

INCREASING GROWING-SEASON LENGTH IN ILLINOIS DURING THE 20TH CENTURY

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Abstract. Using daily minimum air-temperature (T_{\min}) data from the state of Illinois, the dates of spring and fall freezes – and the resulting growing-season length – are examined for trends during the period 1906–1997. Of the stations in the Daily Historical Climate Network, most show trends toward earlier spring freezes; however, trends in fall freezes are not consistent over the station network. Although the time series are highly variable (noisy), results suggest that the growing-season length in Illinois became roughly one week longer during the 20th century. To examine how changing freeze-date statistics relate to changing air-temperature probability distributions, percentiles of T_{\min} for moving 10-year periods were analyzed for trends during the typical times for spring and fall freezes in Illinois (i.e., the months of April and October). The lower portion of the April probability distribution shows substantially larger warming ($0.5\text{--}0.7\text{ }^{\circ}\text{C}/100\text{ yrs}$) than the upper portion of the distribution ($0.2\text{--}0.3\text{ }^{\circ}\text{C}/100\text{ yrs}$), suggesting that although cold events are warming during April, warm events are not warming as fast. Conversely, the lower portion of the October probability distribution shows modest cooling in T_{\min} ($-0.2\text{ }^{\circ}\text{C}/100\text{ yrs}$ for the 10th percentile), while middle and upper portions of the distribution show very large rates of cooling (up to $-1.5\text{ }^{\circ}\text{C}/100\text{ yrs}$ for the 40th–70th percentiles). Analysis of the entire probability distribution provides a more-comprehensive perspective on climatic change than does the traditional focus on central tendency.

1. Introduction

Systematic changes and natural variations in growing-season length and associated freeze-date statistics have important implications for natural and managed ecosystems. Many plants and insects are particularly sensitive to the timing of extreme cold events at the beginning and end of the growing season. Variations in growing-season length and the timing of freeze events also can be an important indicator of climatic change that may not be represented in mean conditions. While there are a wide variety of extreme events and their impacts can be highly variable (e.g., Easterling et al., 2000; Karl and Easterling, 1999; Katz and Brown, 1992), this research seeks to examine variations in last spring freeze, first fall freeze, and growing-season length for the state of Illinois as an indicator of climate variations in this region. Illinois was selected both for the quality of long-term data and its agricultural importance. Maps and spatial averages of trends in these statistics, as well as the time-evolution of probability distributions of daily minimum air temperature (T_{\min}), are examined to evaluate space-time patterns.



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2. Background

Although there are many possible definitions of growing-season length and freeze dates (Brinkmann, 1979), the most common are those associated with dates of occurrence for 0 °C minimum air temperatures. Numerous studies have evaluated the variability in the freeze-free period and associated statistics (e.g., Baron et al., 1984; Brinkmann, 1979; Brown, 1976; Cooter and LeDuc, 1995; Moran and Morgan, 1977; Schmidlin and Dethier, 1986; Skaggs and Baker, 1985; Suckling, 1986; Thom and Shaw, 1958). Both increases and decreases in growing-season length have been reported, depending on location and period of record. Nearly all of the more recent studies, however, have reported increases. Not since the work of Changnon (1984) have variations in growing-season length been evaluated for Illinois. Decadal averages for nine representative stations were analyzed in that study, whereas annual time series for 36 stations are used here. In addition, this research explores how freeze dates are related to time-varying probability distributions of T_{\min} .

Growing-season length variations are a useful climatic indicator and have a number of important climatological applications. As an example, if growing-season length were decreasing, this may suggest that planting dates should be altered and that traditionally planted crops may not fully mature, resulting in lower yields. Increasing growing-season length could result in earlier planting, ensuring maturation and allowing the possibility of multiple cropping (contingent on water availability). Longer growing seasons can be particularly beneficial for perennial crops (e.g., alfalfa and other hay crops), but can also result in more insect and disease damage (Patterson et al., 1999; Porter et al., 1991). Growing-season length variations also are closely related to variations in overall seasonality, which are an important component of recent climatic change research (Keeling et al., 1996; Mann and Park, 1996; Myneni et al., 1997; Thomson, 1995).

For most locations in Illinois, a minimum air temperature of 0 °C or lower has a probability of around 10% during April and October (typical months for spring and fall freezes). As a general indicator of climatic change, therefore, the timing of freezes can be viewed as an extreme event that provides a meaningful position along the lower tail of the air-temperature frequency distribution. Examining temporal variations in the tails of probability distributions provides a climate-change perspective that is an important alternative to the traditional focus on central tendency (Katz and Brown, 1992).

3. Data

The data used here are derived from the daily United States Historical Climatology Network archive (Easterling et al., 1999; data and documentation are available from CDIAC, <http://cdiac.esd.ornl.gov/>). Daily HCN stations have been selected for

their long-term quality, based on criteria such as consistent observation times, low potential for heat-island bias, and other quality assessments that were developed for the monthly version of the HCN. These data represent some of the highest quality data available for instrumental climate-change detection; however, changes in observation time, instrumentation, and the nature of the local environment around stations still have the potential to produce biases (see Easterling et al. (1996) for a discussion of many of these issues). Although a number of procedures have been developed for correcting monthly air-temperature data for inhomogeneities, daily data present additional challenges (Janis, 2000).

Daily minimum air-temperature data from 36 cooperative stations in the state of Illinois were used (Table I). Although several records extended back to the late 1800s, many started in the early 1900s. To provide a consistent time-frame of analysis, 1906 was used as a starting date – this starting date allowed the greatest number of stations to be used for most of the 20th century. As a result, for the purposes of this analysis, all stations from the daily HCN had T_{\min} time series from 1906–1997. If small amounts (<10%) of data were missing at critical times of the year (i.e., within a 4-week period around the average date of spring and fall freezes), their values were linearly interpolated. If 10% or more of the data from these critical periods were missing, data for that year were not used. As a result, from 0–10 years of data were ‘missing’ for each station (see ‘ n ’ in Table I). Visual inspection of histograms depicting the distribution of years with missing data suggested that there were no systematic temporal patterns to the missing data.

A number of growing-season dates were extracted for each year from the T_{\min} data, based on the occurrence of a threshold daily minimum. Specifically, the date of last spring freeze (SF), date of first fall freeze (FF), and the resulting length of the freeze-free growing season (GSL) were determined for four threshold air temperatures: -4.4°C , -2.2°C , 0°C , and 5.6°C (original data were recorded in $^{\circ}\text{F}$ and these values correspond to 24°F , 28°F , 32°F , and 44°F , which are the threshold air temperatures that are used in U.S. government publications). The three lower values for T_{\min} represent progressively ‘harder’ freezes, while the 5.6°C value is a useful climatic indicator for cold-sensitive plants (e.g., warm-season vegetables).

Initially, the analyses presented here are based on 0°C ; however, previous research (Brinkmann, 1979) has shown that growing-season statistics based on a single threshold air temperature can sometimes be misleading. Variations and trends in SF, FF, and GSL for a variety of threshold air temperatures, therefore, are analyzed in the sections below. Linkages of growing-season variations with historical T_{\min} probability distributions also are evaluated.

4. Trends in Growing-Season Dates

Examination of individual-station time series of SF, FF, and GSL shows that all three variables are somewhat noisy, with very little interannual autocorrelation

Table I

Estimated linear least-squares trends (days/100 yrs) for last spring freeze (SF), first fall freeze (FF), and growing-season length (GSL) for 36 stations in Illinois (using 0 °C as the critical T_{\min}). Sample size (n) indicates the number of years that contained sufficient data during the period 1906–1997. P -values for a two-tailed t -test are shown in parentheses next to each trend. Negative (positive) trends in SF indicate warming (cooling), while negative (positive) trends in FF and GSL indicate cooling (warming). The 12 stations denoted as Illinois ‘benchmark’ stations by Changnon et al. (1997) are denoted by italics.

Coop station name	Coop ID	Longitude	Latitude	n	SF trend (P -value)	FF trend (P -value)	GSL trend (P -value)
<i>ALEDO</i>	<i>110072</i>	<i>-90.74</i>	<i>41.24</i>	89	<i>-11.4 (0.02)</i>	<i>1.7 (0.38)</i>	<i>14.1 (0.06)</i>
<i>ANNA 1E</i>	<i>110187</i>	<i>-89.24</i>	<i>37.47</i>	90	<i>5.6 (0.19)</i>	<i>-4.1 (0.26)</i>	<i>-9.7 (0.13)</i>
AURORA	110338	-88.35	41.76	88	-10.9 (0.04)	4.4 (0.23)	15.8 (0.02)
<i>CARLINVILLE</i>	<i>111280</i>	<i>-89.87</i>	<i>39.29</i>	88	<i>-12.3 (0.01)</i>	<i>-4.6 (0.25)</i>	<i>7.3 (0.19)</i>
CHARLESTON	111436	-88.17	39.49	89	-12.9 (0.01)	6.5 (0.16)	19.0 (0.01)
DANVILLE	112140	-87.66	40.14	84	1.6 (0.38)	-0.4 (0.40)	0.2 (0.40)
DECATUR	112193	-89.02	39.84	90	-6.4 (0.19)	-7.2 (0.11)	-1.6 (0.39)
DIXON 1NW	112348	-89.52	41.84	91	-9.7 (0.04)	-1.4 (0.38)	8.1 (0.19)
DUQUOIN 4SE	112483	-89.20	37.99	87	-6.5 (0.13)	0.5 (0.40)	5.9 (0.27)
GALVA	113335	-90.05	41.17	89	-12.4 (0.01)	2.9 (0.32)	15.6 (0.02)
GRIGGSVILLE	113717	-90.74	39.72	82	-2.5 (0.36)	-3.5 (0.32)	-1.8 (0.39)
HARRISBURG	113879	-88.52	37.74	88	-2.3 (0.35)	-4.9 (0.22)	-4.0 (0.33)
HILLSBORO	114108	-89.49	39.16	88	-17.7 (0.00)	-7.2 (0.11)	11.5 (0.06)
<i>HOOPESTON 1NE</i>	<i>114198</i>	<i>-87.67</i>	<i>40.47</i>	87	<i>-14.0 (0.00)</i>	<i>6.1 (0.20)</i>	<i>18.4 (0.01)</i>
JACKSONVILLE 2E	114442	-90.20	39.74	92	-5.2 (0.20)	1.7 (0.37)	6.9 (0.23)
LA HARPE	114823	-90.97	40.59	92	-7.7 (0.08)	3.4 (0.30)	11.1 (0.09)
LINCOLN	115079	-89.41	40.16	86	-20.9 (0.00)	9.9 (0.05)	34.0 (0.00)
<i>MARENGO</i>	<i>115326</i>	<i>-88.60</i>	<i>42.26</i>	85	<i>0.8 (0.39)</i>	<i>-7.8 (0.07)</i>	<i>-8.1 (0.18)</i>
<i>MCLEANSBORO 2ENE</i>	<i>115515</i>	<i>-88.50</i>	<i>38.11</i>	90	<i>1.4 (0.38)</i>	<i>-4.3 (0.26)</i>	<i>-6.0 (0.27)</i>
<i>MINONK</i>	<i>115712</i>	<i>-89.05</i>	<i>40.91</i>	88	<i>-9.5 (0.05)</i>	<i>0.7 (0.39)</i>	<i>8.6 (0.18)</i>
MONMOUTH	115768	-90.64	40.92	91	-12.5 (0.00)	1.8 (0.37)	13.9 (0.05)
MORRISON	115833	-89.97	41.82	86	-6.0 (0.18)	-1.6 (0.37)	3.9 (0.34)
<i>MOUNT CARROLL</i>	<i>115901</i>	<i>-89.99</i>	<i>42.11</i>	87	<i>5.1 (0.23)</i>	<i>-9.7 (0.03)</i>	<i>-16.9 (0.02)</i>
MT VERNON 3NE	115943	-88.87	38.36	88	-2.0 (0.36)	-7.9 (0.07)	-5.2 (0.29)
OLNEY 2S	116446	-88.07	38.71	83	5.7 (0.19)	-11.7 (0.01)	-17.0 (0.01)
OTTAWA 4SW	116526	-88.92	41.34	88	-13.3 (0.01)	10.3 (0.04)	21.6 (0.00)
PALESTINE	116558	-87.62	39.01	87	-4.6 (0.25)	-1.0 (0.39)	2.8 (0.37)
PANA	116579	-89.09	39.39	90	-15.4 (0.00)	-1.7 (0.37)	13.6 (0.07)
PARIS WATERWORKS	116610	-87.70	39.62	89	-18.0 (0.00)	-0.1 (0.40)	18.2 (0.01)
PONTIAC	116910	-88.64	40.89	91	-11.2 (0.02)	1.4 (0.38)	12.4 (0.06)
<i>RUSHVILLE</i>	<i>117551</i>	<i>-90.55</i>	<i>40.12</i>	88	<i>-12.7 (0.01)</i>	<i>-5.4 (0.20)</i>	<i>8.8 (0.15)</i>
<i>SPARTA 3N</i>	<i>118147</i>	<i>-89.70</i>	<i>38.17</i>	90	<i>-2.3 (0.35)</i>	<i>-4.1 (0.27)</i>	<i>-1.9 (0.38)</i>
URBANA	118740	-88.24	40.11	92	-9.8 (0.02)	-2.5 (0.34)	7.2 (0.19)
<i>WALNUT</i>	<i>118916</i>	<i>-89.60</i>	<i>41.55</i>	90	<i>-5.1 (0.20)</i>	<i>-5.9 (0.19)</i>	<i>-0.3 (0.40)</i>
WHITE HALL 1E	119241	-90.39	39.44	88	-14.2 (0.00)	9.0 (0.06)	22.1 (0.00)
<i>WINDSOR</i>	<i>119354</i>	<i>-88.60</i>	<i>39.44</i>	92	<i>-17.9 (0.00)</i>	<i>10.9 (0.03)</i>	<i>28.7 (0.00)</i>

(Figure 1). After detrending, first-order autocorrelation coefficients for all time series are typically less than 0.1. Distinct trends (as estimated by ordinary least-squares regression), however, are present at many stations. Data from Pontiac, IL, for example, show a large negative trend in SF (11 days earlier over the last 100 years) and a small negative trend in FF (1 day later over the last century). As a result, the growing-season length increase for Pontiac is 12 days per 100 years (values refer to trends derived by using 0°C as the threshold T_{\min}).

Overall, the results of the trend analysis for 0°C can be summarized as follows (1) most stations have large negative trends in SF, (2) stations have a mix of positive and negative trends in FF, and (3) many stations have large positive trends in GSL (Figures 2c–4c; note that in all maps, dark circles indicate cooler conditions and open circles represent warmer conditions). When trends from the 36 stations are gridded and spatially averaged over Illinois, the trends are -8 days/100 yrs for SF, 1 day/100 yrs for FF and 7 days/100 yrs for GSL (Figure 5a).

Although some climatological applications of trend detection do not benefit from significance testing (e.g., trends are obvious, data do not meet the assumptions of the test, statistically significant results can be scientifically unimportant – often due to large sample sizes), analyzing trends in growing-season statistics from a statistical significance perspective is beneficial because the time-series data are both noisy and close to being normally and independently distributed. The inherently noisy nature of growing-season time series make it important to evaluate trends in the context of natural variability. As a result, p -values associated with each of the trends (for 0°C) were calculated using a 2-tailed t -test (Table I). More than half of the stations showed trends in SF and GSL that can be considered strong signals (i.e., p -values less than 0.1), while only about 20% of stations had trends in FF that rose above the noise in the data.

For each variable (SF, FF, and GSL), multiple ‘tests’ of statistical significance were evaluated – i.e., at each of the 36 stations. Adjustments to the permissible type-I error sometimes are used when multiple tests are performed (Miller, 1981). One of the most commonly used adjustments (Bonferroni), however, is very conservative (e.g., the Bonferroni adjustment would recommend a type-I error of α/k , where k is the number of tests performed; see Perneger (1998) and followup articles for additional discussion of multiple tests). Other adjustment procedures for using multiple tests exist (Aikin and Gensler, 1996; Westfall and Young, 1993; etc.), although it is equally enlightening to simply state how many of the multiple tests would be expected to be significant by random chance alone. For the growing-season statistics – when using a critical type-I error of 0.1 and applying 36 tests – there is an expectation that 3–4 of the p -values would be considered significant by random variations alone (i.e., 10% of the 36 tests). The trends in GSL and LF rise well above this level while those for FF barely do.

Other thresholds for T_{\min} , such as -2.2°C and 5.6°C , produced trends in SF that were similar to those for 0°C ; however, the lowest threshold used, -4.4°C , produced smaller trends overall and did not show the systematic decrease in SF

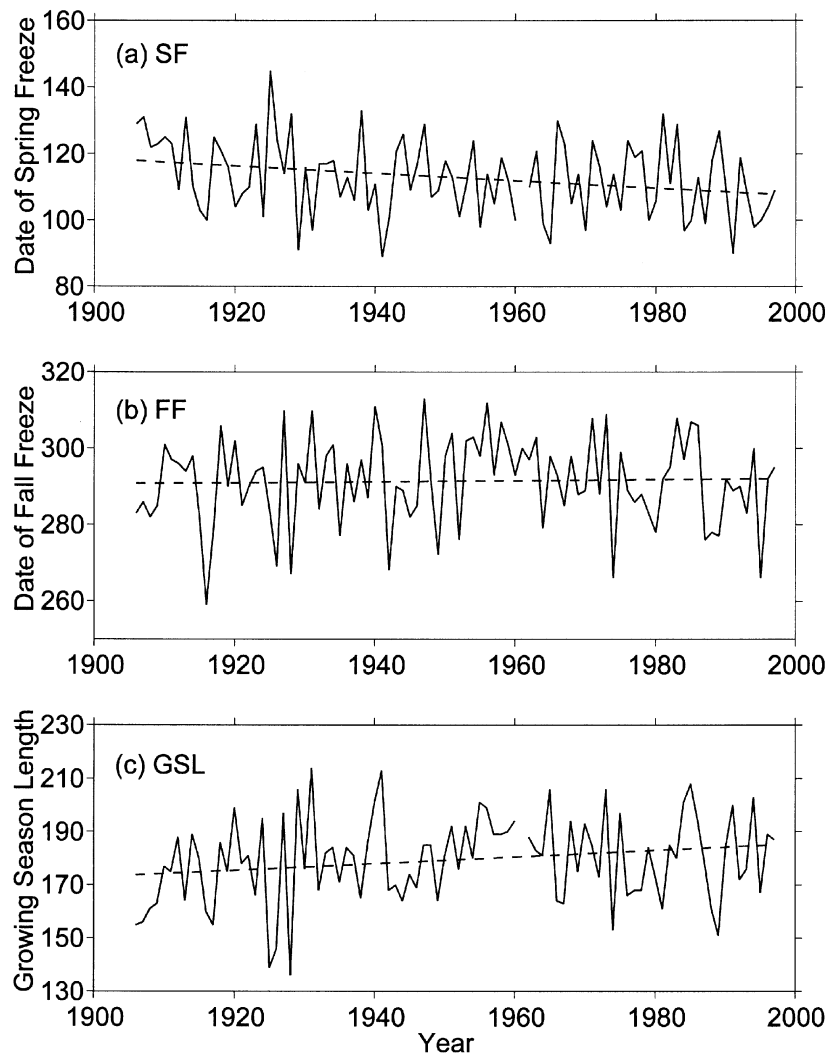


Figure 1. Time series of (a) date of last spring freeze, (b) date of first fall freeze, and (c) growing-season length for Pontiac, IL (40.89° N, 88.64° W) using 0° C as the threshold T_{\min} . Ordinary least-squares regression is shown as dashed line. Pontiac was chosen as an example because it had the most typical time series, based on its mean absolute difference from the mean of all station time series.

(Figure 2). Trends in FF varied widely, with the two lower threshold air temperatures (-4.4° C and -2.2° C) showing warming and the higher thresholds showing cooling (Figure 3). For GSL, all threshold air temperatures produced a mix of positive and negative trends across the 36 stations. There were many more positive trends than negative ones, with positive trends also tending to be larger than neg-

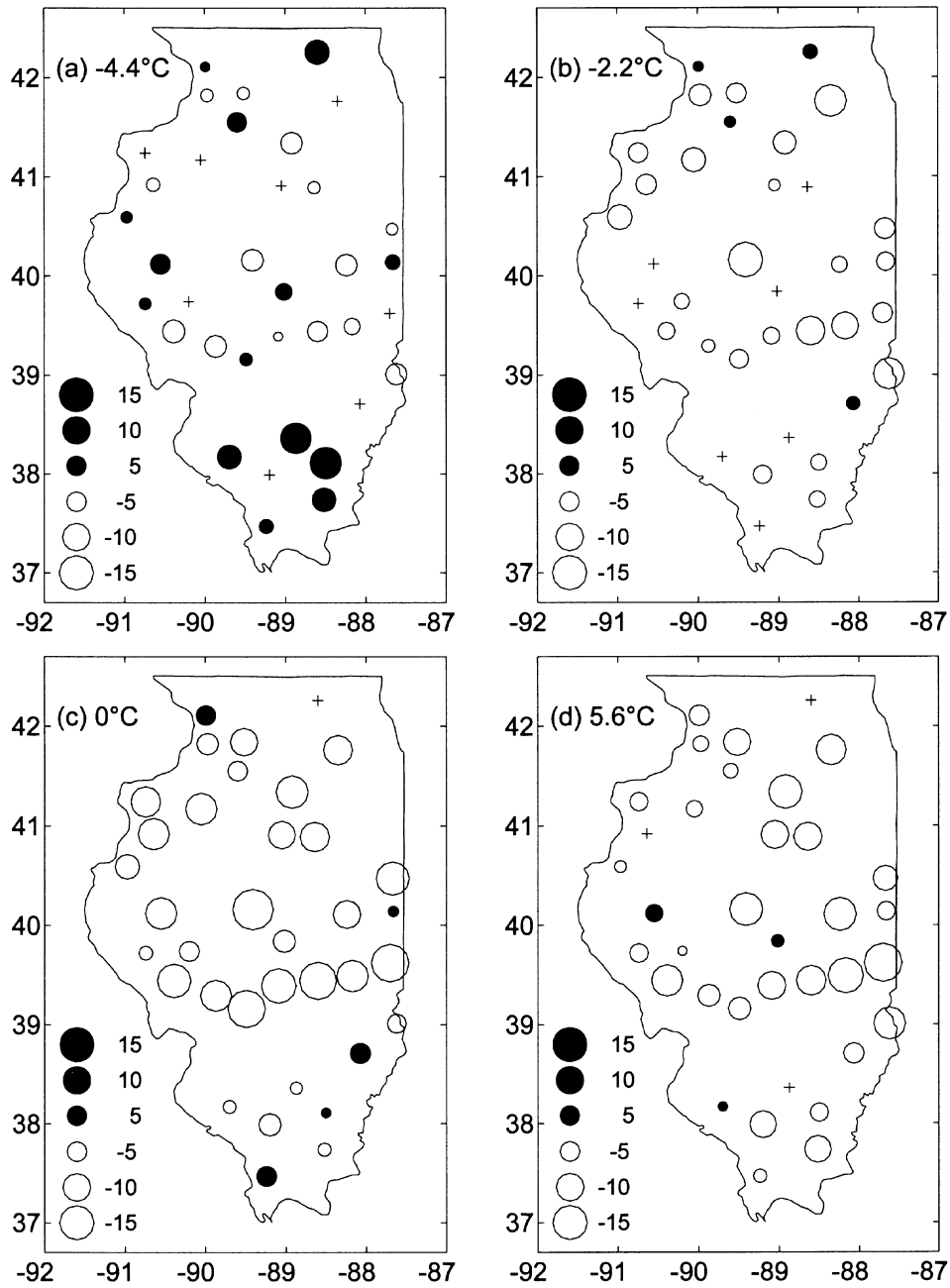


Figure 2. Linear trends (days/100 yrs) in the date of last spring freeze for Illinois using the following threshold temperatures: (a) -4.4°C, (b) -2.2°C, (c) 0°C, (d) 5.6°C. Period of record for all stations is 1906–1997 ('+' indicates stations with trends having absolute values < 1 day/100 yrs).

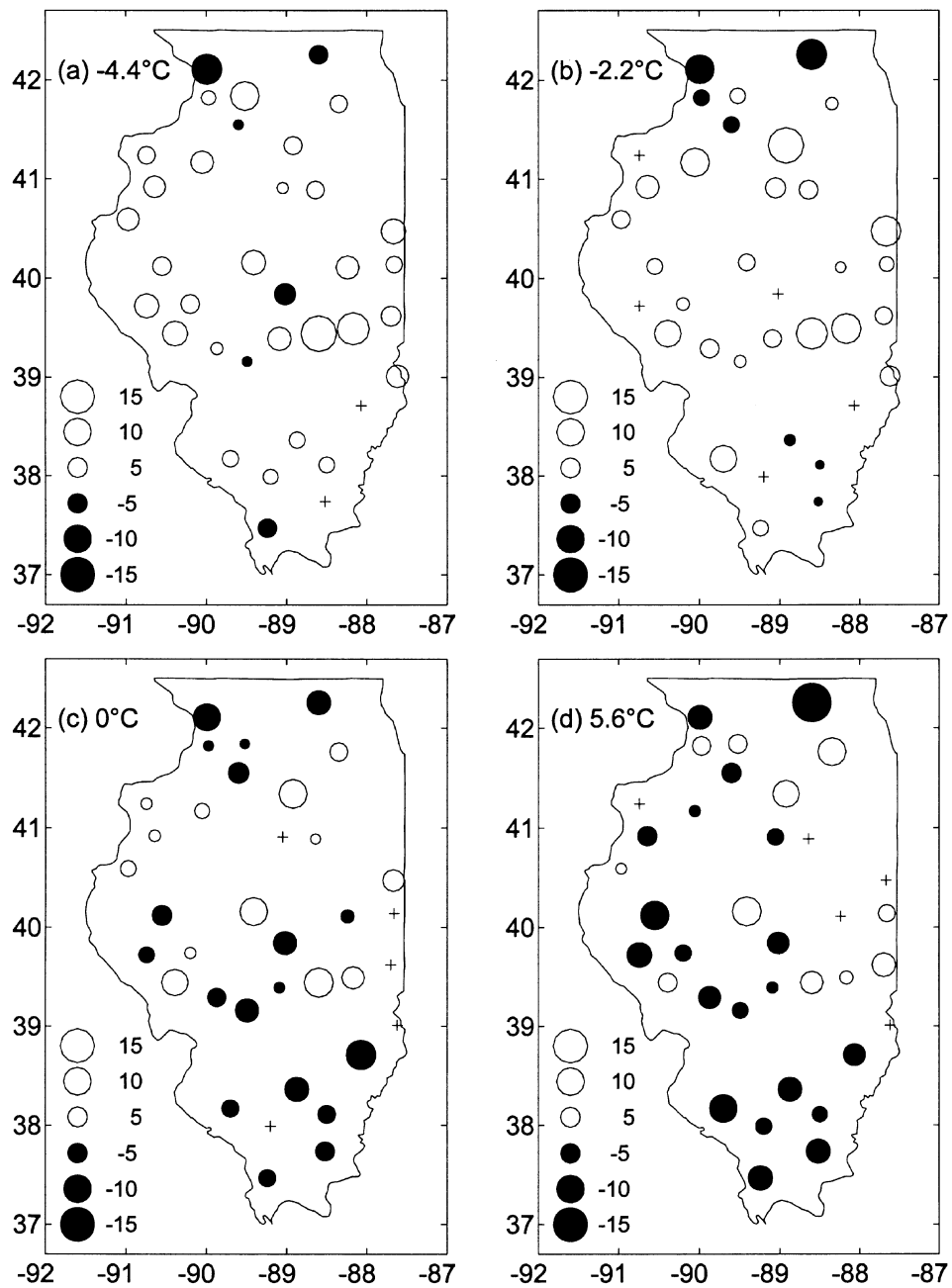


Figure 3. Linear trends (days/100 yrs) in the date of first fall freeze for Illinois using the following threshold temperatures: (a) -4.4°C , (b) -2.2°C , (c) 0°C , (d) 5.6°C . Period of record for all stations is 1906–1997 ('+' indicates stations with trends having absolute values < 1 day/100 yrs).

ative trends (Figure 4). Overall, varying the threshold air temperatures had greater impacts on the FF trends than on SF or GSL trends.

To assess spatial averages over Illinois, trends at station locations were interpolated to a 0.1 degree latitude/longitude grid and averaged using cosine-of-latitude weighting. The spatially averaged trends produce results that are more easily summarized: SF trends are large and negative except for those for -4.4°C , FF has a mix of both positive and negative trends, and GSL trends are positive across all threshold air temperature (Figure 5a).

One method for evaluating the sensitivity of the trends to possible inhomogeneities in the T_{\min} data is to use a subset of stations that are deemed of higher quality (although the daily HCN stations have already had a number of quality control procedures applied). A set of 12 stations in Illinois (all included in the daily HCN) have been identified as 'benchmark' climate stations, based on a number of data-quality and period-of-record issues (Changnon et al., 1997). As a result, trends from just the 12 benchmark stations were gridded and spatially averaged independently of the other 24 stations (benchmark stations are indicated by italics in Table I). Spatially averaged trends using the 12 benchmark are similar to the trends from the 36-station network (compare Figures 5a,b), with some notable differences. Trends in SF and FF, in particular, appear to change little over the two network configurations. Modest differences in the SF and FF trends, however, combine to produce nontrivial differences in GSL trends. In particular, the GSL trends for thresholds of -4.4°C and 5.6°C are near-zero. Trends for threshold temperatures of -2.2°C and 0°C are reduced, but still are approximately 5 days per 100 years. It is interesting to note that individual benchmark stations produced markedly different trends. Using a threshold of 0°C , Mount Carroll had the largest negative trend in GSL of all 36 stations, while Windsor had the second-largest increase in GSL. An additional stratification of the data (not shown), whereby the smallest and largest 5% of the trends were removed (i.e., 10% of the stations were 'trimmed'), produced spatially averaged trends that were nearly the same as those using the 36-station network.

Although most of the results presented here are fairly consistent for the various thresholds for T_{\min} , growing-season length and freeze dates clearly can be viewed as somewhat noisy and equivocal indicators of climatic change (i.e., similar to the conclusions of Brinkmann, 1979). The overall trends presented here for LF and GSL, however, are considerable for the threshold minimum air temperatures of 0°C and -2.2°C , the two thresholds with the clearest applicability. Results suggest, therefore, that Illinois has experienced the following changes over the last century: (1) the date of the last spring freeze is nearly one week earlier now than it was 100 years ago, (2) fall freeze dates have not changed in a systematic fashion, and (3) the growing season is nearly one week longer now, due to the earlier spring freezes. These results corroborate other research, showing that spring is a critical period for detecting recent climatic changes and their impacts (Groisman et al.,

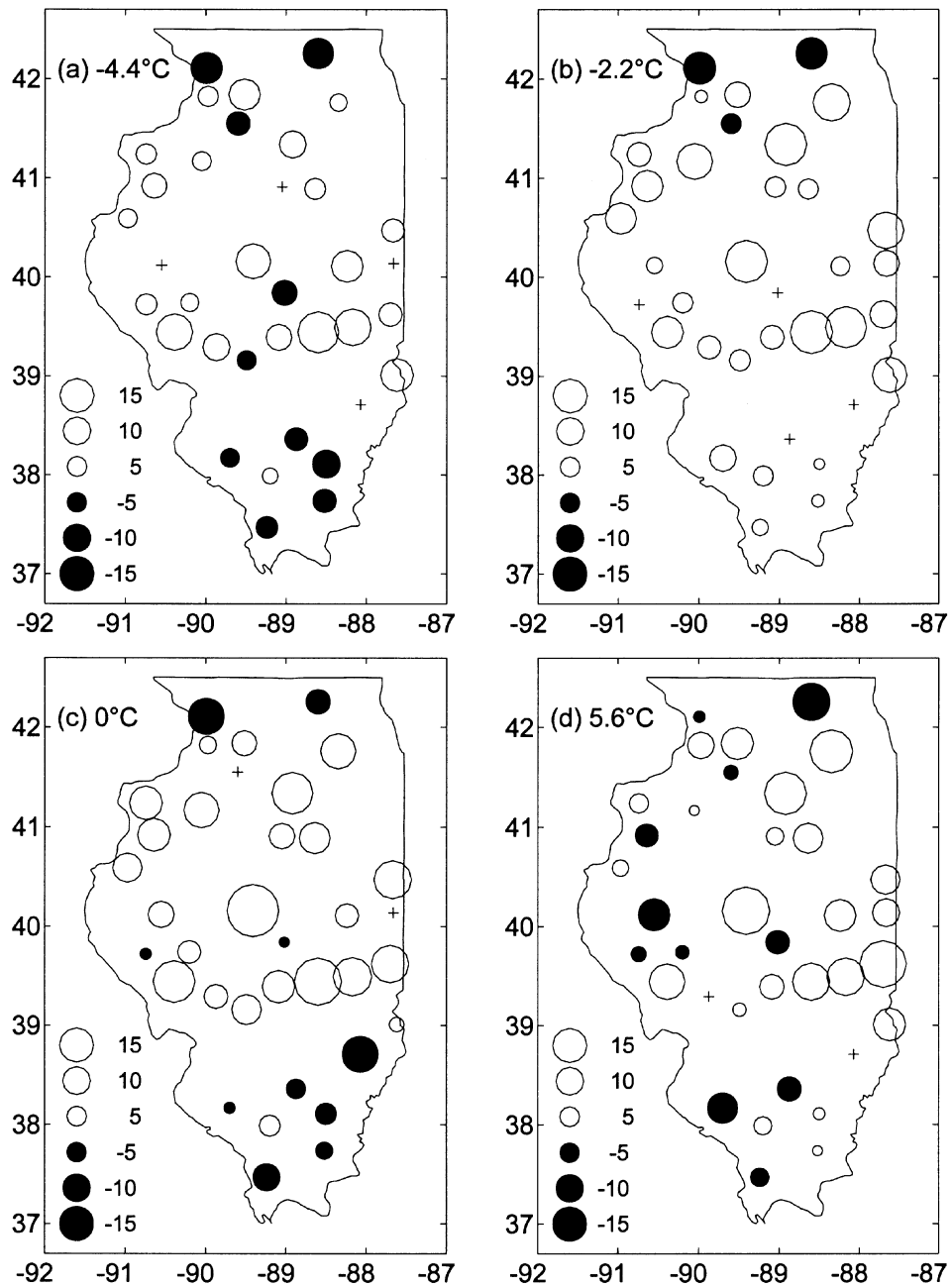


Figure 4. Linear trends (days/100 yrs) in the length of the growing season for Illinois using the following threshold temperatures: (a) -4.4°C , (b) -2.2°C , (c) 0°C , (d) 5.6°C . Period of record for all stations is 1906–1997 ('+' indicates stations with trends having absolute values < 1 day/100 yrs).

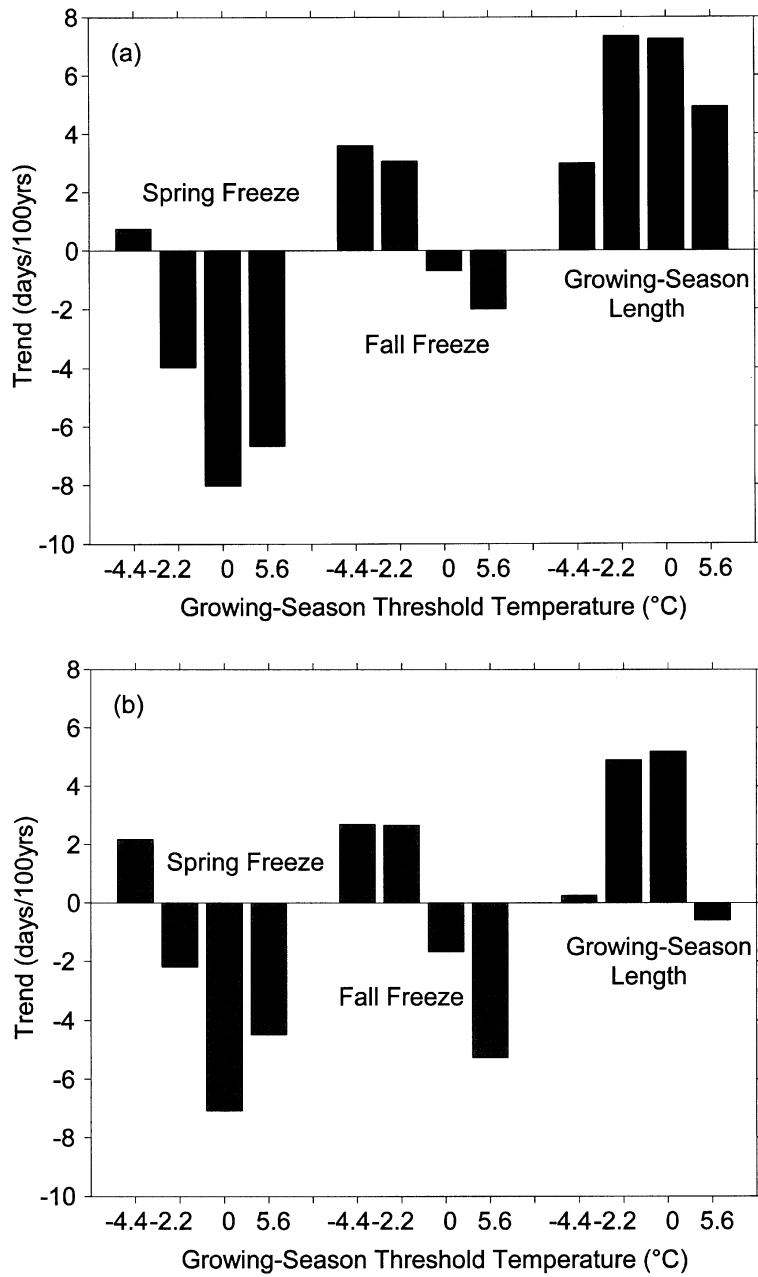


Figure 5. Spatially averaged (over the state of Illinois) trends in spring-freeze date, fall-freeze date, and growing-season length from 1906–97 for a variety of threshold values of daily minimum air temperature using (a) all 36 stations and (b) 12 ‘benchmark’ stations. Trends are in days per 100 years, with negative trends in spring freezes indicating warming and positive trends in fall freeze and growing-season length indicating warming.

1994; Menzel and Fabian, 1999; Myneni et al., 1997; Schwartz and Reiter, 2000; Thomson, 1995).

5. Changes in T_{\min} Probability Distributions

To examine how trends in freeze dates relate to long-term changes in daily minimum air temperatures (T_{\min}), time-varying probability distributions for the periods around SF and FF were examined. In Illinois, SF and FF usually occur during April and October (respectively); therefore, data from those months were analyzed. Decadal moving windows of T_{\min} (i.e., 10 years of daily data for April of 1906–1915, 1907–1916, etc.) were used to determine percentiles of the T_{\min} probability distribution. Subsequently, trends in these percentiles were estimated using ordinary least-squares regression. The changes in SF discussed above – towards earlier spring freezes – are apparent in the trends in April T_{\min} , with all percentiles showing warming (Figure 6). However, there are distinct differences between the various percentiles: spatial averages of trends in the lower percentiles, particularly the 20th–40th percentiles, have larger trends than the upper portion of the distribution (Figure 8a). Changes in the lower portion of the distribution also are more spatially consistent than those in the upper part of the distribution. As a result, the changes in SF are larger than one might expect if only the mean of the T_{\min} probability distribution had been examined.

Trends in the October T_{\min} percentiles are very different from the April trends, with all percentiles showing decreasing air temperatures (Figures 7 and 8b). The lower portion of the October probability distribution, however, exhibits mixed spatial patterns and much smaller trends than the rest of the distribution. The 10th percentile has a spatially averaged trend of $-0.2^{\circ}\text{C}/100$ yrs, while the middle portion of the distribution has trends with magnitudes greater than $-1.5^{\circ}\text{C}/100$ yrs. Examining only the middle portion of the distribution would produce very different results and would suggest that the fall growing-season statistics (and their associated impacts) have changed much more rapidly than they have.

This research suggests that, although overall trends in T_{\min} for April (spring) are modest, the lower portion of the T_{\min} probability distribution is changing most rapidly, resulting in an extension of the growing season during spring. In contrast, the October (fall) T_{\min} data show strong cooling except in the lower tail of the T_{\min} probability distribution. As a result, fall freezes have not changed in any systematic fashion, despite very large decreases in mean October T_{\min} during the 20th century.

6. Possible Causes of Observed Changes in T_{\min}

Long-term changes in daily minimum air temperature can be related to a number of key climatic variables and their variability, such as cloud amount and type,

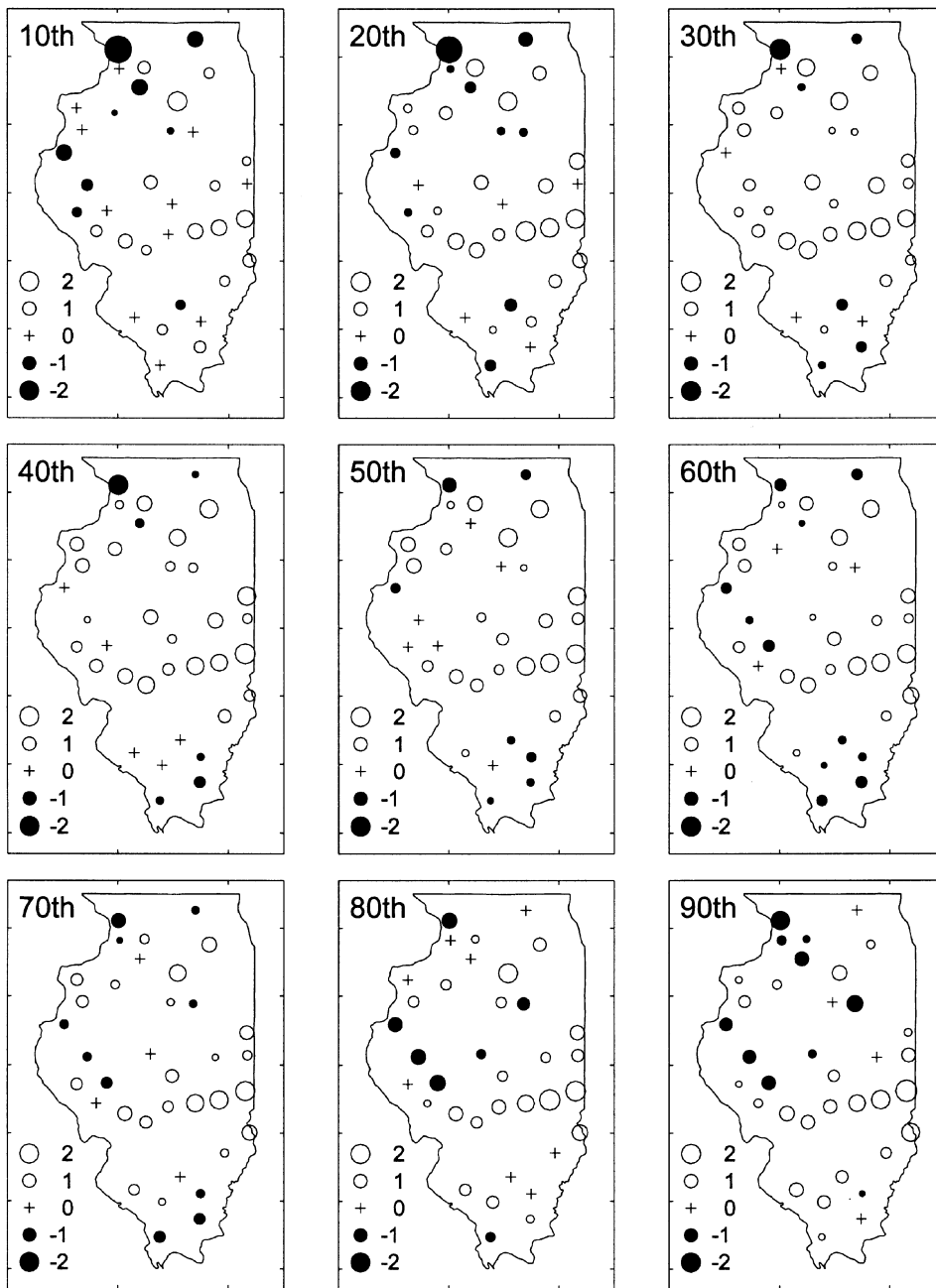


Figure 6. Maps of trends in percentiles of the T_{\min} probability distribution for April. Percentiles were estimated from 10-year moving windows of daily T_{\min} from 1906–1997. Least-squares regression estimates of the linear trend ($^{\circ}\text{C}/100$ yrs) were estimated for percentiles (at every station) ranging from the 10th to the 90th ('+' indicates stations with trends having absolute values <0.1 $^{\circ}\text{C}/100$ yrs).

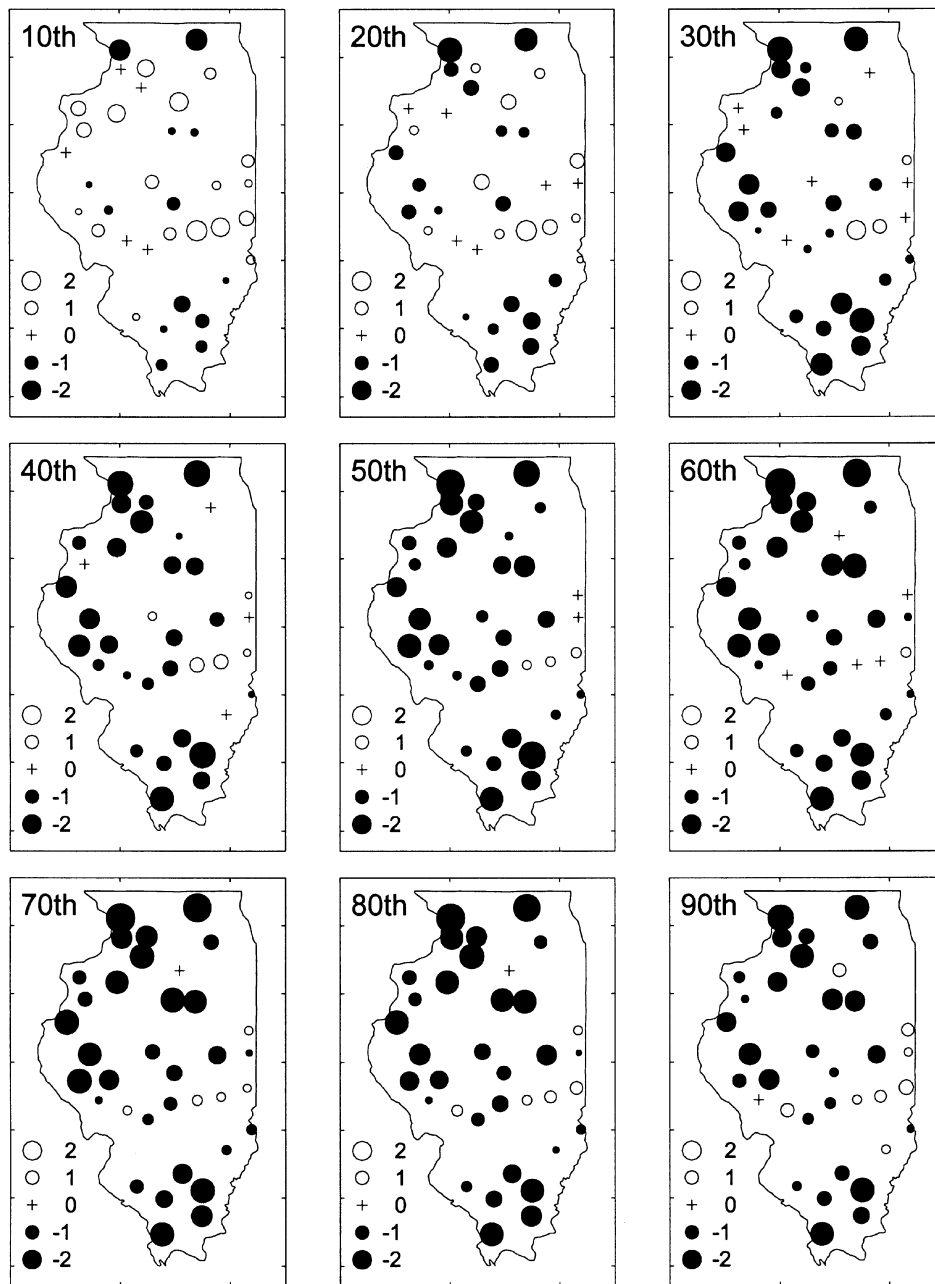


Figure 7. Maps of trends in percentiles of the T_{\min} probability distribution for October. Percentiles were estimated from 10-year moving windows of daily T_{\min} from 1906–1997. Least-squares regression estimates of the linear trend ($^{\circ}\text{C}/100$ yrs) were estimated for percentiles (at every station) ranging from the 10th to the 90th ('+' indicates stations with trends having absolute values <0.1 $^{\circ}\text{C}/100$ yrs).

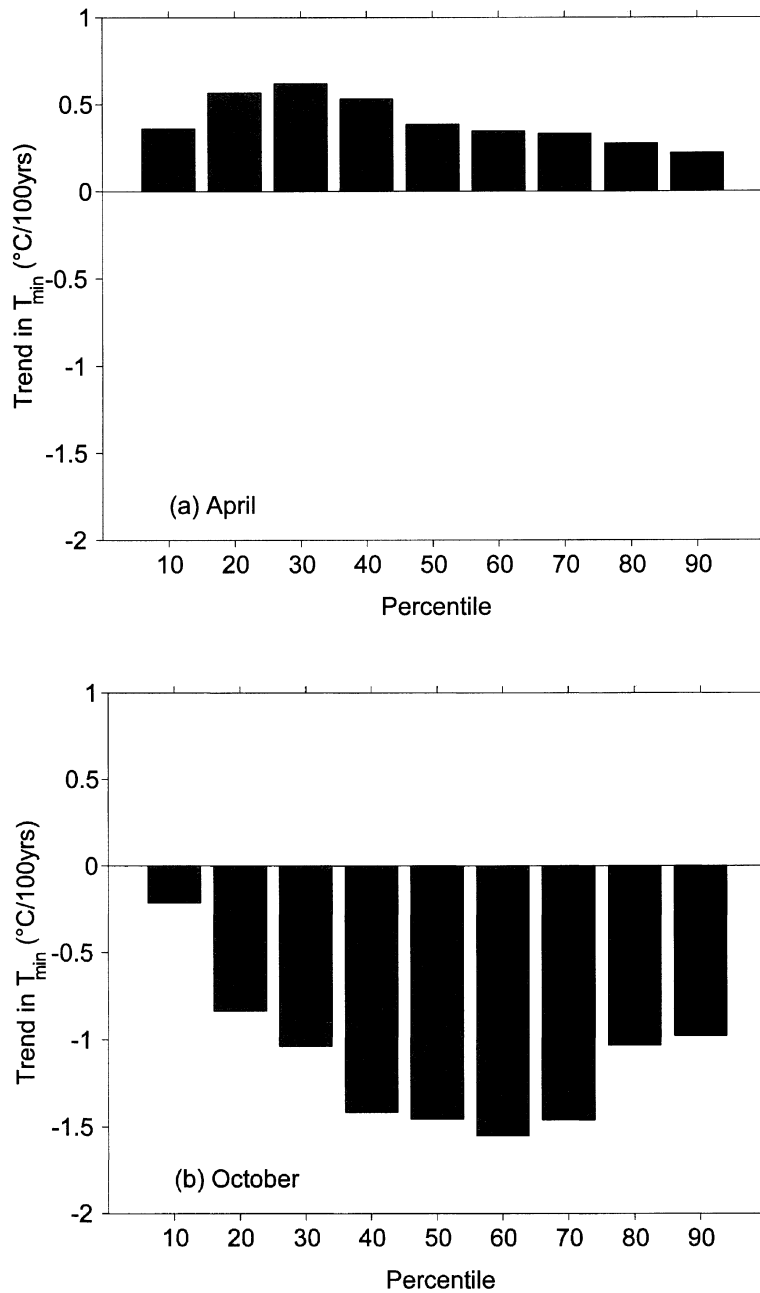


Figure 8. Spatially averaged (over the state of Illinois) trends in percentiles of the T_{min} probability distribution for (a) April and (b) October from 1906–97. Overall, April trends are positive, indicating warming, while October trends are negative, indicating cooling. April trends show that the lower (cold) portion of the distribution has increased more than the upper portion, while October trends show that the lower portion of the distribution has the least change.

humidity, snow cover, greenhouse gases, sulfate aerosols, and wind. Data for many of these potential explanatory variables, however, are not available for the same period of record as air temperature, nor are they available at the same (high) spatial resolution. Although the research presented here is primarily focused on detection of climatic change (rather than attribution), a few comments regarding the possible causes of the observed trends in T_{\min} , particularly as they relate to changes during April and October, are presented below.

Possible causes for trends in annual mean T_{\min} for the U.S. have been evaluated in a number of studies (e.g., Plantico et al., 1990; Karl et al., 1993; Easterling et al., 1997). Although less common, causes for trends in seasonal and monthly data also have been assessed. Different periods of record and spatial scales of analysis (e.g., coarse-resolution grids or climate regions encompassing many states), as well as the focus on changes in mean T_{\min} , make direct comparisons with this research difficult. Nonetheless, nearly all of these studies have pointed to increasing cloud amount as a key cause for increasing T_{\min} . There is ample evidence for increasing cloud amount over large regions that contain Illinois (Plantico et al., 1990; Henderson-Sellers, 1986); however, annual or seasonal cloud amount can be a crude indicator of the impact of clouds on daily T_{\min} . Cloud type (and associated radiative properties) is key, as is the distinction between daytime and nighttime cloud.

Recently, Janis (2000) estimated trends in annual average daytime and nighttime cloud separately for most first-order weather stations in the midwestern U.S. for the period 1961–95. Both daytime and nighttime cloud amount for 5 stations in Illinois show trends of ≈ 0.5 – 1.0 tenths/35 yrs, with the trends in nighttime cloud amount being slightly larger. Trends in the seasonality of nighttime cloud amount over Illinois, however, have not been established. Given the trends estimated here, one would hypothesize that nighttime cloud during April has increased while nighttime cloud during October has decreased (perhaps substantially). As noted before, the difficulty of obtaining high-quality cloud data for commensurately long periods (e.g., most or all of the 20th century), as well as discordant changes in daytime and nighttime cloud, may obscure these relationships.

Accompanying the changes in cloud amount, increasing near-surface humidity has been documented in many parts of the United States (Gaffen and Ross, 1999). Specific humidity, in particular, has increased over the northeastern United States (the region that includes Illinois in Gaffen and Ross, 1999) during 1961–95. For both spring and fall, the trends in specific humidity are stronger for nighttime data (fall trends are near zero for daytime and full-day humidity). Dew-point temperature also shows larger increases during spring than fall; however, relative humidity shows almost no change during both spring and fall (Gaffen and Ross, 1999). Increasing nighttime humidity is a likely cause for some of the changes in growing-season statistics and T_{\min} reported here; however, the lack of a century-long database makes direct comparisons difficult.

An intriguing spatial pattern in the T_{\min} trends is that many of the stations with smaller, cooling trends in SF, FF, and GSL (particularly for the -2.2°C and 0°C thresholds) are located in the southern portion of the state (e.g., Figure 4c). With greater relief and patchy forests, land cover and topography in southern Illinois are distinctly different from the rest of the state. While much of Illinois was deforested from the 1820s to the 1920s (Iverson, 1991), recent land-cover trends show that most of the state has experienced some regrowth. Rates of regrowth in the southern portion of the state, however, are not substantially different from the rest of the state – trends over the last 40 years even show that the south-central portion of Illinois is experiencing loss of forest cover and is becoming more fragmented (Illinois Department of Energy and Natural Resources, 1994). Nonetheless, the impacts of both land-cover and land-use change – at local scales, in addition to regional ones – needs to be considered as a possible cause of differential spatial patterns in T_{\min} .

Another possible explanation for the differential trends in southern Illinois is the effect of seasonal snow-cover variations on air temperature. Trends in snow cover over North America (in general) are downward, at least for the last few decades and especially during spring (Groisman et al., 1994). Since both winter and spring snow cover are uncommon in southern Illinois, the radiative impacts of reduced snow cover (and other indirect effects) may be less pronounced in the southern portion of state.

7. Summary and Conclusions

Statistical analysis of historical minimum air-temperature records suggests that the length of the growing season in Illinois (as defined by daily minimum air temperatures of 0°C) has increased by nearly one week over the last 100 years. This change is the result of earlier spring freezes, which also are occurring nearly one week earlier (when spatially averaged over Illinois). The date of the first fall freeze appears to be virtually unchanged over the last century. Examination of time-varying probability distributions shows that the lower portion of the springtime T_{\min} distribution is experiencing more warming than other parts of the distribution. During fall, however, the lower portion of the T_{\min} probability distribution is experiencing less cooling than the rest of the distribution. This analysis demonstrates the importance of analyzing variations in all portions of the probability distribution when evaluating climatic change and its impacts.

Although nearly all of the climate stations used in this study are located in smaller communities (Easterling et al., 1999), nonclimatic biases still may be an important confounding issue in these data. Issues such as changes in (1) observing times and practices, (2) instrumentation, and (3) the nature of the local environment (e.g., changes in irrigation, land cover, soil compaction, surface roughness) all can have considerable influence on local-scale climate and T_{\min} . Growing-season length, freeze dates, and time-evolving probability distributions, therefore, also

need to be explored in the context of station-history and land-cover information. This information may help to explain why some neighboring stations have trends with differing signs.

Although there are numerous possible impacts of the observed changes reported here, upward trends in the lower portions of the spring T_{\min} probability distribution may be beneficial for agriculture. Impacts on natural vegetation are less clear – native plants have adapted to preexisting climatic conditions and it is possible that they may be out-competed by southern species if current trends continue. Still, the strong cooling observed during October and other seasonal changes may offset these effects. Concurrent changes in water availability, damage from pests, ambient CO₂, technology, etc. also make generalizations regarding the impacts of increasing growing-season length difficult. In the context of detecting climatic change, however, it is clear that additional research is needed to further evaluate the seasonality of changes in air-temperature probability distributions across wider portions of the North American continent.

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