in the south of the region (Dai 2011). Thus there may be a bifurcation of the hydroclimate trajectory over the Midwest with both an intensification of extreme wet-day events, and an overall drying and an increase in the duration of dry-day sequences in summer.

The ensemble average magnitude of the 20 yr return period wind speed in 2041–2062 from the 8 RCMs is within 5% of the historical values for all areas (Fig. 4a). Further for all grid cells there is at least one model that exhibits the opposing sign of change to that of the ensemble mean. Thus, the inference is that the current level of risk posed by extreme wind speeds will likely be unchanged. The NARCCAP RCM suite exhibits a large amount of variability in the frequency of icing in the historical and future periods derived using the simple index. The ensemble average ratio of icing frequency in the future to the past is <1 for virtually all grid cells (Fig. 4b), but the consistency between models in the historical period is very low, and RCMs have previously been shown to exhibit relatively low skill in modeling near-surface water vapor concentrations (Noguer et al. 1998).

5. HIGH-RESOLUTION PROJECTIONS OF KEY CLIMATE IMPACTS FOR MID-21ST CENTURY

5.1. Agriculture

Early empirical models of corn and soybean yields in Illinois found highest corn yields are associated with normal spring precipitation, above normal precipitation in July and August, climatological mean temperatures in June and lower temperatures in July and August (Hollinger & Changnon 1993). Although physiologically more complex models have subsequently been developed and seed development continues, the climate projections from the NARCCAP RCM suite (of a consistent signal of above historical climate norms in spring precipitation [Fig. 3a], below average precipitation in summer [Fig. 3b], and higher temperatures in summer [Fig. 2b], including an increase in the number of days with $T > 32.2$°C, which has historically been suggested as a threshold for corn stress, Herrero & Johnson 1980) would seem to indicate increased meteorological stress on this key component of the Midwestern agricultural system. However, in the absence of compensating changes in other variables, the projected tendency towards increased growing season duration (Fig. 2a) could be beneficial to agricultural yields, and may facilitate adaptations by farmers such as double-cropping

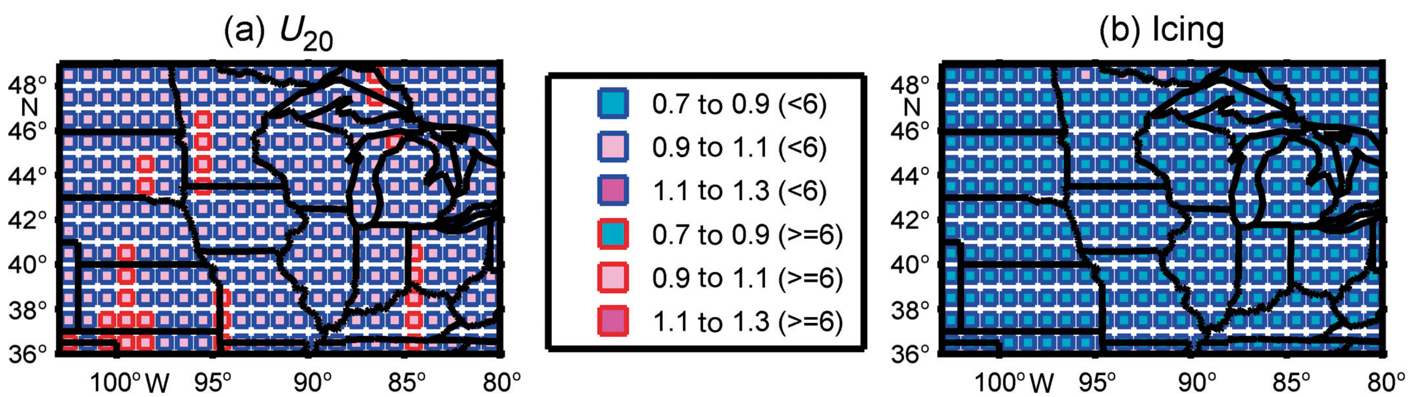

Fig. 4. Ratio in climate projections for 2046–2065 relative to 1979–2000 for (a) 20 yr return period return wind speed (U_{20}) and (b) icing frequency. Background: outlines of the states, Key box: ratios (future:past) based on output from 8 AOGCM-RCM combinations. Grid cell outlines: degree of agreement between the ratios from 8 RCM simulations. Interior of grid cells: magnitude of ensemble mean ratio

(Segerson & Dixon 2004). Further, as with natural ecosystems, moderate temperature increases may hasten plant development and, when coupled with elevated CO_2 concentrations, increase water use efficiency. An analysis of the combined impact of an increase in air temperature of 0.8°C coupled with increased CO_2 to 380-440 ppm found irrigated corn production in Midwestern regions with a mean air temperature during the reproductive period of 22.5°C would decrease by 1.5%, while soybean yields grown under the same circumstances would increase by 9.1% (Hatfield et al. 2011). These crop comparisons emphasize variations in 'balance point' between yield variations with increasing temperatures across different crops, particularly when combined with factors such as changing water availability and CO_2 enrichment, and remain dependent on the timing of extreme events (Hatfield et al. 2011).

Corn and soybean yields in Illinois and Indiana over the last 30 yr are negatively correlated with the average daily maximum temperature during JJA ($r = -0.80$ and -0.64, respectively for corn and soybean), and positively correlated with a standardized precipitation index during these summer months ($r = 0.61$ and 0.48 for corn and soybeans, respectively) (Mishra & Cherkauer 2010). Using these relationships, and presuming the projected increase in domain average summer mean maximum temperature (of 4°C) from the RCMs (Fig. 2b) can be taken in isolation, the ensemble mean changes in JJA mean T_{max} would equate to a decrease in annual mean yields of corn and soybean of ~2.5 and 0.5 t ha^{-1}, respectively, relative to current average yields of ~10 and 3 t ha^{-1} for Illinois and Indiana (Mishra & Cherkauer 2010).

The projections of reduced summertime precipitation (JJA) (Fig. 3b) may indicate a reduction in corn yields (given that historical yields are positively associated with summer precipitation, Mishra & Cherkauer 2010). Since water demand is particularly high during corn anthesis, which typically occurs during July in Midwestern states (Lamm & Abou Kheira 2009), the implication from the increase in summer T_{max} and specifically heat wave occurrence (Fig. 2b,c) coupled with the tendency towards summer drought (Fig. 3b,e) is that, in the absence of adaptation measures, corn yields may be suppressed relative to today. The projected increase in spring precipitation and evidence for increased precipitation extremes (Fig. 3a,c,d) may also be associated with both direct reduction of yields due excess soil moisture or to reduced yields due in part to delayed planting resulting from an inability to operate machinery (Rosenzweig et al. 2002).

5.2. Human health

The increase in heat stress metrics (Fig. 2b,c,d) is consistent with previous research that concluded 90th percentile apparent temperatures across the Midwest are projected to increase by an ensemble mean of 2.5 to 3.2°C by the 2050s (Schoof 2013). The results are also consistent with studies for Chicago (Hayhoe et al. 2010b) that indicated '1995-like heat waves' could occur every other year on average under the B1 SRES, and as much as 3 times a year under the A1F1 SRES by the end of the 21st century. A further analysis of temperature output from 7 AOGCMs in combination with historical mortality estimates projected that by 2081–2100, in the absence of large scale mitigation efforts, the city of Chicago would have between 166 and 2217 excess deaths per year attributable to heat waves (Peng et al. 2011). Using an approximation derived from historical data from St. Louis, that excess mortality per 100 000 residents scales with $0.32T_{max} - 7.76$ (Greene et al. 2011), the change in summertime regionally averaged mean T_{max} from 26 to over 30.2°C, implies an increase in heat-related mortality of nearly 1.5 people per 100,000 residents per year in 2041–2062 relative to 1979–2000.

The 1995 Chicago heat wave was associated with a 7 d running period with maximum temperatures of >32.2°C (Hayhoe et al. 2010b); thus an additional analysis was undertaken to assess the probability of these events in the RCM grid cell containing Chicago. Results indicate an ensemble average increase of 60% in the frequency of occurrence of 7 consecutive days of maximum temperatures >32.2°C, and no RCM indicates a decline in the frequency of occurrence of such events. This projected increase in heat wave occurrence is consistent with, but of smaller magnitude than, results from statistical downscaling of 3 AOGCMs, which indicated a 2 yr return period for 7 consecutive days of maximum temperatures >32.2°C in the historical period (1997–2006), increasing to a 1 yr return period for 2010–2039, and to between 1.8 and 5.5 occurrence rate in any year by 2070-2099 (Hayhoe et al. 2010a). These results thus reemphasize the key importance of implementing heat-wave mitigation measures and building adaptive capacity (Wilhelmi & Hayden 2010).

Urban drainage systems are typically designed for combined precipitation and stormwater discharge with return periods of a few years to a century. Chicago has already experienced CSO events, and the ensemble average ratio of total precipitation accumulated on the wettest pentad in the NARCCAP

RCM suite for the area containing Chicago exceeded 1.11 (Fig. 3d), indicating an intensification of these events by ~10% relative to the historical mean, thus an analysis of the NARCCAP output was undertaken for the city. Of the 8 RCM simulations, 5 indicated increases in the frequency with which a threshold of 6.4 cm of daily precipitation for CSO into Lake Michigan (Patz et al. 2008) was surpassed, and thus an increase in the probability of CSO events. However, large declines in the frequency of exceedance of this threshold in the WRFG-CCSM simulations mean the ensemble average ratio (2041–2062:1979–2000) is only slightly >1.

5.3. Transportation and infrastructure

Humans have extensively modified drainage systems across the US, and the economic consequences of flooding are also influenced by the presence or absence of high-value assets in floodplains (Pinter et al. 2010). However, the response of streamflow to changing precipitation (i.e. precipitation elasticity) is characterized by current values of ~2 over much of the relatively moist Midwest (Sankarasubramanian et al. 2001). Thus streamflow responses to future increases in high magnitude events are likely to be amplified relative to the actual change in precipitation. Positive tendencies in high intensity events (wettest pentad and the top 10 wettest days of the year, see Fig. 3c,d), appear to indicate an increased probability of urban and rural flooding.

Historical analyses of traffic accidents in Chicago indicated a 3-fold increase in occurrence on days with >5 cm of precipitation. Thus, the NARCCAP output for the Chicago region were analyzed in terms of the frequency of occurrence of daily precipitation in excess of this threshold. *In situ* observations from a single station in Chicago indicate a return period of almost 1 yr for days with >5 cm of precipitation (Pryor et al. 2009b), but those for the RCM suite ranged from <1 to 5.5 d yr^{-1} in 1979–2000. Nevertheless, 7 of the 8 RCMs show a higher frequency of occurrence of daily precipitation >5 cm in the future period (2041–2062). The mean ratio in frequency of occurrence (2041–2062:1979–2000) is 1.34 and the absolute range across the 8 RCM is 0.89 to 1.51. Thus this analysis indicates an increase in the frequency of occurrence of daily precipitation that has historically been associated with airport delays and road transportation accidents and delays.

Airport delays are also caused by extreme wind events, and near-surface icing also represents a significant threat to aviation safety. Based on analyses presented herein, it appears that the current magnitudes of extreme winds are a reasonable proxy for the middle of this century, and there is no evidence for enhancement of the geophysical component of the risk (Fig. 4a). While icing probability according to the simple index applied herein appears to be reduced in the future time window (Fig. 4b), the implication of reduced threat to transportation and the power distribution network must be viewed as somewhat speculative in the absence of evaluation of the skill with which this metric describes current conditions and the importance of ice cover extent on the Great Lakes to atmospheric humidity during the cold season (Kristovich 2009).

5.4. Energy

A first order estimate of consequences of an increase in summertime T_{max} (Fig. 2b) on the electricity sector can be made using a reported linearity response function of thermal efficiency of a power plant wherein each 1°C increase in air temperatures produced a ~0.6 to 0.72% reduction in power output from a 'typical' gas turbine (Linnerud et al. 2011). Using this approximation the increase in T_{max} of 4°C would equate a reduction in thermal plant efficiency in the Midwestern summer in the order of 2 to 3%. This magnitude of change can likely be accommodated within the electricity system but implies a reduction in safety margins, particularly when viewed in the context of other effects (e.g. possible increases in peak demand).

As described above, a significant fraction (~22%) of energy use is directed towards heating and cooling needs (Ruth & Lin 2006). Thus, in the absence of major changes in socio-economic conditions in the Midwest, any increase in the number of CDD will likely cause an increase in regional electricity demand. Earlier research in Chicago found that for 3 h average temperatures >15°C there is a nearly linear increase in hourly electrical load as air temperatures approach and exceed 35°C (Hayhoe et al. 2010a). Further, the ratio of monthly peak hour demand to mean base load within the MISO network during June and July 2010 was 1.45 and 1.55, respectively. Given July had a 50% higher number of CDDs, this might indicate a positive association between the peak demand for electricity and extreme high temperatures. The RCM simulations for 2041–2062 indicate a consistent (across both space and the RCM suite) tendency towards higher CDD in the future.

Almost one-third of grid cells show a CDD ratio >1.66, and >80% of the domain exhibit CDD values in all 8 RCM simulations that are larger in the future period (Fig. 2e). To provide an estimate of the potential impact of these changes in CDD, one can consider electricity demand in the MISO region in 2009 and 2010. In 2010 the membership-adjusted average load was 6% higher and loads in excess of 100 GW were experienced on 112 h. According to the MISO 2010 market report, averaged across 4 representative cities the number of CDD in July was 2.4 times higher in 2010 than in 2009, leading to a 22% higher average load (Potomac Economics 2011). Holding all other factors that influence electricity demand constant, and presuming this relationship is linear, the 1.7 times higher CDD estimates for 2041–2062 imply a summertime electricity demand in the MISO region that is ~14% higher than the historical average.

It is challenging to quantify the possible implications for thermoelectric power generation within the Midwest from the implied reductions in freshwater availability during summer (Fig. 3b). However, 2 counties in Chicago rank as the 2nd and 3rd highest metropolitan areas in the US most at risk to water shortages due to electricity generation by 2025 (Sovacool & Sovacool 2009). Since average freshwater withdrawal for once-through cooling is significantly higher (~95 l kWh^{-1}; ~25 gal kWh^{-1}) than wet recirculating cooling (1.9 l kWh^{-1}; 0.5 gal kWh^{-1}) (Shuster 2009), generation units with once-through cooling would appear to be most vulnerable to potential decreases in water availability or increased water temperatures. In accord with this scenario, summer of 2012 saw curtailment of electrical plants in Illinois due to concerns regarding discharge water temperatures.

6. CONCLUDING REMARKS

We present key vulnerabilities to climate variability and change for the Midwest and use possible analogues and relationships between key aspects of the socio-economic system and climate metrics based on historical data to determine first-order approximations of how projected changes for the middle of the current century might influence the region. The climate metrics presented focus on climate extremes that have been associated with impacts on agriculture, energy, transport and infrastructure or human health, and include those parameters that can be derived with a reasonable level of skill from RCM output. For each metric we assess not only the ensemble average difference in the metric in the mid-21st century relative to the end of the 20th century, but also the consistency in the direction of change across the 8 RCM simulations (which represent combinations of AOGCMs and RCMs). It is acknowledged that the suite of downscaled projections used does not fully sample the entire uncertainty space associated with making projections of key climate risk indices, and that the inferences drawn from those results can only be considered approximations of possible impacts. It is further acknowledged that climate variability will also influence the results presented herein and that use of 'temporal windows' may cause misattribution of variability as a climate tendency. Nevertheless, this work is intended to make a contribution towards identifying and ultimately reducing regional vulnerability to climate change and variability.

Analysis of RCM skill in reproducing observationally derived estimates of the metrics during the historical period indicates substantial positive bias in the ensemble average growing season length from the RCMs. Mean summertime maximum and apparent temperatures are, however, negatively biased in the ensemble average of the RCMs (by ~14%). No bias is evident in the mean number of cooling degree days. The ensemble average from the RCMs is negatively biased in terms of annual total precipitation receipt (by ~8%) and precipitation receipt in spring (~30%) and summer (~12%), precipitation accumulation on the wettest pentad (~25%), and mean dry day duration, but is slightly positively biased in terms of total precipitation accumulated on the 10 wettest days of the year (~17%). These biases do not preclude use of the RCM output for developing climate projections but do provide a critical context for those projections.

Results presented herein indicate a continued lengthening of the growing season in the future. However, this change is of lesser magnitude than the bias in the historical period, and thus while it is consistent with prior analyses it must be viewed with caution. The implied agricultural benefits from the increase in growing season length and CO_2 fertilization may be at least partially offset by increases in numerous yield-limiting stresses (e.g. water availability, insects, weeds, nutrient availability). Specifically, in the absence of additional adaptation measures, based on historical variability it seems likely that the projected increase in summertime mean daily maximum temperature (of 4°C) will suppress corn yields. Further, the increased frequency of heatwaves and the indications of increased summertime drought may reduce yields or increase costs due to increased demand for irrigation. Possible changes in yields for corn are particularly sensitive to water availability and the occurrence of extreme heat during anthesis. While climate projections at this level of temporal detail are subject to larger uncertainties, the tendency towards increased mean summertime maximum temperatures may indicate that at least in some parts of the region this may represent the largest near-term risk for corn production. Additionally, the tendency towards intensification of extreme (typically) springtime rain events may negatively impact the agro-economy by delaying planting, possibly reducing productivity. These projections indicate the value of measures to enhance the degree of resilience to climate changes (such as those projected herein) that are already being undertaken. These include breeding approaches to mitigate the effects of increased heat and drought in crop production (Trethowan et al. 2010). Further, opportunities for coupling increased water storage during projected increases in springtime abundance both as a flood risk mitigation strategy and to supply supplemental irrigation may also be available within the Midwest (Baker et al. 2012).

Human health within the Midwest is already compromised by climate related risks. Historical heat waves have caused major loss of life and elevated morbidity, a substantial fraction of the population experience air pollution known to be deleterious to human health and water quality has been compromised by occurrence of CSO events. Consistent with prior research, the climate projections presented here appear to indicate an amplification of these risks. For example, the occurrence of conditions analogous to the high-mortality 1995 heat wave are projected to increase by a factor of ~66% by the middle 21st century. These projections, and the apparent success of mitigation and adaptation programs in major Midwestern cities, emphasize the importance of building increased resilience to excessive heat by measures such as those designed to lessen the intensity of the urban heat island, and implementation of heat warning systems. Given the enhancement of extreme precipitation events, again in the absence of mitigation measures, there is evidence that the occurrence of CSO is likely to be enhanced in the future. Remediation measures are available (e.g. increased capacity of combined storm water and sewage discharge systems), but require substantial financial investment.

The major threats to critical infrastructure, the electricity sector and transportation deriving from extreme aspects of the hydroclimate appear to be amplified in the climate projections. It is important to acknowledge that a major cause of increased risk (and economic losses) associated with flooding is development in flood-prone regions (Pinter et al. 2010), and furthermore, that changes in water management and land cover have greatly modified hydrological responses (and socio-economic vulnerability) to extreme precipitation in the Midwest. Nevertheless, the historical tendencies in metrics of extreme precipitation, and the climate projections presented herein, appear to indicate climate-driven amplification of flood risk. Extreme precipitation metrics (e.g. wettest pentad and total accumulation on the top 10 wettest days of the year) indicate positive tendencies (domain average ratios indicate 10% increases in the magnitude of these metrics), suggesting an amplification of the associated risks. These results thus re-emphasize the importance of ongoing efforts to reduce this vulnerability (Opperman et al. 2009).

In the absence of major compensating changes in the socio-economic composition of the region, the energy sector, and particularly the electrical power production and distribution sector, the region will likely see a shift in the seasonal electricity demand curve, and possibly an increase in the peak load driven by an increasing need for summer cooling. The number of CDDs in the climate projection period is on average 1.7 times that in the historical period. As with the agricultural industry the energy sector has adaptation methods available that may need to be deployed to reduce the risk of system failures (e.g. use of different materials for transmission lines to reduce sagging, Alawar et al. 2005). Thermoelectric power generation from the region's large number of once-through cooling units may also exhibit vulnerability to the projected increases in summertime meteorological drought. Metrics of key risk indices for the electrical power industry and transportation sector associated with icing and extreme wind events are developed and presented herein, but it is important to note that they are likely associated with greater uncertainty than those deriving from temperature and precipitation, in part due to the lack of research into RCM skill for these variables and the divergence in the RCM projections. Given the importance of these phenomena to key economic sectors, more research is warranted.

Acknowledgements. Financial support was supplied by the National Science Foundation (NSF) (grant Nos. 1019603 and 1019620). We thank the NARCCAP for providing RCM output used in this paper. NARCCAP is funded by NSF, US Department of Energy, National Oceanic and Atmospheric Administration, and the US Environmental Protection Agency Office of Research and Development. This manuscript benefited from the input of 3 anonymous reviewers.

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Editorial responsibility: Oliver Frauenfeld, College Station, Texas, USA

Submitted: July 23, 2012; Accepted: November 12, 2012
Proofs received from author(s): February 7, 2013