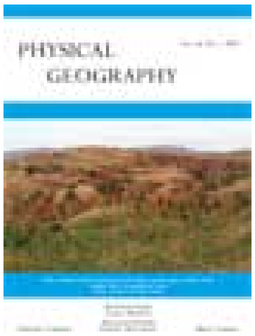

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PATTERNS OF CLIMATE CHANGE ACROSS WISCONSIN FROM 1950 TO 2006

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Abstract: Trends in meteorological and ecological variables were calculated across the state of Wisconsin from 1950 to 2006 to quantify recent patterns of climate change. In summary, annual average nighttime low temperatures have increased by 0.6 to 2.2° C, whereas the annual average daytime high temperatures have warmed by 0.3 to 0.6° C. Annual average precipitation has increased by 50–100 mm in the central and southern portions of the state, about a 10–15% increase, while precipitation across the far northern portion of the state appears to have declined by 20–60 mm since 1950, with the most pronounced decrease occurring during summer. On a seasonal basis, warming temperatures are more pronounced during winter and springtime, and nighttime temperatures are warming faster than daytime high temperatures. Some cooling trends in daytime high temperatures were observed during late summer and fall, particularly in the northeast and far southwest portions of the state. We calculated that the length of the growing season has increased by 5 to 20 days, with the greatest change in the central and northern part of Wisconsin. The annual number of days each year with low temperatures less than 0° F (–17.8° C) has diminished substantially, while the number of days each year with highs greater than 90°F (32.2° C) has remained relatively constant. A slight shift northward of the ecological "Tension Zone" was also documented. [Key words: climate change, Wisconsin, growing season, Tension Zone.]

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INTRODUCTION

Climate change across the U.S. Midwest has great potential to directly impact the quality of life of its inhabitants as well as indirectly affect other segments of the global population. The societal importance of Wisconsin and other key forestry and agricultural states in the Midwest will continue to increase as the global population increases and a new market for bioenergy develops in the next few decades. As human needs and global economies become increasingly intertwined with the goods and services that are provided by the natural and managed ecosystems of the region, changes in mean climate and the frequency of extreme weather events may threaten ecosystem productivity, potentially compromising food and fiber supplies as well as bioenergy feedstocks (Kucharik and Ramankutty, 2005; Scheller and Mladenoff, 2005; Lobell et al., 2006; Kucharik and Serbin, 2008; Goldblum, 2009; Karl et al., 2009). Detailed assessments of the historical influence of climate change and variability on forest productivity and species distributions, water quality, and changes to hydrological systems and fisheries, as well as impacts on agriculture stand to be highly beneficial for the development of adaptive management and future planning purposes (Kucharik, 2006). However, before such assessments can generally take place, the best possible understanding of previous climate change is needed.

Previous assessments of climate change have been performed for individual observation stations across the globe, leading to national and global assessments. For example, the International Panel on Climate Change (IPCC) Fourth Assessment (AR4) report showed that global average temperatures increased by 0.74° C from 1906 to 2005, with greater increases in northern latitudes, and more pronounced warming over land (Trenberth et al., 2007). The executive summary of the 2007 IPCC AR4 report stated that it is very likely that just in the last 50 years very cold nighttime temperatures have become less frequent over most land areas, but hot days and nights are occurring more frequently. At a national level, several reports have documented recent climate change as well as the potential impacts. The Union of Concerned Scientists (2009) has put together a series of reports documenting recent global warming and impacts of climate change in the Midwest and Great Lakes Regions. Furthermore, the 2009 U.S. Global Change Research Program report entitled *Global Climate Change Impacts in the U.S.* (Karl et al., 2009) illustrated that the average U.S. temperature has increased by 1.1° C (2° F) since about 1960, precipitation has increased by 5%, and the frequency of heavy precipitation events has also increased by a factor of two, with two catastrophic floods since the early 1990s. The growing season has lengthened on average by one week since 1960, mainly due to a retreat of the date of the last spring frost. Large portions of the U.S. are now experiencing a shorter, less intense wintertime on the basis of a decrease in extremely cold temperatures. The Midwest Regional Climate Center (2009) has quantified climate changes at the state level across the Midwest for 1895–2006 based on state averages from the National Climatic Data Center (NCDC) Climate Division Dataset. Results across Wisconsin showed that the annual mean temperature from 1895 to 2006 has increased 0.6° C (1.1° F), mean spring temperature +0.7° C (1.3° F), mean summer temperature +0.1° C (0.2° F), mean autumn temperature –0.1° C (–0.2° F), and mean winter temperature +1.5° C (2.7° F). Annual mean precipitation has increased 56 mm (2.2 in), mean spring precipitation +18 mm (0.7 in), mean summer precipitation +28 mm (1.1 in), and mean autumn precipitation 13 mm (0.5 in); no change in winter precipitation was recorded.

While these large-scale, national and state-level assessments are important to policymakers and scientists, long-term climate change does not occur in a homogeneous pattern across entire continents, and can differ largely in terms of the direction and magnitude of the associated changes (Moran and Hopkins, 2002; Karl et al., 2009). Minimum and maximum temperatures may be changing by different magnitudes and directions, and, on a seasonal time frame, climate change may not be consistent in any given small region. Therefore, to provide researchers, natural resource managers, communities, as well as government officials with more detailed data and new insights on the impacts of climate change, state or multistate assessments could be argued as an absolute necessity to support the best possible decision-making and adaptive strategies. The National Oceanic and Atmospheric Administration's (NOAA) Regional Integrated Sciences and Assessments program is an excellent example of this type of approach to studying interactions between regional climate change and impacts on ecosystems, public health, and natural resource management at the multi-state level (NOAA, 2009). In keeping with this theme, a new effort called the Wisconsin Initiative on Climate Change Impacts (WICCI) was initiated in 2007 in response to questions received from a committee of bipartisan Wisconsin state legislators who were concerned about how climate changes might impact the communities and people they serve. The WICCI effort has since brought together scientists and decision makers from the University of Wisconsin system, the Wisconsin Department of Natural Resources (WI-DNR), as well as other institutions and state agencies to assess how climate change may impact the natural resources, ecosystems, industry, agriculture, and tourism across the state. The ultimate goal is to support the development of adaptation strategies that would be put into place via public officials, municipalities, farmers, resource managers, and businesses to reduce the risk associated with continued climate change (WICCI, 2009).

In order to facilitate climate change impact studies at the state level through efforts such as WICCI, high-resolution (spatial and temporal), historical, gridded climate datasets are needed so that scientists can better understand how climate change has potentially affected ecosystem functioning. In addition, such higher resolution climate data allow for basic climatological research and numerous other applications, such as validation of climate models in localized regions (Widmann and Bretherton, 2000), monitoring or detecting and assessing potential impacts of regional climate changes (Zhang et al., 2000; Lobell et al., 2006; Kucharik and Serbin, 2008), as well as risk assessment (Kaplan and New, 2006).

Our charge was to build off of previous larger scale assessments of climate change, and create new data and knowledge that explicitly documented climate change patterns across Wisconsin at higher spatial (8 km) and temporal (daily) resolution from 1950 through 2006, using both daily minimum and maximum temperatures instead of monthly means. Our analyses are possible due to the recent

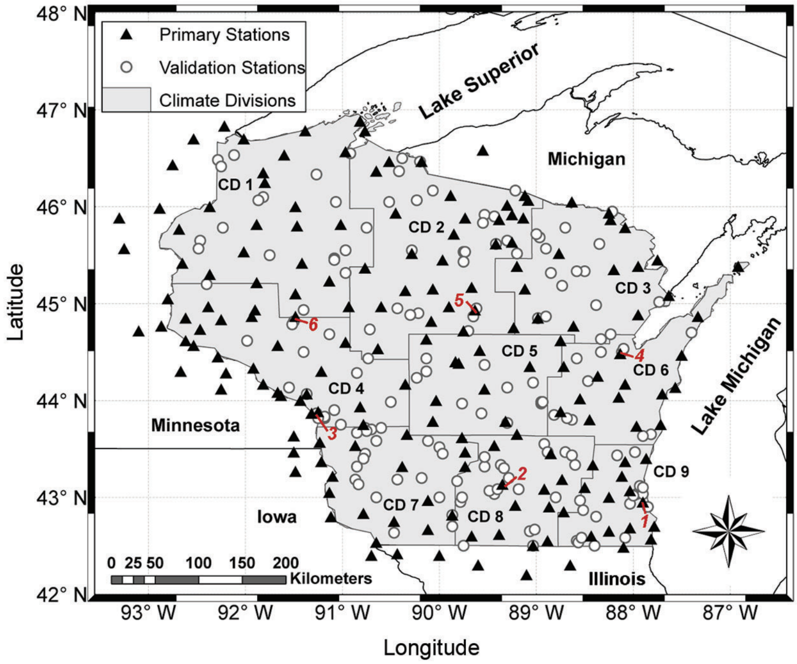

Fig. 1. Location of COOP stations used to construct the gridded daily climate database (primary stations) and those stations used to validate the statistical interpolation (validation stations). Adapted from Serbin and Kucharik (2009). Red numbers indicate the location of observation stations used in the extreme precipitation analysis: 1 = Milwaukee; 2 = Madison; 3 = LaCrosse; 4 = Green Bay; 5 = Wausau; 6 = Eau Claire.

creation of a high-resolution, daily historical climate dataset for Wisconsin (Serbin and Kucharik, 2009). The overall goal of this project is to provide scientists, state agencies, policymakers, the energy industry, non-governmental organizations, natural resource managers, and other researchers a statistical quantification of how previous changes in climate occurred across Wisconsin from 1950 to 2006, and how those patterns, derived using the highest quality data available, differ across geographic space. This paper specifically reports changes in annual and seasonal temperatures and precipitation; trends in extreme temperature occurrences; shifts in the growing season length, growing degree days, heating degree days, and cooling degree days; the occurrence of extreme precipitation events; and changes in the position of the so-called ecological "Tension Zone" (Curtis, 1959).

METHODS

Climate Data

The study region for this analysis is Wisconsin or an area extending from about 86.8° to 92.9° W Long. and 42.5° to 47.1° N Lat. (Fig. 1). Wisconsin is characterized by generally minor topographic variations, with gently rolling landscapes so that elevation changes do not play a large role in driving the average climate regime across the state. Lakes Superior and Michigan, however, can have significant impacts on seasonal (i.e., traditional meteorological three-month seasons) temperature and precipitation (Moran and Hopkins, 2002). Time series of daily weather observations across Wisconsin of maximum temperature, minimum temperature, and total precipitation for the 1950–2006 time period had been previously interpolated to a terrestrial 5 min × 5 min grid (0.0833° Lat. × 0.0833° Long.) using an inverse distance-weighting (IDW) algorithm to generate a continuous 57-year time series of gridded daily weather (Serbin and Kucharik, 2009).

Station data were obtained from the NOAA cooperative (COOP) observer network, available from the NCDC website (NCDC, 2009). The COOP stations used were distributed relatively evenly, with a slightly lower station density toward the northern part of the state (Fig. 1). Additional COOP stations from Illinois, Iowa, Michigan, and Minnesota that were within 70 km of the Wisconsin state boundary were also used to mitigate edge effects during statistical interpolation (Fig. 1). Stations that did not have at least 53 years of data (during 1950–2006) were removed to avoid synthetic bias through the addition of stations during the time period of interpolation. Approximately 133 temperature and 176 precipitation stations were used in the development of the dataset, giving an average distance between observing stations of 25.0 km for temperature, and 21.2 km for precipitation.

We performed a rigorous test of the predictive accuracy of the IDW gridded surfaces using 104 stations withheld in the production of the climate grids in a post-gridding validation step. For a complete description of the methodology used to create the gridded climate dataset as well as statistical testing and quality control, please refer to Serbin and Kucharik (2009). We used a smaller subset of National Weather Service station data for the years 1950–2008 (Madison, Milwaukee, Eau Claire, La Crosse, Wausau, Green Bay) in a separate analysis of trends in extreme precipitation events (Fig. 1). We favored this to the interpolated dataset because there is some likelihood that very high daily precipitation events may be smoothed over by the statistical interpolation that was used.

Statistical Analysis

Simple linear regression analysis, using a least squares approach, was used to calculate time-dependent trends of meteorological variables for annual and seasonal (winter—Dec, Jan, Feb; spring—Mar, Apr, May; summer—Jun, Jul, Aug; fall—Sep, Oct, Nov) maximum and minimum temperature, diurnal temperature range, and total precipitation for each grid cell. Simple linear regression was also used to compute changes in: (1) the date of last spring and first fall freeze (0° C threshold) and the growing season length between those dates (days); (2) growing degree days (GDD, base 10° C); (3) heating and cooling degree days (HDD and CDD, respectively), using a base temperature of 18.33° C (65° F); (4) the total number of days each year with minimum temperatures less than –17.78° C (0.0° F) and greater than 32.22° C (90° F); and (5) an indication of the onset of spring, approximated by a 10-day running mean temperature reaching 10° C (50° F). Growing-degree-day calculations were performed with a base temperature of 10° C because this is a commonly used index for calculating thermal time for summer row crops grown in the region (e.g., corn), and heating- and cooling-degree-day calculations assuming the base temperature of 65° F (18.33° C) correspond to the methodology used by the National Weather Service. The 10-day running mean temperature of 10° C was chosen as an onset of spring because it is approximately correlated with the calendar date when corn is planted across southern and central Wisconsin, and 10° C is also the corn seed germination temperature. A statewide average value and the percentage of all grid cells that had a significant trend ($p < 0.1$) for each variable were also calculated.

In his 1959 publication, *The Vegetation of Wisconsin*, John T. Curtis described the two distinct floristic provinces in the state of Wisconsin; namely, the southwestern half of the state where tallgrass prairie and oak savannah vegetation once dominated before European settlement, and the northeast half where northern forests (the boreal element) are dominant (Curtis, 1959). A small continuous band, termed the Tension Zone, where vegetation from each geographic region can be found, divides these two regions. Curtis (1959) listed several important climatic factors that were generally found in those two floristic provinces of the state of Wisconsin. An analysis of changes in the approximated position of the ecological Tension Zone was performed (Curtis, 1959) using two temperature thresholds: (1) a change in position of the 13.5° C mean temperature isotherm for the period of April through June, computed using the daily average temperature, and (2) a change in position of the 60-day isarithm for the number of days each year with daily average temperature above 20° C (68° F) (Curtis, 1959).

An *F*-test of each regression analysis was calculated to provide the level of statistical significance (*p*-value) based on a mathematical function programmed into an automated Fortran computer program (Abramowitz and Stegun, 1964). The slope of each linear regression performed was multiplied by the total number of years (n = 57) to calculate the total change in variables occurring during the study period. One random, representative grid cell from each Wisconsin climate district was subjected to additional visualization and statistical analysis in the software package JMP (v5.01a) (SAS Institute Inc., Cary, NC) for each quantity analyzed to ensure that no step-function changes were present in the data record (e.g., test for stationarity in the time series).

An analysis of the change in frequency of daily heavy rainfall events (25.4, 50.8, and 76.2 mm or 1″, 2″, and 3″) at six first-order climate stations was conducted using ordinary least squares (OLS) and the Mann-Kendall method, a nonparametric test described by Helsel and Hirsch (1992) that has been utilized widely in the hydrological community (Molnar and Ramirez, 2001; Chen et al., 2007; Hamed, 2008). Mann-Kendall measures the strength of the monotonic relationship between event frequency and time and leads to the Kendall-Thiel robust trend line, defined as the median of all possible slopes between pairs of data points in the time series. Compared with the OLS technique, Mann-Kendall minimizes the importance of outlier data points and thus tends to provide a more rigorous detection of trends that is especially suitable for extreme events.

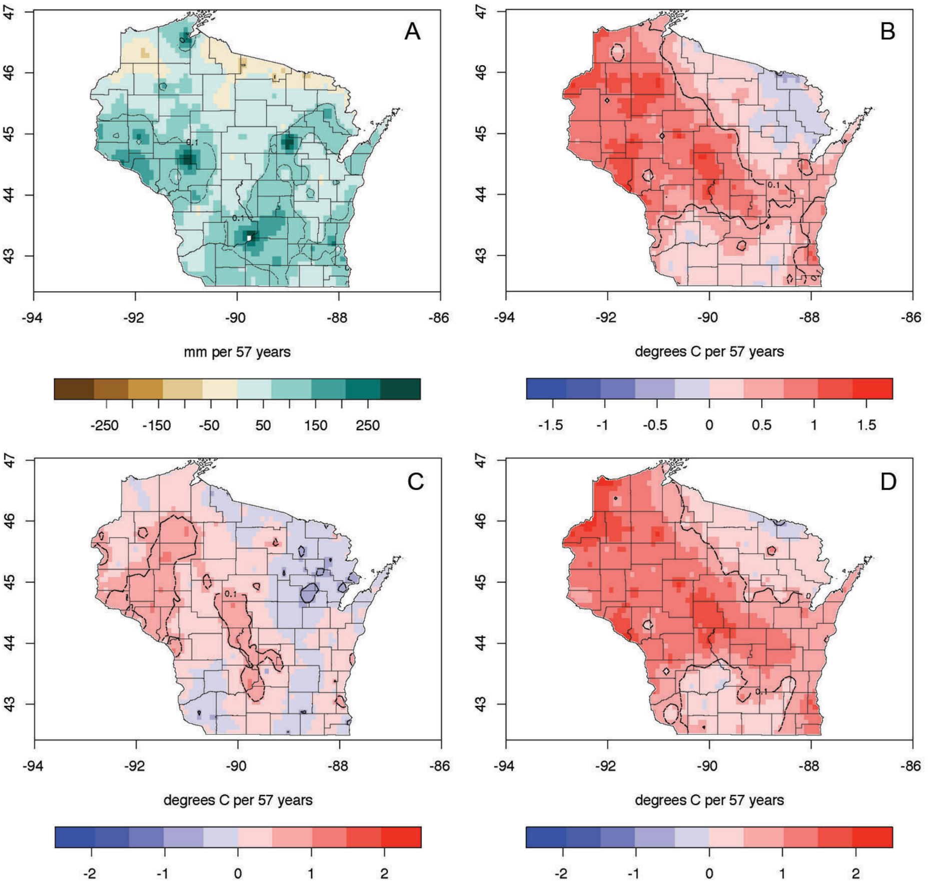

Fig. 2. Trends from 1950 to 2006 in (A) total annual precipitation, (B) annual average temperature, (C) annual average maximum temperature, and (D) annual average minimum temperature. Regions that had statistically significant ($p > 0.1$) trends are enclosed or bounded by dark dashed lines.

RESULTS

Annual Precipitation and Temperature Trends

Annual average precipitation has increased by approximately 50 to 100 mm (~5–15%) across large portions of Wisconsin (statewide average of 79.0 mm; Table 1), with the highest increases in the west-central and a corridor from south-central regions to the northeast (Fig. 2A). In general, in locations with increases of at least 75 mm over the 57-year period, changes were statistically significant ($p < 0.1$ in 33% of grid cells). Sections of the northwest and north-central were the only regions that experienced declines in annual average precipitation of ~25–50 mm, but the trends were not significant. Annual average temperatures increased by

Table 1. Statewide Average Trends for Variables Analyzed and the Corresponding Percentage of the Total Number of 8 km × 8 km Grid Cells in Wisconsin That Had $p < 0.1$[a,b]

Variable	Statewide average	Percentage of grid cells ($p < 0.1$)
Annual average minimum temperature	1.00	69.9
Dec-Jan-Feb minimum temperature	1.85	50.0
Mar-Apr-May minimum temperature	1.13	64.0
Jun-Jul-Aug minimum temperature	0.83	59.2
Sep-Oct-Nov minimum temperature	0.02	5.0
Annual average maximum temperature	0.21	17.3
Dec-Jan-Feb maximum temperature	0.97	19.1
Mar-Apr-May maximum temperature	0.77	22.4
Jun-Jul-Aug maximum temperature	–0.36	13.1
Sep-Oct-Nov maximum temperature	–0.59	11.4
Dec-Jan-Feb daily temperature range	–0.89	64.6
Mar-Apr-May daily temperature range	–0.35	21.7
Jun-Jul-Aug daily temperature range	–1.19	88.6
Sep-Oct-Nov daily temperature range	–0.61	40.4
Annual precipitation	79.0	33.1
Dec-Jan-Feb precipitation	13.5	10.3
Mar-Apr-May precipitation	14.9	5.1
Jun-Jul-Aug precipitation	5.1	14.2
Sep-Oct-Nov precipitation	48.1	36.4
Total days above 90° F (32.2° C)	–0.3	0.6
Total days below 0° F (–17.8° C)	–9.5	54.0
First fall freeze date (32° F, 0° C)	6.5	55.0
Last spring freeze date (32° F, 0° C)	–5.6	19.2
Growing season length	12.0	59.4
Spring onset date	–4.1	19.4
Growing degree days (base 10° C, 50° F)	5.4	15.2
Cooling degree days (base 18.3° C, 65° F)	17.8	9.2
Heating degree days (base 18.3° C, 65° F)	–202.0	51.2

[a]Statewide average trends (1950 to 2006) are the average over all 8 km × 8 km grid cells in Wisconsin, where each individual grid cell's value represents the total change in the quantity based on the slope of the linear regression.
[b]Temperature and degree-day trends are in °C; precipitation trends are in mm; remaining variables are in days.

0.3° C to 1.2° C ($p < 0.1$) over a large portion of the state in a corridor from the northwest and west-central through the east-central counties and down the western shore of Lake Michigan in Milwaukee, Waukesha, Racine, and Kenosha counties (Fig. 2B). In the northeast, annual average temperatures decreased approximately -0.1° C to –0.3° C, but were not significant. Annual average maximum temperature has increased by 0.3° C to 0.9° C across portions of the northwest, west-central, and central parts of the state, along with a small portion of the lakeshore counties from Manitowoc to Milwaukee (Fig. 2C). A smaller region in the northwest and central had significant trends ($p < 0.1$) toward warmer daytime highs. Sections of the southwest and northeast saw annual average daytime highs become cooler by –0.3° C to –0.6° C, but the trends were significant ($p <0.1$) only in isolated locations (Fig. 2C). Overall, the state annual average inetrend in daily high temperature was 0.21° C (Table 1). The spatial pattern of changes in annual average minimum temperatures was remarkably consistent with that of annual average changes, but the magnitude of the positive changes was approximately 0.6° C to 2.5° C ($p < 0.1$), and the spatial extent of a trend to cooler temperatures was confined to a couple of counties in the northeast (Fig. 2D**).** Overall, the state annual average trend in daily low temperature was 1.0° C, with nearly 70% of all grid cells having a significant trend (Table 1).

Seasonal Precipitation Trends

Wintertime precipitation has increased by 10–20 mm across most of Wisconsin from 1950 to 2006 (statewide average of 13.5 mm; Table 1), but the trends were generally weak, with only a few isolated locations being significant ($p < 0.1$) (Fig. 3A). In springtime, precipitation has increased by 20 to 60 mm across the southern and western portions of the state (Fig. 3B), with a few geographic regions across the north experiencing a trend toward somewhat drier conditions (–10 mm). However, the only significant trends were for increased precipitation in a small part of south-central Wisconsin near Sauk and Dane counties (Fig. 3B). Overall, the state average springtime precipitation trend was 14.9 mm (Table 1). Summer precipitation has increased by 30 to 60 mm across the large portion of the southern two-thirds of Wisconsin, in which summer precipitation trends for a smaller subregion, running from the southwest to northeast, were significant (Fig. 3C). However, a rather striking contrast was found across the northern one-third of the state, which has seen a trend toward decreasing summer precipitation of 30 to 60 mm, with significant trends across the region near the Michigan border (Fig. 3C). A small portion of the southeast corner of the state has also seen a significant trend toward less summer precipitation. The entire state has experienced a trend toward 10 to 80 mm more precipitation during the autumn (Fig. 3D). Across approximately the northwest one-half of the state from LaCrosse to Green Bay, these changes have been significant ($p < 0.1$). The state average autumn precipitation trend was +48.1 mm, which was the most significant increase, and significant trends were found in 36% of grid cells (Table 1).

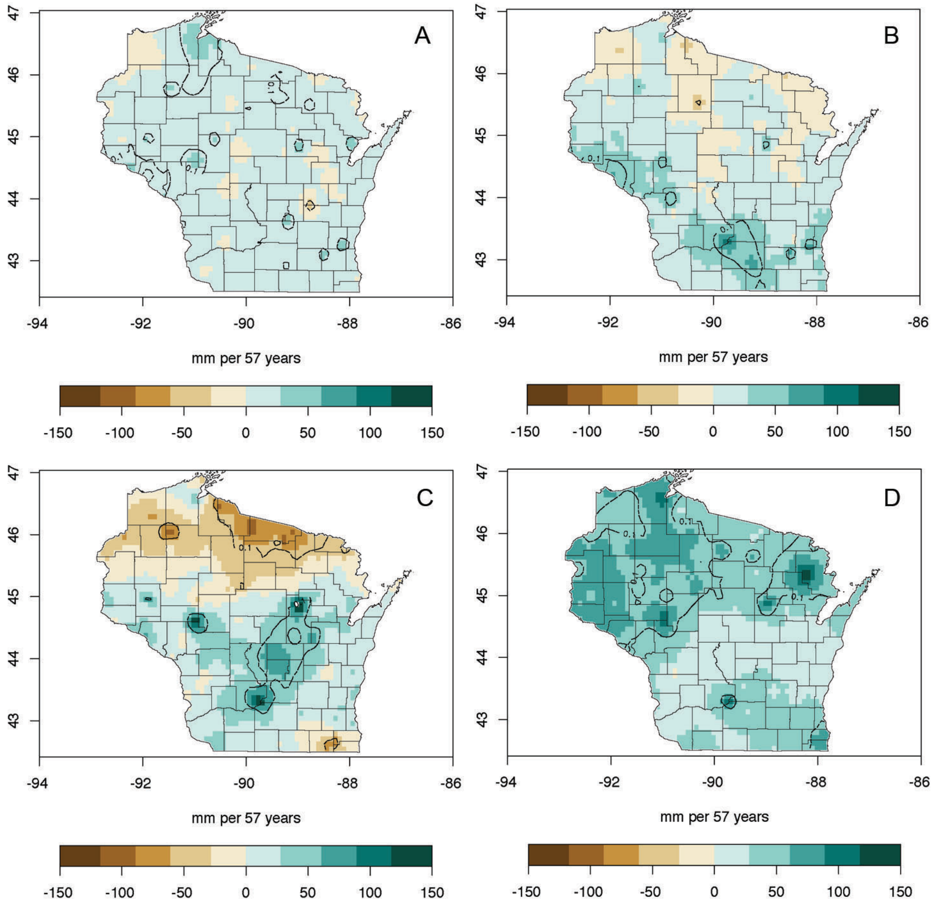

Fig. 3. Trends in total precipitation from 1950 to 2006 for (A) winter (Dec–Jan–Feb), (B) spring (Mar–Apr–May), (C) summer (Jun–Jul–Aug), and (D) fall (Sep–Oct–Nov). Regions that had statistically significant ($p > 0.1$) trends are enclosed or bounded by dark dashed lines.

Extreme Precipitation Events

An important but unanswered question is whether the characteristics of extreme weather differ in response to climate change. This possibility is particularly a concern for heavy precipitation events, whose frequency and magnitude are expected to increase in a warming climate, due to the rise in atmospheric moisture content (Trenberth, 1999). There is evidence that heavy precipitation has become more common in the U.S., including Wisconsin, during the past several decades (Madsen, 2007; Karl et al., 2008). To explore this question in more depth, we calculated the frequency of daily precipitation amounts exceeding 25.4, 50.8, and 76.2 mm (1″, 2″, and 3″) from 1950 to 2008 at six major airport weather stations covering the central and southern portions of the state: Eau Claire, Green Bay, La Crosse, Madison, Milwaukee, and Wausau.

Decadal frequencies of these extreme daily events are displayed in Figure 4, along with the corresponding annual mean precipitation amounts for comparison. The graphs show generally wetter conditions over time, with respect to both mean and extreme daily precipitation. For a more rigorous determination of the existence of trends in the extremes, we calculated the slope of each station's 1″, 2″, and 3″ time series using every individual year value rather than the decadal frequencies. The traditional method of trend calculation using OLS regression indicates an increasing frequency with time for 16 of the 18 time series, the only exceptions being negative trends of 1″ events at Wausau and 2″ events at Green Bay. The preponderance of positive slopes is consistent with the trends of mean precipitation by decade, which are increasing at all of the stations. There is a strong correlation between the mean decadal precipitation and the decadal frequency of 1″ events (six-station average of $r = 0.84$), whereas the less common 2″ and 3″ events are less highly correlated with the mean ($r = 0.39$ and 0.33, respectively), suggesting that they are more stochastic occurrences.

Based on the alternative Kendall-Thiel application, only two interannual trends of extreme events can be considered non-zero: positive trends (0.037 events year^{-1}) in 1″ events in Milwaukee and La Crosse. Both of these trends are statistically significant at the 90% confidence level but not the 95% level. The small number of significant trends and the modest amount of non-zero trends with Kendall-Thiel compared with the OLS method is somewhat surprising, given the apparent increase in heavy precipitation by decade at many of the stations (Fig. 4). The reason for this discrepancy stems not only from the stringent nature of the Kendall-Thiel test, but also from the characteristics of the extremes time series, which contain many years without any 2″ and 3″ daily events. The frequent occurrence of years without any such events results in a large number of pairwise slopes of zero in the Kendall-Thiel calculation, thus increasing the likelihood that the median of all possible slopes will be zero. Applying the Kendall-Thiel test instead to the decadal frequencies (Fig. 4) produces many more non-zero slopes (13 out of 18, 11 of which are positive), but none of the trends is statistically significant.

To investigate whether extreme events are shaping the observed trend toward wetter climatic conditions, we calculated each station's change in precipitation intensity (average daily precipitation amount on days with measurable rainfall or snowfall) and precipitation frequency between 1950 and 2008. Over this time period, all six stations experienced an increase in the number of wet days per year, and all but Wausau showed a positive trend in intensity. Averaged over all the stations, the increase in total precipitation (13.2%) is primarily explained by an increase in the frequency of wet days (10.2%), rather than by greater precipitation intensity (3.1%). Given that the sum of the trends in frequency and intensity almost exactly matches the increase in total precipitation, we can attribute approximately three-fourths of the positive, multi-decadal precipitation increase to more frequent (rather than more intense) events.

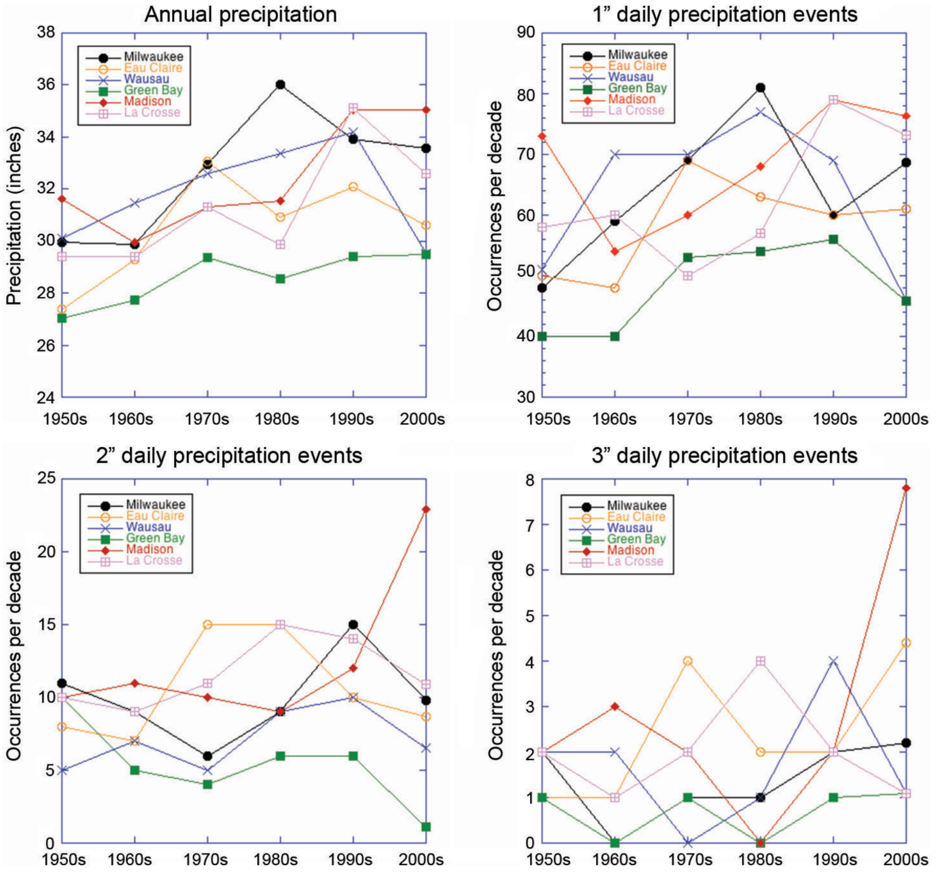

Fig. 4. Annual and extreme precipitation at six stations in Wisconsin, 1950–2008. The 2000s decade was adjusted upward by 11% to account for the missing 2009 year.

Seasonal Maximum Temperature Trends

Wintertime daily average maximum temperatures have increased by 0.2° C to 2.0° C over almost all of Wisconsin (statewide average of 0.97° C; Table 1), with the largest magnitude of changes ($p < 0.1$) located in the central and west-central regions (Fig. 5A). There have been no significant trends toward cooler wintertime daytime high temperatures. Springtime daily average maximum temperatures have increased by 0.5° C to 1.5° C across most of the state (Fig. 5B), with the exception being the far northeast counties north of Green Bay (statewide average of 0.77° C; Table 1). Significant trends ($p < 0.1$) were found in the central and west-central locations. Summer daily average maximum temperatures have generally decreased by 0.2° C to 1.0° C across most of the state (Fig. 5C), with some exceptions in portions of the northwest and central (statewide average of –0.36° C; Table 1). The trend toward cooler summer daytime highs was most significant ($p < 0.1$) in the

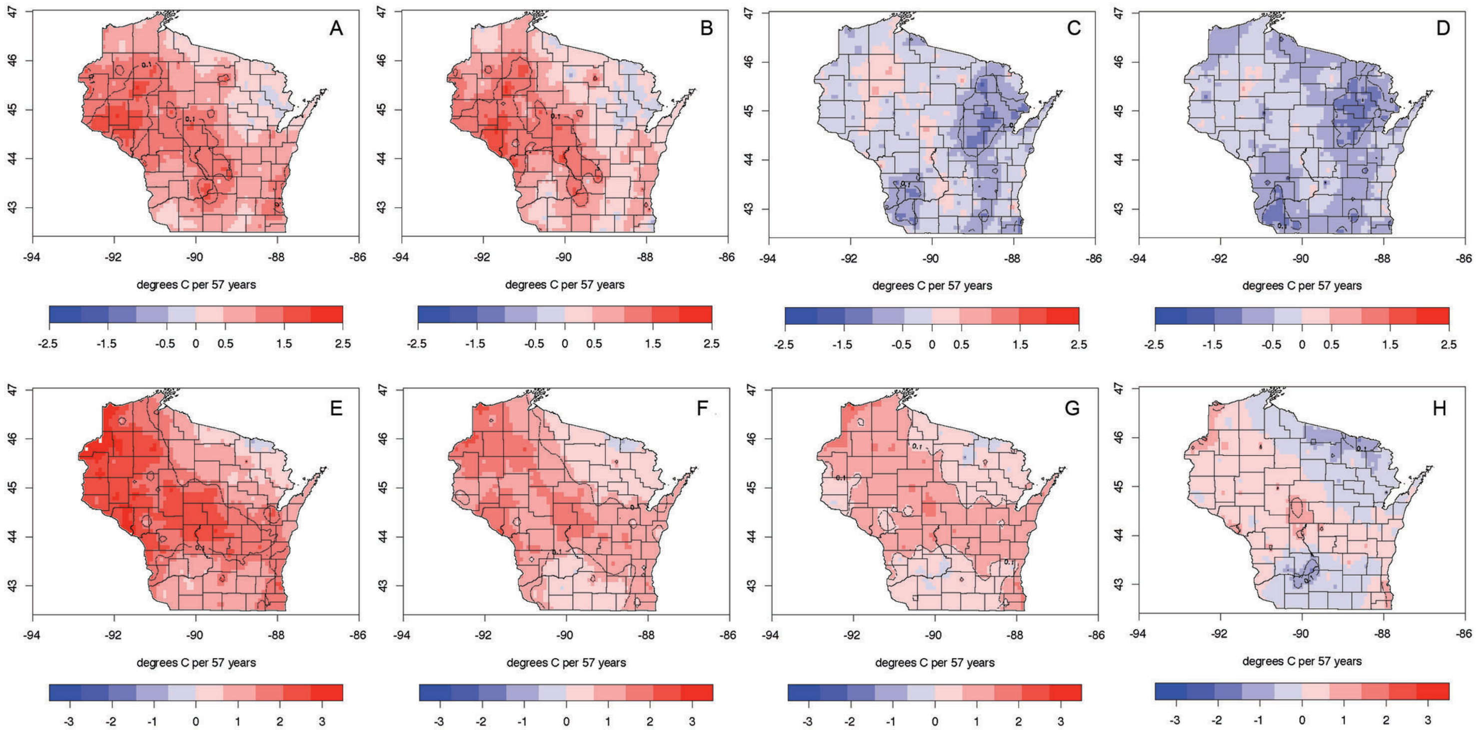

Fig. 5. Trends from 1950 to 2006 for daily maximum temperatures in (A) winter (Dec–Jan–Feb), (B) spring (Mar–Apr–May), (C) summer (Jun–Jul–Aug), and (D) fall (Sep–Oct–Nov), and trends in daily minimum temperatures for (E) winter (Dec–Jan–Feb), (F) spring (Mar–Apr–May), (G) summer (Jun–Jul–Aug), (H) fall (Sep–Oct–Nov). Regions that had statistically significant ($p > 0.1$) trends are enclosed or bounded by dark dashed lines.

southwest corner and northeast section of the state, where the magnitude was approximately –1.0° C (Fig. 5C). Autumn daily average maximum temperatures have decreased by 0.2° C to 1.4° C across most of the state (Fig. 5D). Similar to summer spatial patterns, the trend toward cooler autumn daytime highs was most significant ($p < 0.1$) in the southwest corner and northeast section of the state, where the magnitude was approximately –1.0 to –1.4° C (Fig. 5D). The overall statewide average trend for autumn daily high temperatures was –0.59° C (Table 1).

Seasonal Minimum Temperature Trends

Wintertime daily average minimum temperatures have increased by 1.0° C to 3.5° C over most of Wisconsin, with the largest magnitude of changes ($p < 0.1$) located in the central regions through the entire western portion of the state (Fig. 5E). There is a general absence of significant trends toward cooler wintertime nighttime low temperatures, and the statewide average seasonal minimum temperature change for winter was highest out of all temperature trends analyzed (1.85° C; Table 1). Springtime daily average minimum temperatures have increased by 0.3° C to 1.5° C across most of the state (statewide average of 1.13° C; Table 1), and significant trends ($p < 0.1$) were found in 64% of all grid cells (Table 1), mostly concentrated in a large corridor from the western portions of the state, through the central and east-central counties (Fig. 5F). Summer daily average minimum temperatures have increased by 0.5° C to 1.3° C across most of the state (statewide average of 0.83° C; Table 1), with the most significant trends ($p < 0.1$) in a corridor from the northwest and west-central portions of the state, through the east-central counties (Fig. 5G). A few isolated regions saw a trend toward cooler summer temperatures. Autumn daily average minimum temperatures have decreased by 0.5° C to 0.7° C across northeast and southern portions of the state, but the corridor from the northwest and west-central through the east-central part of the state experienced increases of 0.1° C to 0.5° C (Fig. 5H) (statewide average of only 0.02° C; Table 1). The trend toward cooler autumn nighttime lows was most significant ($p < 0.1$) in small sections of the south-central and far northeast near at the Michigan border (Fig. 5H). Significant increases in nighttime lows during autumn were also noted in the far southeast counties near Milwaukee, Racine, and Kenosha.

Diurnal Temperature Range

In general, most of Wisconsin has seen a trend toward a decreasing diurnal temperature range across all seasons. In wintertime (Fig. 6A), the statewide average trend was –0.89° C, with 65% of all grid cells having a significant trend (Table 1). The highest magnitude of change was found in the northwest and central portions of the state, with values around –1.5 to –2.0° C (Fig. 6A). In springtime (Fig. 6B), the statewide average trend was –0.35° C, with 21% of all grid cells having a significant trend (Table 1). The highest magnitude of change was focused in the east-central and some regions of the south-central that actually saw an increase in diurnal temperature change that was significant. In summertime (Fig. 6C), the statewide average trend for the diurnal temperature range was –1.2° C, with 89% of all grid cells

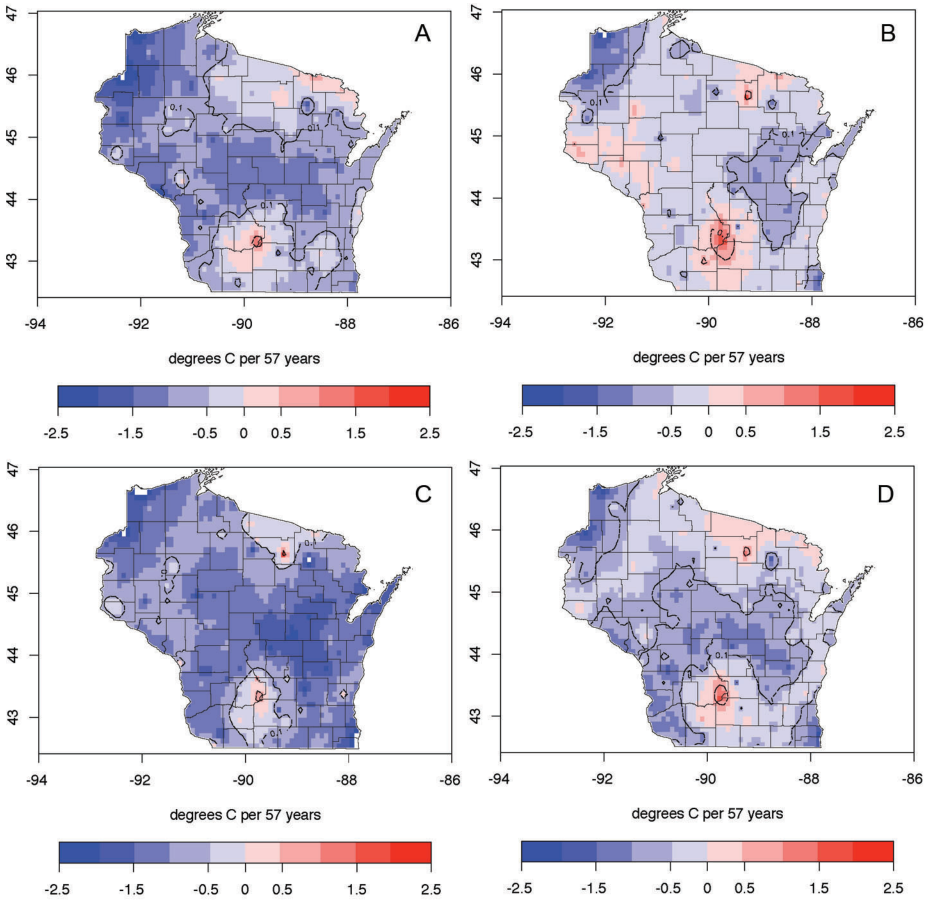

Fig. 6. Trends from 1950 to 2006 for diurnal temperature range in (A) winter (Dec–Jan–Feb), (B) spring (Mar–Apr–May), (C) summer (Jun–Jul–Aug), and (D) fall (Sep–Oct–Nov). Regions that had statistically significant ($p > 0.1$) trends are enclosed or bounded by dark dashed lines.

having a significant trend (Table 1). Of the four seasons, summertime was the time period that experienced the greatest and most widespread compression of the diurnal temperature range. The highest magnitude of change was found in the southeast, east-central, and northwest portions of the state, with values around –1.5 to –2.0° C (Fig. 6C). In autumn (Fig. 6D), the statewide average trend for the diurnal temperature range was –0.61° C, with 40% of all grid cells having a significant trend (Table 1). The highest magnitude of change was found in the southeast, west-central, and central portions of the state, with values around –0.75 to –1.5° C (Fig. 6D).

Extreme Temperature Trends

In general, most of Wisconsin has experienced a significant trend toward fewer days each year with daily minimum temperatures below –17.8° C (0.0° F) (Fig. 7A).

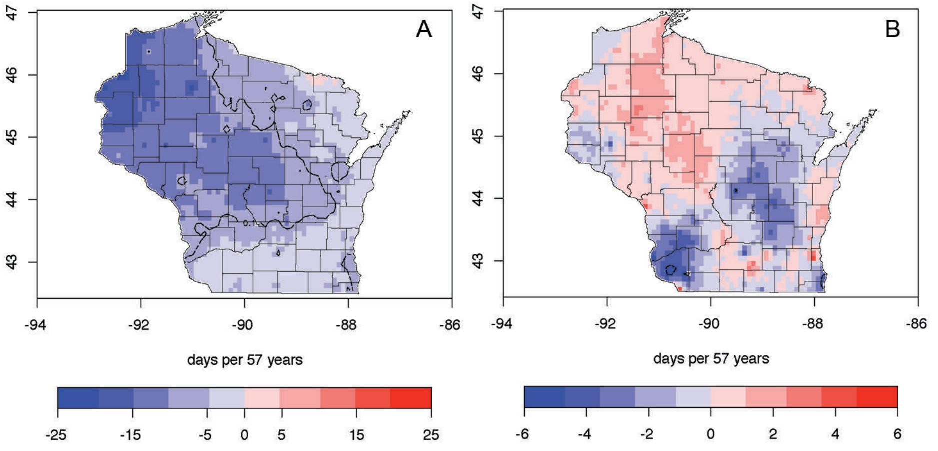

Fig. 7. Trends from 1950 to 2006 for the annual occurrence of daily temperatures (A) less than –17.8° C (0.0° F), and (B) greater than 32.2° C (90° F). Regions that had statistically significant ($p > 0.1$) trends are enclosed or bounded by dark dashed lines.

The rate of annual occurrence of these extremely cold temperatures has declined by a total of 5 days across the south and northeast, and –15 to –20 days in the far northwest corner of the state (Fig. 7A). These trends are significant ($p < 0.1$) for approximately 54% of the state (Table 1), predominantly in the northwest, west-central and central regions, and the statewide average rate of change was –9.5 days (Table 1). In general, the annual frequency of daily maximum temperatures greater than 32.2° C (90° F) has not changed significantly from 1950 to 2006 across Wisconsin (Fig. 7B); the statewide average change was only –0.3 days (Table 1). Across the southwest through northeast part of the state, there has been a small trend toward fewer days each year with daily maximum temperatures greater than 32.2° C. Large portions of central and northwestern Wisconsin have experienced a slight increase in the annual occurrence of these very warm daily high temperatures, but the majority of these changes have been insignificant (Fig. 7B); only 0.5% of all grid cells had a significant trend (Table 1).

GDD, CDD, and HDD Trends

A majority of the southern quarter of the state as well as the northeast has experienced a trend toward fewer GDDs (base 10° C, 50° F) (Fig. 8A). The majority of these changes from 1950 to 2006 have been around –30° C to –100° C, but they were significant ($p < 0.1$) at only a few isolated locations. However, it appears that in the southeast, the Milwaukee metropolitan region has seen a significant ($p < 0.1$) increase in GDD of 50° C to 100° C (Fig. 8A). The statewide average change in GDDs was 5.4° C, with only 15% of grid cells having a significant trend (Table 1). The number of CDDs (base 18.3° C, 65° F) across the central, west, and northwest portion of Wisconsin has increased by 20° C to 70° C (Fig. 8B), and in small regions

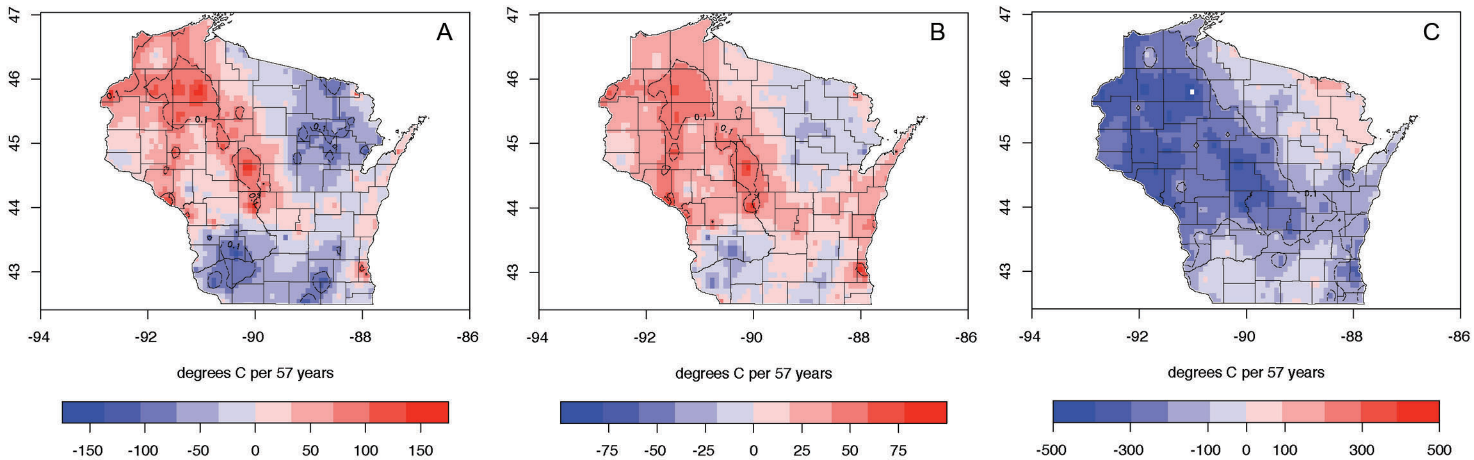

Fig. 8. Trends from 1950 to 2006 for annual total (A) growing degree days (base 10° C), (B) cooling degree days (base 18.3° C, 65° F), and (C) heating degree days (base 18.3° C, 65° F). Regions that had statistically significant ($p > 0.1$) trends are enclosed or bounded by dashed lines.

in the central and northwest the trends were significant ($p < 0.1$). The Milwaukee/Waukesha metropolitan regions as well as other lakeshore (Lake Michigan) counties north of Milwaukee also saw an increase in CDDs of between 10° C and 40° C (Fig. 8B). Similarly to trends in GDD, portions of the southwest, southeast, and northeast saw a trend toward a lower accumulation of CDDs of –10° C to –50° C; however, none of these trends were significant. Only 9.2% of all grid cells had a significant trend in CDDs, and the overall state average was 17.8° C (Table 1). A large part of the northwest, west, central, and east-central portions of Wisconsin have seen a significant trend toward fewer HDDs (base 18.3° C, 65° F) of –50° C to –450° C (Fig. 8C). The northeast portion of the state (roughly northeast of a Green Bay to Hurley line) has seen a slight increase in HDDs, but the magnitude was not significant (Fig. 8C). Over the entire state, 51% of grid cells had a significant trend, and the average statewide trend was –202.0° C (Table 1).

Trends in Last Spring Freeze, First Fall Freeze, Growing Season Length, and Onset of Spring

In general, most of the state of Wisconsin has experienced a trend toward an earlier occurrence of the last spring freeze date (0.0° C, 32° F threshold) by about 2 to 10 days (Fig. 9A), with an overall statewide average of –5.6 days (Table 1). The most significant changes have occurred in the southwest corner, the central through northeast region, as well as the extreme northwest counties. In the far northwest, the date of the last spring freeze has retreated by up to two weeks in just 57 years (Fig. 9A). Less significant trends were found across most of the southeast portion of the state. The lakeshore region in the Milwaukee and Racine area had a significant trend toward an earlier occurrence of the last spring freeze date by about one week. Most of the central, northeast, and northwest part of Wisconsin has experienced a trend toward a later date of occurrence of the first fall freeze (0.0° C, 32° F threshold) by about 3 to 12 days (Fig. 9B). Less significant trends were found across most of the southeast and extreme southwest portion of the state near the Mississippi River. A total of 55% of all grid cells had a significant trend in fall freeze date, with an overall state average of 6.5 days later (Table 1). Some of these regions actually saw a trend toward an earlier arrival of the first fall freeze date, but those trends were not significant (Fig. 9B). These spring and fall freeze-date trends, which are diverging in many regions of the state, have led to a highly significant increase in the length of the growing season in many locations (Fig. 9C). The largest trends are located in the northwest and central regions, where typically the growing season has been extended by two to three weeks. Some counties in the extreme northwest have seen the growing season lengthen by about four weeks in 57 years, or about 5 days per decade (Fig. 9C). The western counties near the Mississippi River, the south- central, southeast, and east-central counties have experienced insignificant changes in growing-season length. The Milwaukee metropolitan area is the exception in the southeast, where it appears the growing season trend is significant, and has lengthened by approximately 10 days from 1950 to 2006 (Fig. 9C). The statewide average change in growing-season length was 12.0 days longer, and 59% of all grid cells had a significant trend (Table 1).

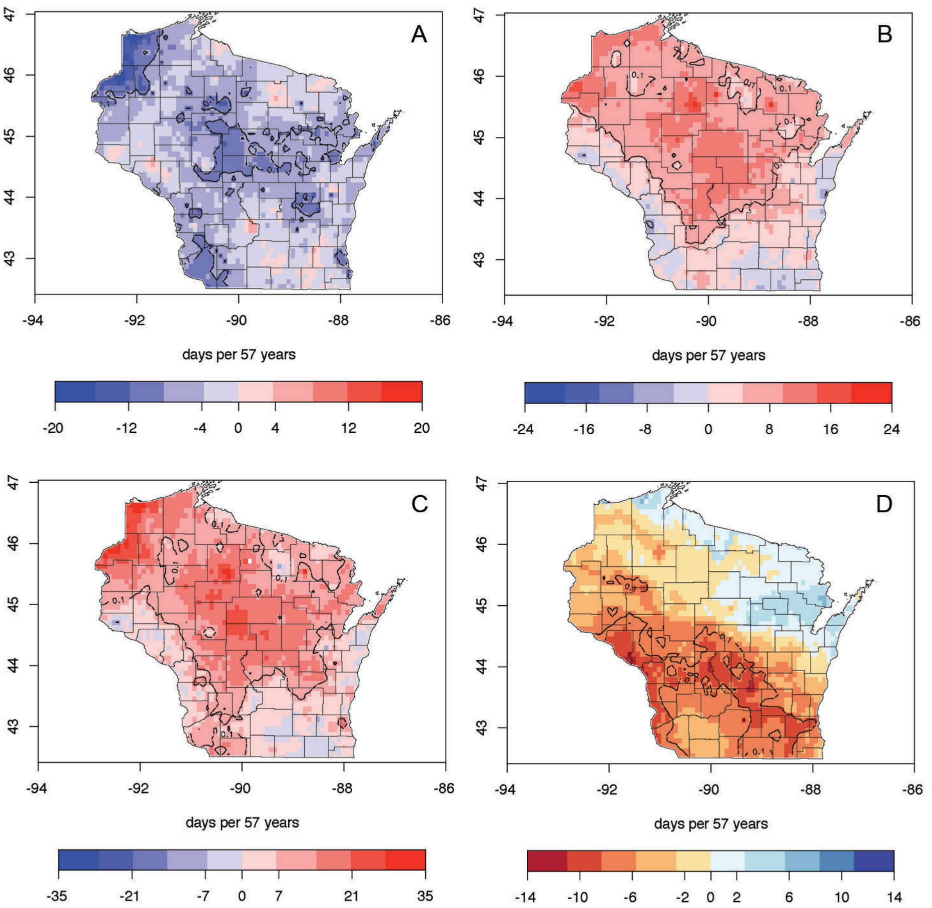

Fig. 9. Trends from 1950 to 2006 for changes in (A) date of last spring freeze (threshold 0.0° C), (B) date of first fall freeze (threshold 0.0° C), (C) growing-season length (days between last spring freeze and first fall freeze), and (D) date of onset of spring (when 10-day running mean daily temperature reaches 10° C or 50° F). Regions that had statistically significant ($p > 0.1$) trends are enclosed or bounded by dashed lines.

In order to better understand whether significant changes in the arrival of spring have occurred, changes in the date when a 10-day running mean daily temperature threshold of 10° C (50° F) was reached were studied (Fig. 9D). This might be a more robust indication of sustained changes in spring onset rather than a single-day threshold like the last spring freeze date. For example, if Figures 9A and Fig. 9D are compared, it is easy to see how different interpretations can result in the interpretation of springtime climate change. In general, most of the state southwest of a Manitowoc-to-Ashland line has experienced an earlier onset of spring (Fig. 9D). The most significant changes have been found in the southern half of the state, where the date of occurrence of spring onset has become earlier by 3 to approximately 10 days. While the northeast and north-central portion of the state has seen a minimal

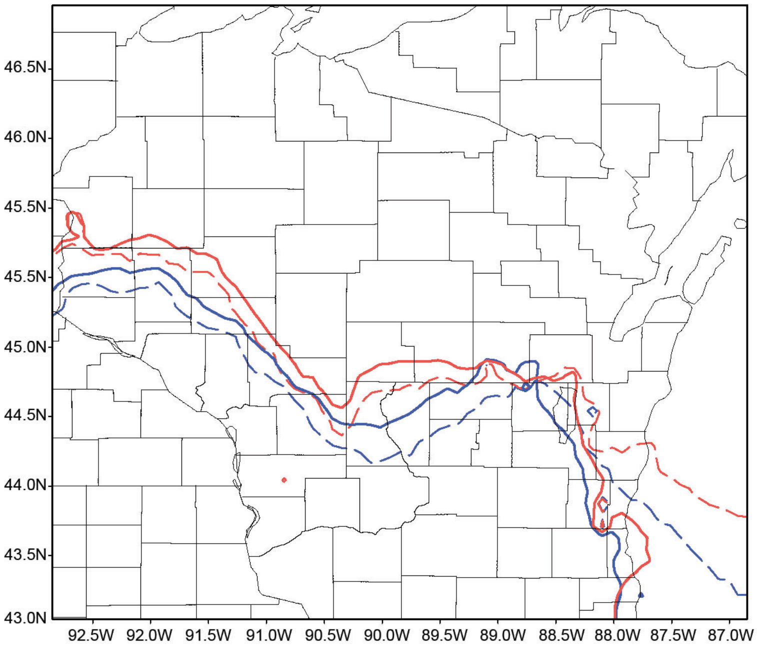

Fig. 10. Depiction of changes in the location of the Tension Zone across Wisconsin. The solid lines indicated the location of the 13.5° C (56.3° F) isotherm for mean daily average temperature in Apr–May–Jun, and dashed lines are isarithms for 60 days per year with the average temperature above 20º C (68º F). Blue lines indicate the 30-year average for 1950–1979, and red lines indicate the 27-year average for 1980–2006.

trend toward a later onset of spring of about 1 to 4 days over 57 years, those trends were not significant (Fig. 9D). The statewide average change in spring onset date was –4.1 days (Table 1).

Location of the Tension Zone

An analysis was performed that looked at two key climatic factors to determine if changes in the location of the Tension Zone have occurred during the 1950 to 2006 period. Figure 10 shows the changes in position of the 13.5° C isotherm, corresponding to average daily temperature for April through June as well as the changes in the isarithms for 60 days per year with average daily temperatures above 20° C. It appears that there have been subtle shifts northward (15 to 20 km) of these climatic factors that are well correlated with the position of the Tension Zone as documented by Curtis (1959). While the factors appear to be correlated with each other in the western two-thirds of the state, they appear to be less correlated in counties closer to Lake Michigan (Fig. 10), and systematic shifts are less clear for the 13.5° C isotherm for May–June in the southeast corner of the state. This might reflect the temperature-moderating influence of Lake Michigan as well as the potential urban heat island that exists in the southeast corner of the state near Milwaukee and Waukesha and other lakeshore communities.

DISCUSSION

The results suggest that changes in climate during the 1950–2006 period across Wisconsin have varied considerably in geographic space, raising some question as to what the underlying mechanisms are to have caused such diverging trends from one region of the state to another. Because Wisconsin is adjacent to two of the Great Lakes, located in the vicinity of the Corn Belt where a high density of land area planted in corn and soybeans efficiently move water from the soil back to the atmosphere during July and August (Changnon et al., 2003), and impacted by the interaction of multiple air masses through the changing seasons (Bryson, 1966), it is possible that patterns of future climate change may be quite difficult to predict by Global Circulation Models (GCMs) based on the historical record of climate variation. Some of the spatial variability in the results are likely impacted by local climate drivers such as the proximity to Lake Michigan or Lake Superior, or from local land cover changes that have occurred near COOP stations which might have affected surface albedo and energy balance. Future studies that couple the quantitative results in this study with an analysis of changes in agricultural management, synoptic-scale weather patterns, and the position of jet streams and frontal boundaries could possibly lead to a better understanding of the underlying causes of the patterns and trends of recent climate change in Wisconsin.

Results should be interpreted with a bit of caution because the starting and ending points (i.e. year) for which numerical trends are calculated only represent one snapshot of the changes that have occurred over the long term. Undoubtedly, some variation in the magnitude of trends would result if different periods were analyzed. The 1950 starting year was selected to maximize the number of stations with continuous data to help construct the best dataset, and still extend back in time at least 50 years. According to Kalnicky (1974), the 1950 starting date also coincides with a time when the hemispheric circulation transitioned from more frequent zonal flow between 1900 and 1950 to more frequent meridional flow after 1950.

Historical changes in land use and land cover in the vicinity of observing stations could have modified local energy balance and the resulting temperature record (Hale et al., 2006). However, the data we used (Serbin and Kucharik, 2009) had a high level of quality control applied so that erroneous or questionable data (or even entire station records) were filtered before becoming a part of the statistical interpolation. The interpolated values were tested against data that were withheld from the original dataset (Serbin and Kucharik, 2009). Most importantly, the spatial coherence of results in our analysis leads to greater confidence that the findings are realistic and are not an arbitrary result based on just a few single locations. The analysis shows spatial continuity of how climate has changed, but just as easily depicts the complexity of these changes due to a good deal of heterogeneity.

Several other studies (of the behavior of plants, animals, and lakes) support the general climate trends that have recently occurred across Wisconsin. Studies of phenological events (e.g., bud break, plant flowering, bird arrival) by Bradley et al. (1999) and Zhao and Schwartz (2003) have both documented an earlier arrival of spring. Bradley et al. (1999) studied changes in 74 phenophases at a farm near Baraboo in southern Wisconsin, including arrival dates of migratory birds and spring flower blooming dates, over a total of 61 years, starting in the 1930s with observations made by Aldo Leopold. The mean change for a total of 55 phenophases studied was –0.12 days per year (Bradley et al., 1999), which compares favorably to a value of –0.15 days per year at the same approximate location (Fairfield Township, Sauk Co.) from 1950–2006 using data in this study (e.g., Fig. 9D). Zhao and Schwartz (2003) reported that the onset of spring from 1965–1998 was arriving earlier by 0.46 days yr^{-1} in the southwest and 0.25 days yr^{-1} in the central and eastern regions. The geographic pattern of these trends approximates the simple index (Fig. 9D) used in the current study, but the overall trends are slightly higher in magnitude. Zhao and Schwartz (2003) also cited the influence of Lake Michigan in modifying the advance of the onset of spring in the eastern portion of the state. Magnuson et al. (2003, 2006) reported that there has been a long-term trend toward shorter winters and a shorter ice season across Wisconsin. For example, in southern Wisconsin, the ice cover duration trend for Lake Mendota from 1980–2002 was declining by 12.6 days per decade (Magnuson et al., 2006). Magnuson et al. (2003) concluded that because of the widespread nature of these changes across Wisconsin, a regional forcing such as climate change was the more likely cause than land use change (Ghanbari and Bravo, 2009).

The isolated significant trends that were calculated for some variables (i.e., growing-season length, GDD, and CDD) in the southeast part of the state near Milwaukee suggest that an urban heat island signal is likely present in a few stations in that area that might have experienced an increase in urban development. Zhang et al. (2004) used remote sensing data from MODIS to look at the influence of urbanization in the eastern one-half of the U.S. on land surface temperatures and vegetation green-up in spring for the year 2001. They showed that in the urban areas of Madison, Milwaukee, and the Appleton to Green Bay corridor, vegetation green-up occurred 0–2, 4–6, and 6–10 days earlier, respectively, than in the surrounding rural landscapes. Springtime land surface temperatures were found to be 0–1° C, 2–3° C, and 3–3.5° C higher in the core of Madison, Appleton–Green Bay, and Milwaukee, respectively, in 2001. While an urban signal was detected in the Milwaukee area for changes in degree-day calculations (Fig. 8) and growing-season length (Fig. 9C) from 1950–2006 in the current study, an urban signal was generally absent for the other large cities. This might be partially due to a lack of COOP stations in the center of those cities, which is generally a positive attribute for local climate change studies. The large majority of COOP stations are not generally found within dense, urban settings in Wisconsin. However, given the results derived from high-resolution remote sensing information (e.g., Zhang et al., 2004), it is suggested that a combination of *in situ* temperature data combined with other remotely sensed data gives us an even better likelihood of understanding local to regional patterns of climate change and how land cover change may confound those results as well as differentially impact ecosystems, hydrology, and carbon cycling.

Several of the observed trends in temperatures and related quantities deserve additional discussion. The first is the strikingly opposite trends in summertime maximum vs. minimum temperatures (Figs. 5C vs. 5G), and the second is the mismatch between trends in growing-season length, which are generally increasing almost everywhere across Wisconsin (Fig. 9C), and GDD, where large regions in the southwest, south-central, and northeast have seen a strong decline in GDD, even though the growing season has increased. The coincidence of large areas with negative trends in GDD with the nearly ubiquitous increase in growing-season length across the state is likely related to the absence of a positive trend in summertime daytime high temperatures. Generally, if the growing season is longer, it should favor the accumulation of more GDD, so it is noteworthy that cooling of summer daytime temperatures (not nighttime) and the decreasing average diurnal temperature range must be responsible for counteracting the expected increasing trend in GDD that would accompany a lengthening of the growing season. These results are particularly important to agricultural productivity across Wisconsin because Kucharik and Serbin (2008) found that a trend toward cooler and wetter conditions across Wisconsin during summer favored higher trends in corn and soybean yields. Furthermore, a lengthening of the growing season would allow farmers to plant crop varieties with higher yield potential (Kucharik, 2006); thus, a combination of a longer growing season and cooler summertime maximum temperatures could be extremely beneficial to increasing crop yields.

Other studies have proposed that a decline in the frequency of very hot days—or at least an unexpected absence of increases as observed in this study as well as across larger regions of the Midwest and Great Plains—could be attributed to increasing daytime cloudiness (Dai et al., 1997; Pan et al., 2004; Zhou et al., 2008), more surface evapotranspiration from expanding agriculture (Changnon et al., 2003), and altered atmospheric circulation patterns, including those associated with the development of the nocturnal low-level jet in the Great Plains (Pan et al., 2009). Schwartz (1995) took an even closer look at the change in frequency of different air-mass types across the North Central U.S. from 1958 to 1992 to better understand the dynamic changes and reasoning for fluctuations in temperatures over long periods. He found that the majority of stations used in his analysis, including Green Bay, Wisconsin, experienced a significant ($p < 0.001$) upward trend in 850 hPa dew point temperatures of approximately 0.5 to 1.0° C per decade from 1958 to 1992 (Schwartz, 1995). If more water vapor were present in the lower atmosphere, it could also work to decrease daily maximum temperatures through increased haze, or by providing the fuel necessary for greater cloudiness, both of which would lead to lower values of incoming shortwave radiation. Correspondingly, if humidity and cloud cover were increased at nighttime, air temperatures would not cool off as quickly. Furthermore, if soil moisture were higher due to increased precipitation and decreased evapotranspiration, the energy available must continue to work to evaporate H_2O before heating the air (through sensible heating), and therefore it may not be surprising to see minimal changes in the frequency of very hot days. Thus, the overall diverging trends that have been observed in daytime versus nighttime temperature changes during summertime, and a compression of the diurnal temperature range, are potentially representative of increased water vapor in the atmosphere. The approximate 10% increase in precipitation from springtime through autumn across Wisconsin might be an indication of an increase in lower atmospheric moisture.

The recent changes in climate across Wisconsin appear to have already impacted plant and animal species (Bradley et al., 1999; Zhao and Schwartz, 2003), lake ice dynamics (Magnuson et al., 2006), and agricultural productivity (Kucharik and Serbin, 2008). These are all representative of important biological and ecological systems of the region, not to mention important to the state's economy. Such evidence of the impacts of climate change suggest that if trends in climate were to continue, possible adaptive measures would be needed so that managers of forests, producers of agricultural products, and our caretakers of natural resources (e.g., wildlife, water) would stand the best chance of successfully dealing with a new climate regime. The development of adaptation strategies would be implemented via public officials, municipalities, farmers, resource managers, and businesses to reduce the risk associated with continued climate change. In the spirit of WICCI, the analysis of recent climate change will hopefully provide a good foundation for which to build new adaptive strategies for the state of Wisconsin.

CONCLUSIONS

During the 1950–2006 period across Wisconsin, significant changes in climate have occurred, but the spatial patterns and magnitude of these changes vary significantly from location to location. In general, the most widely applicable statement that can be made about climate change in Wisconsin is that the state's residents are experiencing a trend toward wetter conditions with less extreme cold, but the number of extremely hot days during summer does not appear to have increased. This is consistent with other recent studies of changes in temperature extremes (Peterson et al., 2008). The four seasons have experienced widely varying degrees of climate change, with the most pronounced warming having occurred in winter and spring, and nighttime low temperatures are increasing at a rate that is faster than daytime highs. The difference in the rate of warming between daytime and nighttime temperatures has caused the diurnal temperature range to compress by 0.35° C in springtime to as much as 1.2° C in summertime, as reported in other studies (Dai et al., 1997; Zhou et al., 2008). The growing season has become longer by about 1 to 3 weeks across the interior portion of the central and northern parts of the state. The Tension Zone appears to have shifted slightly to the north and northeast by a modest 15 to 20 km, but the shift suggests that continued climate change could pose a threat to the distribution of vegetation and animal species in the region, as well as have an impact on productivity of our croplands and forests (Kucharik and Serbin, 2008). The increase in CDDs and decrease in HDDs have likely impacted energy usage and heating and cooling demands, but might be overshadowed by increasing consumption by residents of the state for everyday energy use (EIA, 2009).

In future studies, an extension of the current study to a larger region in the Midwest is anticipated to better understand whether the patterns observed across Wisconsin are connected to larger patterns or drivers in the Great Lakes region. The results presented here are meant to provide policymakers, land managers, and scientists a starting point from which to discuss recent climate change across Wisconsin, and how these changes, if they were to continue, might impact the broader natural resources, industry, and future planning in the state of Wisconsin. Furthermore, the results are also intended to help climate scientists better understand the robustness of GCM output for the region, and provide the initial basis for discussions about where discontinuities exist between the recent historical record of change and what is projected to occur in the future.

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