Daily-Mean Temperature Reconstructed for Kansas from Early Instrumental and Modern Observations

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(Manuscript received 28 January 2008, in final form 9 October 2009)

ABSTRACT

A continuous record of 65 987 daily-mean temperature observations since 1828 has been developed for Manhattan, Kansas, by screening and correcting original station records of the U.S. Army Surgeon General, the Smithsonian Institution, and the Signal Service. Hourly, minimum, and maximum temperature observations from seven discontinuous historical stations and four modern stations in Kansas, Missouri, and Oklahoma were used to compile this unbroken record of daily-mean temperature. The historical temperature data were linked with the modern temperature record for Manhattan after these data were adjusted for time of observation differences, station movements, and changes in the environment around the station. The new daily-mean temperature reconstruction for Manhattan now extends with confidence back to 1 July 1855 and with more uncertainty back to 1 July 1828. The uncertainty prior to 1855 is due to instrumentation changes in 1843 and changes in observation practices in 1855 that occurred at many stations. The error estimates reported in this paper do not reflect these potential inhomogeneities and should be considered lower limits. Nonetheless, this new daily record indicates significant warming in all seasons; in heating and cooling degree-days; in the warmest and coldest days of the year; in extremes above the 90th percentile and below the 10th percentile; in the frequency of winter cold waves and summer heat waves; and in the overall annual-mean temperature, which has warmed by 1.57° ± 0.23°C since 1855 (1.27° ± 0.23°C since 1829). The warm Dust Bowl event in the summer of the 1930s and cold winters of the 1870s and 1880s dominate the reconstruction and included some of the warmest and coldest daily extremes, respectively, of the last 154–180 yr. This new reconstruction is currently the longest unbroken daily corrected record in the Americas. These data indicate that the nineteenth century was fundamentally cooler than the twentieth and early twenty-first century.

1. Introduction

Long time series of instrumental temperature provide key insight into natural and anthropogenic climate variability. The longest daily and continuous instrumental temperature records in the world are for Uppsala, Sweden (1722–present; Bergström and Moberg 2002); Stockholm, Sweden (1756–present; Moberg et al. 2002); Milan, Italy (1763–present; Maugeri et al. 2002); central England (1772–present; Parker et al. 1992); Padova, Italy (1774–present; Cocheo and Camuffo 2002); Cádiz, Spain (1817–present; Barriendos et al. 2002); and central Belgium (1833–present; Demarée et al. 2002). All of these exceptionally long and unbroken daily records are for Western Europe, but daily temperature measurements extending back to the mid-1700s also exist in select North American archives (Baron 1989; Fleming 1990). Unfortunately, most of the pre-twentieth-century daily temperature data recorded in the United States were subject to primitive observation practices, instrumentation changes, and station relocations, and these observations have only limited overlap with the modern standardized measurements of the U.S. National Weather Service. These problems can introduce serious discontinuities into early temperature records and make it difficult to recover unbiased daily temperature time series. The scarcity of observations also makes it difficult to screen

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DOI: 10.1175/2009JCLI2445.1

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and correct individual records, which has been done extensively in the relatively data-rich context of Western Europe.

In this study, we use a network of daily temperature records from Kansas, Oklahoma, and Missouri to reconstruct a daily-mean temperature history for eastern Kansas. This new reconstruction is based on careful screening of all documented and detected discontinuities in the historical temperature data, as well as corrections for observation time, diurnal averaging, and instrument homogeneity. Interstation comparisons of the daily data were used to identify statistical outliers, and the reconstruction was based on regression of overlapping daily data extending backward from the modern U.S. Historical Climatology Network station at Manhattan, Kansas.

The Great Plains are known for dramatic extremes in weather and climate such as the mid-nineteenth-century and Dust Bowl droughts and some of the worst blizzards in American history (Mattison 1964; Wheeler 1991; Herweijer et al. 2007). Kansas has some of the longest historical weather resources available for the central United States, and nineteenth-century Kansas represents an interesting chapter in American history, because the pursuit of Manifest Destiny drove settlement westward and settlers confronted the realities of weather and climate on the central Great Plains (e.g., Malin 1946).

The quantitative techniques of historical climatology to date largely include statistical-based reconstructions using overlaps between modern and historical data to construct long time series (Chenoweth 2007). In this paper, the daily meteorological records of the U.S. Army Surgeon General, the Smithsonian Institution, and the U.S. Signal Service have been analyzed and linked with modern instrumental observations into a continuous regression-based reconstruction of daily-mean temperature in eastern Kansas, with demonstrated skill and confidence back to 1 July 1855 and with greater uncertainty back to 1 July 1828. Documented and undocumented discontinuities have been identified, and the historical time series were segmented when significant changes were detected. However, comparative data are limited and the resulting reconstruction still contains nonclimatic artifacts, especially at the major instrumental change at 1843 and important observational routine changes at 1855. The attachment of the historical and modern datasets at 1893 is corroborated by standard instrumentation. Thus, confidence in this new reconstruction is highest from 1 July 1855 to 28 February 2009. The remaining hidden artifacts are not accounted for in the uncertainties reported in this paper, and all error estimates should therefore be considered lower limits. The new reconstruction can be used for the assessment of long-term changes in a variety of important meteorological phenomena at daily, monthly, seasonal, and annual time scales since the mid-nineteenth century, some of which may be sensitive to anthropogenic forcing.

Fisk (1984) and Baker et al. (1985) used daily data from Fort Snelling, Minnesota, and other nearby civilian records to develop a monthly-mean temperature record for southeastern Minnesota back to 1820. This is the longest monthly-mean temperature record currently available for the central United States, and it indicates significant warming from the nineteenth to twentieth centuries. Both reconstructions were performed independently and assessed the daily data to compute monthly means. Fisk (1984) performed more daily level analyses than Baker et al. (1985) and incorporated wind and cloud conditions into an estimate of daily maximum and minimum temperatures for Fort Snelling from 1820 to 1872. However, only the monthly-mean, maximum, and minimum temperature data were provided in the final product (Fisk 1984). Fisk (1984) did not attach these data to the modern record, but Baker et al. (1985) attached their reconstruction to the Farmington 3 northwest station, which had a similar microclimate as Fort Snelling, less urban influence, and a single family that recorded the observations. Neither Fisk (1984) nor Baker et al. (1985) screened all observations for documented or undocumented discontinuities, such as changes in station location, instrumentation, or observational practices, which can induce serious inhomogeneities in the time series (Chenoweth 1998). The number of nearby stations available for interstation comparisons is limited, especially prior to the advent of Smithsonian observations in 1847 (Darter 1942), and there is no evidence that the Minnesota data were corrected for nonstandard instrument exposure, which can induce a warm or cold bias or seasonal inconsistencies in temperature measurement (Chenoweth 1992, 1993; Parker 1994). With this new reconstruction of daily-mean temperature in Kansas, we attempt to deal with the biases and discontinuities prevalent in nineteenth-century temperature records from the central United States.

The methodology used to screen, correct, and reconstruct daily-mean temperature from historical records is presented in section 2, which includes nine sequential routines and a new toolkit developed to automate these operations. The resulting 180-yr-long daily-mean temperature data are presented in section 3, and they include analyses of the warmest and coldest days of the year, daily temperature extrema, cold waves, heat waves, and heating and cooling degree-days. We summarize our findings in section 4 and note the rich variability in Kansas temperature at daily to centennial time scales and the significant warming in daily, seasonal, and annual temperature variables from a fundamentally cooler nineteenth century

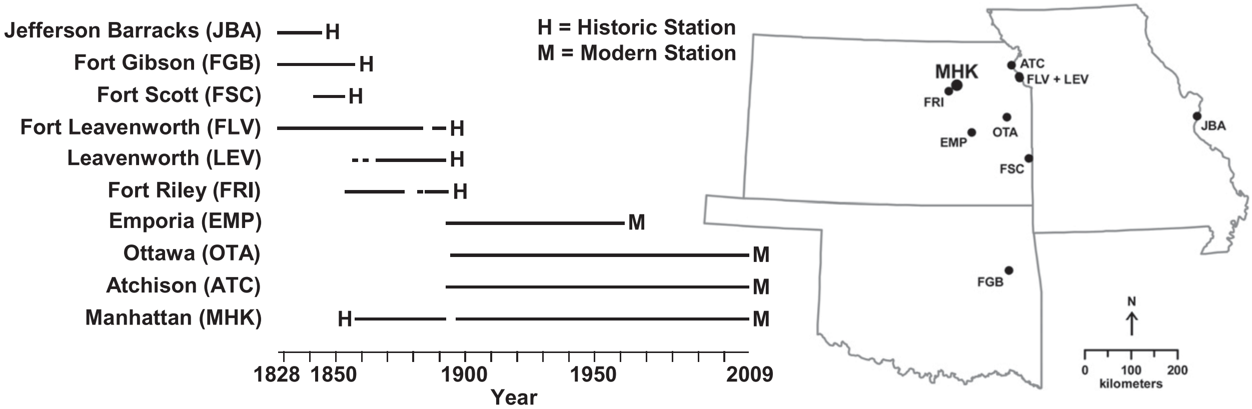


FIG. 1. The 180-yr eastern Kansas temperature reconstruction was computed from discontinuous data available from four modern (M) and seven historic (H) weather stations. Over 213 000 individual temperature observations were manually digitized from the historic meteorological journals. The original station data used to compute the daily-mean temperature for each day from 1828 to 2009 are available online (see http://www.uark.edu/dendro/kansas/).

into the secular warming of the twentieth and early twenty-first centuries.

2. Reconstruction methodology

a. The selection of daily-mean temperature and the Manhattan station

Previous studies have utilized daily temperature records from North America (e.g., Horstmeyer 1989; Fisk 1984; Baker et al. 1985), but quantitative daily level correction schemes have not been widely employed to remove several types of potential bias in these early observations including time of observation, poor instrumentation exposure, and undocumented station movements. Corrections to these historical daily temperature data are therefore imperative to minimize their discontinuities (Chenoweth 1992, 1993). Monthly-mean instrumental temperature records for the United States, some extending into the nineteenth century, have been recovered, corrected, and published in versions 1 and 2 of the U.S. Historical Climatology Network (USHCN; Williams et al. 2006; Menne et al. 2009). However, high-quality daily meteorological data are vital for the most rigorous daily level corrections needed to assess data quality, which are required in computing daily, monthly, seasonal, and annual temperature trends, and to document changes in daily extremes and their socioeconomic and environmental impacts (e.g., Patz et al. 2005; Alexander et al. 2006).

Daily minimum and maximum temperatures are rare in pre-1871 weather observations made by the U.S. Army Surgeon General and Smithsonian Institution. Instead, weather observations were generally made at three or four fixed times during the day [e.g., 0700, 1400, and 2100 local time (LT)]. Minimum and maximum temperatures occur outside the variance of these fixed observation time routines and are much more difficult to reconstruct. Thus, the more robust daily-mean temperature was selected as the reconstruction variable in this study.

The USHCN was developed with a focus on well-distributed, mostly rural stations with good metadata and a long period of record (Quinlan et al. 1987; Peterson and Vose 1997; Menne et al. 2009). Therefore, the selection of the target station for the reconstruction of daily-mean temperature in this study was limited to stations within the USHCN that contained 1) a long period of daily data available for the nineteenth century from the National Archive microfilms and 2) a long period of daily data available in the modern record (Darter 1942; Peterson and Vose 1997; Menne et al. 2009). Two stations in eastern Kansas met these criteria: Independence and Manhattan. Manhattan was selected as the target location because it is more centrally located with respect to the longest station temperature records available in Kansas during the nineteenth century, which will influence the quality of the regression models used to transfer the best daily data from surrounding stations to Manhattan (Fig. 1). Manhattan also has a long nineteenth-century record (1858–92; Fig. 1), and it has recorded observations within a cotton region shelter since 1901 (Williams et al. 2006). Finally, Doty (2005) has provided valuable information on the history of the Manhattan station. Daily temperature observations at Manhattan available in the microfilms began in February 1858 and were taken by Isaac Goodnow at Bluemont Central College, which became Kansas State Agricultural College in 1863, Kansas State College of Agriculture and Applied Science in 1931, and eventually Kansas State University in 1975. The daily weather observations were primarily recorded by faculty members on the campus until 1994, when staff at the

Kansas State University Weather Data Library assumed the duty (Doty 2005).

b. Screening, correction, and reconstruction of the historical record

Daily-mean temperature data from six historical stations and three modern stations (Fig. 1) were transferred to Manhattan via regression after all historical data were screened and corrected. Nine sequential operations were performed on the temperature observations to develop the historical portion of the Manhattan record (1828–93):

1) initial screening;
2) metadata screening;
3) corrections for time of observation;
4) screening for discontinuities in interhourly temperature range;
5) adjustments for homogeneity;
6) corrections for diurnal averaging;
7) construction of station segments;
8) regression model calibration and verification; and
9) derivation of the final regression models.

These operations are discussed in sections 2b(1)–(9). We then describe the importance of these screening and correction procedures in section 2c and the reconstruction of the modern record in section 2d. The attachment of the historical to the modern record is described in section 2e, followed by an evaluation of the consistency in the reconstruction in section 2f. Finally, we present a toolkit used to screen, correct, reconstruct, and analyze these data in section 2g.

1) Initial screening

The handwritten historical observations were first screened for legibility as each station was digitized. Data available in the Web Search Store Retrieve Display system of the National Oceanic and Atmospheric Administration (NOAA) Climate Database Modernization Program (Dupigny-Giroux et al. 2007) were consulted, but the quality of these scanned microfilms can be poor. Therefore, the historical data were primarily digitized directly from microfilms obtained from the National Archives (Darter 1942). Observations that were too illegible were recorded as missing.

2) Metadata screening

All observation changes indicated by metadata were recorded as a potential discontinuity for later scrutiny and correction, if necessary [see sections 2b(5) and 2b(7)]. Metadata listed on the meteorological registers were generally limited to station latitude and longitude, station elevation, and the name of the observer. However, the remarks section was sometimes informative. Specific remarks about the thermometer exposure were rare, but one remark from the Fort Leavenworth meteorological register in June 1873 revealed that some early weather observers were aware of potentially poor exposures (Natus 1873):

> The case containing the meteorological instruments has been removed from the exposed position w[h]ere the sun shone constantly on the close covered screen that surrounded the box containing the thermometer, thereby giving a register of intensified temperature the result of radiation from the screen and want of fore [sic] circulation of air arround [sic] the box.
>
> The instruments are now 21 feet west of the hospital building by which they are frequently shaded at the time of the morning reading and there is a roof 5 feet square covering the perforated box containing the instruments that shades it at 2 O'clock.

3) Corrections for time of observation

Hourly temperature data available at select stations from 1961 to 1995 were used to provide a modern framework to assess the historical fixed hourly observations. St. Louis, Missouri; Topeka, Kansas; Tulsa, Oklahoma; and Wichita, Kansas, were used in this study. These modern hourly temperature data were corrected so that a 0700 LT observation could be directly compared to a 0700 LT observation in the historical period (see the appendix). A standard practice of U.S. National Weather Service observers from 1961 to 1995 was to observe the temperature at approximately 20 min prior to the top of the hour (e.g., a 0700 LT observation occurred at 0640 LT). Thus, one required adjustment was to extrapolate the modern hourly temperature data to the top of the hour.

Many nineteenth-century observations were recorded by solar time instead of the standardized time zones used today. Therefore, solar time correction values were derived for each historical station [in minutes; see Eqs. (A1a) and (A1b) in the appendix], and these values were used to adjust the modern hourly temperature data to solar time as necessary. No solar time corrections were needed for U.S. Signal Service observations, because they were instructed to take observations by Washington time (Darter 1942). However, one hour was subtracted from the Signal Service observation times to adjust the time of observation to central time.

Equations (A2a) and (A2b) in the appendix were used to extrapolate modern hourly temperature data to the top of the hour and to solar time. However, sunrise was a common fixed observation time in the 1840s and 1850s (Lawson 1855), which required a different set of equations [(A2c)–(A2g) in the appendix]. Tables with sunrise and sunset times were consulted to adjust the modern hourly

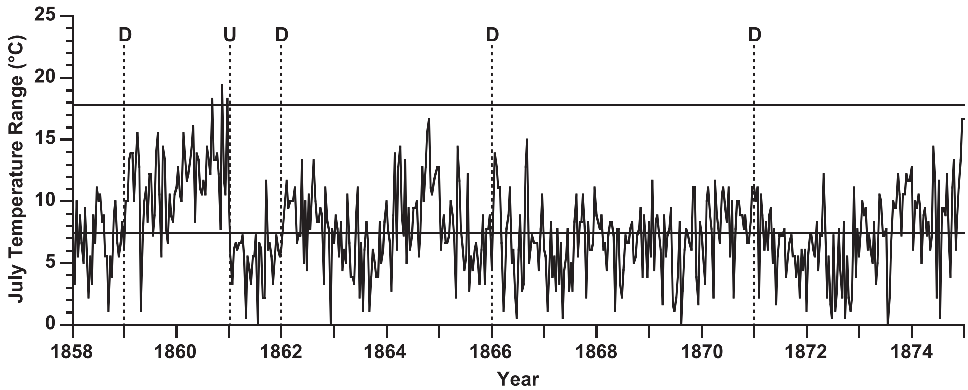


FIG. 2. Analyses of the temperature range between morning and afternoon observations in July during the nineteenth century were used to identify potentially undocumented changes in observation practices and/or exposure. These data were assessed relative to the same hourly temperature range in the high-quality modern period available from 1961 to 1995 [top horizontal line denotes the maximum range (17.8°C) and bottom line denotes the mean range (7.4°C) in the modern period]. Four documented station movements were detected in Manhattan's metadata from 1 Feb 1858 through 30 Jun 1875 (dashed lines labeled D). An undocumented abrupt shift in the time series was also detected in the July temperature range between 1860 and 1861 (dashed line labeled U). This shift may have arisen from a change in the observation practice or exposure of the instrument. This portion of the Manhattan record was separated into six segments at each documented and undocumented discontinuity (see Table 1).

temperature data to sunrise as needed [U.S. Naval Observatory 2007; see Eqs. (A2c)–(A2g) in the appendix].

4) Screening for discontinuities in interhourly temperature range

Time series plots of the temperature difference between the afternoon and morning observations in the historical data were constructed for every month to screen for undocumented discontinuities. In particular, the time series plots for July were carefully screened because the low July temperature variance facilitates the detection of discontinuities. Any abrupt excursion in the time series structure of the interhourly temperature difference would indicate a probable change in observing methodology (e.g., Fig. 2). These daily temperature ranges were also compared on a monthly basis to the same range in the modern record derived from the nearest modern hourly temperature station. Any historical temperature ranges above the 95th percentile or below the 5th percentile in the modern record were flagged and helped identify undocumented discontinuities that were masked by the large temperature variance during the cold seasons.

5) Adjustments for homogeneity

All documented and undocumented discontinuities identified in sections 2b(2) and 2b(4), respectively, were compiled for each historical station. The stations were then separated into segments (Table 1), so they could be adjusted for poor thermometer exposure signals. Previous studies have adjusted individual segments of daily temperature data on a monthly basis relative to the modern diurnal temperature cycle (e.g., Chenoweth 1998; Bergström and Moberg 2002). We followed this methodology. First, all historical segments and modern temperature data were transformed into anomalies relative to the overall averages (e.g., of several fixed hours or of maximum and minimum) of their individual time periods. Differences between these anomalies and the corresponding anomalies in the modern period were then calculated on a monthly basis. These differences yielded monthly correction values that were applied to the absolute daily temperatures in each historical segment to minimize the influence of nonstandard thermometer exposure on data homogeneity.

Analyses of these historical segments relative to the modern daily temperature cycle also yield clues about thermometer exposure. Figure 2 shows an assessment of the discontinuities in the daily observations for July at Manhattan from 1 July 1858 through 31 July 1874 (all were recorded at 0700, 1400, and 2100 LT). The jump in the time series at July 1859 was probably associated with a station move on 1 December 1858. Analysis of the interhourly temperature range in all months running from 1 December 1858 to 31 December 1860 relative to the modern diurnal temperature cycle revealed that the 1400 LT temperature data required negative adjustments (largest adjustments were −3.1°C in May and July). Temperatures recorded at 0700 and 2100 LT necessitated a positive correction, but the magnitudes of

TABLE 1. The documented and undocumented potential discontinuities identified in the seven nineteenth-century daily temperature records used in this analysis are listed (identified with metadata and with analyses of interhourly temperature differences). All historical records were separated into segments at each discontinuity as identified below (6 segments at Fort Gibson, 13 at Fort Leavenworth, etc.). Each segment was adjusted separately using modern hourly temperature data to account for varying thermometer exposures. All potential discontinuities were then tested for significant changes between the segments (e.g., Table 2). In the third column, M = movement of the station, T = change in time of observation, and U = undocumented station move.

Station	Segment	Discontinuity
Fort Gibson, OK	1 Jul 1828–31 Mar 1841	
	1 Apr–31 Aug 1841	T
	1 Sep 1841–31 Dec 1842	M
	1 Jan 1843–31 Jan 1848	T
	1 Feb 1848–30 Jun 1855	M
	1 Jul 1855–30 Jun 1857	T
Fort Leavenworth, KS	1 Jul 1828–31 Dec 1829	
	1 Jan 1830–31 Dec 1837	U
	1 Jan 1838–31 Dec 1840	U
	1 Jan 1841–31 Dec 1842	T
	1 Jan 1843–31 Aug 1845	T
	1 Sep 1845–30 Nov 1846	M
	1 Dec 1846–31 Dec 1852	M
	1 Jan 1853–31 Jul 1855	U
	1 Aug 1855–31 Mar 1866	T
	1 Oct 1866–31 May 1873	U
	1 Jun 1873–31 Aug 1883	M
	1–31 Jul 1888	M
	1 Aug 1888–29 Feb 1892	T
Fort Riley, KS	1 Nov 1853–30 Jun 1855	
	1 Jul 1855–30 Jun 1876	T
	1 Jan 1886–31 Aug 1888	M
	1 Sep 1888–31 Dec 1893	T
Fort Scott, KS	1 Jul 1842–13 Jan 1843	
	14 Jan 1843–31 Mar 1853	T
Jefferson Barracks, MO	1 Jul 1828–31 Dec 1835	
	1 Oct 1836–30 Sep 1837	M
	1 Apr 1838–30 Sep 1840	M
	1 Oct 1840–31 Dec 1841	T
	1 Jan–31 Dec 1842	M
	1 Jan 1843–30 Apr 1844	T
	1 May–31 Dec 1844	M
Leavenworth, KS	1 Nov 1857–31 Dec 1858	
	1 Apr 1861–30 Apr 1862	M
	1 Jan 1866–31 Mar 1868	M
	1–30 Apr 1868	M
	1 May 1868–31 Dec 1872	M
	1 Jan 1873–30 Jun 1877	T
	1 Jul 1877–31 Dec 1892	T
Manhattan, KS	1 Feb 1858–30 Nov 1858	
	1 Dec 1858–31 Dec 1860	M
	1 Jan 1861–30 Jun 1862	U
	1 Jul 1862–30 Sep 1865	M
	1 May 1866–31 Oct 1871	M
	1 Nov 1871–30 Jun 1875	M
	1 Jun 1876–31 Jul 1883	T
	1 Aug 1883–31 Dec 1892	M

those corrections were not as large. These adjustments suggest that the thermometer may have had a southern exposure because of the anomalously warm temperature readings in the afternoon relative to the other observation times.

6) CORRECTIONS FOR DIURNAL AVERAGING

Daily-mean temperatures calculated from an average of the fixed hourly temperature readings (e.g., 0700, 1400, and 2100 LT) are significantly different from daily-mean temperatures calculated from an average of minimum and maximum temperature values. Therefore, a correction is required to ensure that daily means calculated from the fixed hourly observations of the nineteenth century are compatible with modern daily means calculated from minimum and maximum data. The modern hourly temperature datasets were used to compute average differences between these two estimates of daily-mean temperature in the relevant calendar month. These differences were then scaled by the day-to-day variations of diurnal temperature range [see Eq. (A3) in the appendix].

7) CONSTRUCTION OF STATION SEGMENTS

All discontinuities in Table 1 were carefully examined at each station in an attempt to identify possible biases, after the daily-mean temperature had been corrected for time of observation and homogeneity. Difference series were computed comparing the station with the suspected discontinuity against a nearby station already tested for significant change in the daily means before and after its discontinuities. The suspect daily-mean time series was plotted and inspected visually for major changes in the mean and variance. The difference series between the two stations was tested with a two-tailed *t* test for up to five months before and after the discontinuity and using the monthly-mean difference series for up to three years before and after the discontinuity (length of analysis before and after the discontinuity was dependent on the availability of homogenous data). If these analyses revealed no significant shift in the mean or obvious change in variance, then the two segments before and after the discontinuity were joined together into one continuous series. A total of 11 continuous series were identified, and they were used subsequently for the reconstruction of daily-mean temperature (Table 2).

Most of the nonsignificant discontinuities were associated with either a change in the time of observation or with an undocumented change that was detected by screening the interhourly temperature range [section 2b(4)]. The historical data associated with these potential discontinuities may have been partially corrected by adjusting the daily means for time of observation, homogeneity,

TABLE 2. All discontinuities reported in Table 1 were carefully examined by constructing daily and monthly difference series using a previously tested series from a nearby station. If no significant change was detected at the discontinuity, then the two segments were joined into one continuous series. This resulted in the 11 continuous daily temperature segments listed below (test stations as in Fig. 1). Monthly analyses could not be performed on short segments (denoted as NA). Four segments had no documented or detected discontinuities (Leavenworth 1, 1877–92; Leavenworth 2, 1873–77; Fort Gibson 2, 1828–41; and Jefferson Barracks 1, 1828–35). Note that the Fort Leavenworth record is treated as continuous from 1828 to 1845 (and Fort Gibson from 1828 to 1841 and Fort Riley from 1853 to 1893), based on our empirical analyses. These early data may not be truly homogeneous given the frontier conditions and potentially inconsistent observation practices. However, no glaring inhomogeneities were detected in these continuous segments.

Station segment	Continuous series	Test station	Daily test period	Monthly test period
Manhattan 1	1 Nov 1871–31 Dec 1892	FLV	1 Feb 1875–31 Oct 1876	Jun 1872–Jun 1879
		LEV	1 Mar–31 Dec 1883	Jul 1880–Aug 1886
Fort Riley 1	1 Nov 1853–31 Dec 1893	FLV	1 Jun–31 Jul 1855	NA
		MHK	1 Feb 1876–31 May 1886	Oct 1873–Aug 1888
		MHK	1 Apr 1888–31 Jan 1889	Jan 1886–Sep 1888
Manhattan 2	1 Jul 1862–31 Oct 1871	FRI	1 May 1865–30 Sep 1866	Sep 1862–May 1869
Leavenworth 1	1 Jul 1877–31 Dec 1892		No Discontinuities	
Leavenworth 2	1 Jan 1873–30 Jun 1877		No Discontinuities	
Fort Leavenworth 1	1 Dec 1846–31 Mar 1866	FGB	1 Aug 1852–31 May 1853	Jun 1850–Jun 1855
		FGB	1 Jul–31 Aug 1855	NA
Fort Scott 1	1 Jul 1842–31 Mar 1853	FLV	1–31 Jan 1843	NA
Fort Gibson 1	1 Sep 1841–30 Jun 1857	FSC	1 Dec 1842–13 Jan 1843	NA
		FLV	1 Sep 1847–30 Jun 1848	Dec 1846–Mar 1849
		FLV	1 Jun 1855–31 Jul 1855	NA
Fort Leavenworth 2	1 Jul 1828–31 Aug 1845	JBA	1 Aug 1829–31 Mar 1830	Jul 1828–May 1831
		FGB	1 Aug 1837–31 May 1838	Jan 1835–Dec 1840
		JBA	1 Oct 1840–31 Mar 1841	Jan 1840–Dec 1841
		FSC	1 Dec 1842–13 Jan 1843	NA
Fort Gibson 2	1 Jul 1828–31 Mar 1841		No discontinuities	
Jefferson Barracks 1	1 Jul 1828–31 Dec 1835		No discontinuities	

and diurnal averaging in previous steps [sections 2b(3), 2b(5), and 2b(6)]. Four nonsignificant discontinuities were associated with recorded changes in the latitude, longitude, or elevation of the station, but most of these apparent station movements appear to have been simple revisions in the documentation and not true station relocations.

The analyses of the interstation difference series were constrained by the fragmentary nature of the historical temperature records. Furthermore, meteorological variations may impact the difference series between two widely separated stations, especially at daily resolution. Thus, interstation difference series based on monthly data were also carefully scrutinized, especially for Fort Leavenworth, Fort Scott, Fort Gibson, and Jefferson Barracks.

Potential discontinuities at 1855 and 1843 were difficult to evaluate because changes in instrumentation and recording practice occurred simultaneously at most weather stations in the central U.S. (Lawson 1855; Darter 1942; Tables 1, 2). Fortuitously, the change in the time of observation at Fort Leavenworth was delayed for one month in 1855. Therefore, daily data for 30 days before and after the change at Fort Riley and Fort Gibson could be compared with the unchanged observations at Fort Leavenworth (Table 2), and no significant difference was detected in a two-tailed *t* test comparing the daily-mean temperature differences between these stations. The potential discontinuity at 1855 occurred when a new set of instructions were also issued to the weather observers (Darter 1942). This combined with the limited overlap available for a thorough assessment of the discontinuity increases uncertainty in the reconstruction before 1855.

The change in observation time in 1843 was more problematic. Again, this change was delayed by almost two weeks at Fort Scott, which allowed for a limited 13-day comparison between Fort Scott and the other available stations before and after the installation of the change. Although no significant differences were detected between Fort Scott and either Fort Leavenworth or Fort Gibson, the observational changes installed in 1843 included new observing directions from the Surgeon General and new thermometers conforming to Naval Observatory specifications (Lawson 1855; Darter 1942). These changes in methodology and the paucity of uniform instrumentation increase the uncertainty in the reconstructed daily temperature data prior to 1843. In spite of our efforts to identify inconsistencies in the historical temperature data, it is possible that the 11 continuous series used for the reconstruction of daily-mean temperature (Table 2) still retain potential problems associated with the changing methods of temperature observation.

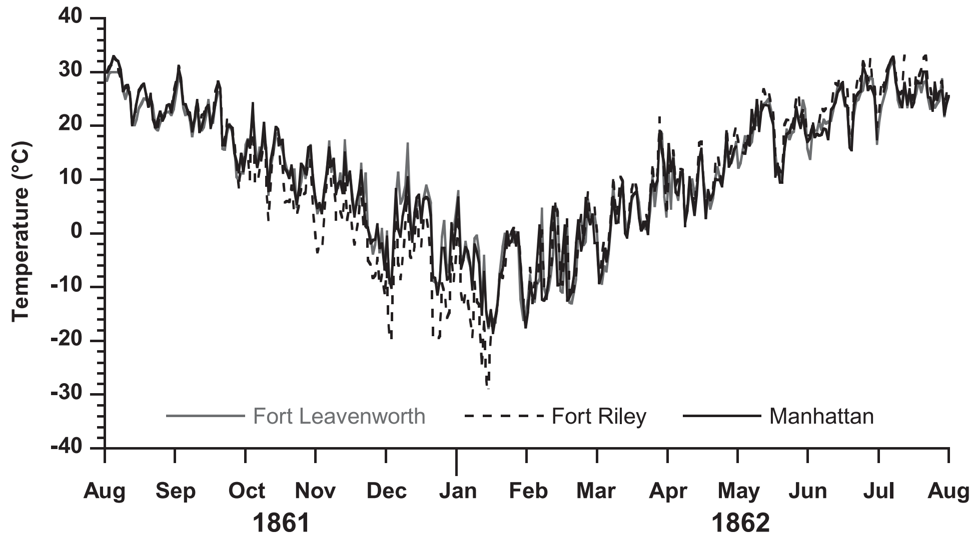


FIG. 3. Comparison of the daily-mean temperatures from Fort Leavenworth, Fort Riley, and Manhattan detected a probable bias in the Fort Riley observations from September 1861 to January 1862. The Fort Riley observations deviated by as much as 13.2°C from Manhattan between September and January, but the difference disappeared in mid-January. These differences are not meteorologically plausible (Fort Riley and Manhattan are only 6.5 km apart). There was a brief change in the weather observer at Fort Riley in September 1861, and then the original observer returned (Drews 1861; Miles 1861). This observer change could have introduced a poorly calibrated or damaged thermometer, which might explain the anomalous daily-mean temperatures. The suspect Fort Riley data from September 1861 to January 1862 were eliminated from the database.

Further analyses of daily temperature data from historical sources across the central United States will be necessary to more carefully evaluate the early temperature measurements in Kansas.

8) Regression model calibration and verification

Bivariate regression was used to transfer daily-mean temperature data from several short intermittent temperature records located primarily in eastern Kansas to the Manhattan station, thus developing the 180-yr-long record (Fig. 1). Three bivariate regression models were derived for each month, where model 1 was used on the first day of the month and every third day thereafter, model 2 was used on the second day of the month and every third day thereafter, and model 3 was used on the third day of the month and every third day thereafter. Comparisons of this "every third day per month" method with a method that derives only one bivariate regression model per month showed higher R^2 values, higher correlations between estimated and independently observed temperatures, lower standard error (SE) values, and less autocorrelation in the regression residuals. This improvement is a consequence of the reduced interdependence of the every third day per month data (Draper and Smith 1981).

The regression process began by using stations closest to Manhattan, which are generally the most highly intercorrelated. Prior to regression, an interstation screening routine was run twice on the daily-mean temperature differences between the independent and dependent stations. Days were flagged when the daily-mean temperature differences were above the 90th percentile or below the 10th percentile (cf. Cocheo and Camuffo 2002). Daily-mean temperatures on the dates in question were then compared with the other stations in the network, and the station with a daily-mean temperature most different from the network average was removed from the reconstruction. Stations used for this screening routine included all data from the stations in Fig. 1 and daily data from Atchison, Emporia, Lawrence, and Salina, Kansas. The same routines discussed in sections 2b(1)–2b(6) had also been run on these additional stations. Interstation screening is imperative, because the quality of the daily historical temperature data can be highly variable at short time scales (e.g., Fig. 3).

All regression models were first calibrated and verified forward and backward using approximately equal halves of the overlapping period between the stations. These regression models were evaluated during the calibration period based on the coefficients of determination R^2, standard errors of the estimate, and the Durbin–Watson test for autocorrelated residuals. They were compared with independent temperature data during the verification period using correlation and the coefficient of efficiency

TABLE 3. Regression was used to screen the historical data prior to calculation of the final Manhattan reconstruction. Split period calibration–verification experiments were performed on every overlapping station segment. At each station segment, 36 regression models were used to estimate daily-mean temperature (three models per month using the every third day per month technique) for both halves of the overlapping period. The average R^2, SE, CE, and r values for the models at each station are presented, along with the lowest and highest R^2 and CE values. Models where the sample size fell below 15 were not included in the summary. The two stations most distant from Manhattan had the lowest R^2 and CE values (Fort Gibson and Jefferson Barracks).

Station segment	Calibration				Verification			
	Low R^2	High R^2	Mean R^2	Mean SE (°C)	Low CE	High CE	Mean CE	r*
Fort Riley, KS 1	0.92	0.99	0.98	0.79	0.81	0.99	0.95	0.99
Manhattan, KS 2	0.94	0.99	0.97	0.75	0.84	0.99	0.96	0.99
Leavenworth, KS 1	0.92	0.98	0.96	0.99	0.89	0.98	0.95	0.98
Leavenworth, KS 2	0.92	0.99	0.97	0.93	0.89	0.99	0.95	0.99
Fort Leavenworth, KS 1	0.82	0.98	0.95	1.07	0.70	0.98	0.93	0.97
Fort Scott, KS 1	0.82	0.99	0.96	0.81	0.68	0.99	0.93	0.98
Fort Gibson, OK 1	0.82	0.98	0.93	1.15	0.74	0.97	0.90	0.96
Fort Leavenworth, KS 2	0.82	0.97	0.92	0.80	0.80	0.91	0.87	0.96
Fort Gibson, OK 2	0.74	0.97	0.89	1.31	0.72	0.96	0.87	0.94
Jefferson Barracks, MO 1	0.75	0.99	0.91	1.25	0.68	0.98	0.86	0.95

* r = mean Pearson correlation between actual and estimated daily-mean temperatures.

(CE; Cook et al. 1994), when the sample size was ≥15. The CE is defined as

$$\mathrm{CE} = 1.0 - \sum(x - x_r)^2 \left[\sum(x - x_m)^2\right]^{-1},$$

where the sums are performed over the verification period and x is the actual daily-mean temperature, x_r is the reconstructed daily-mean temperature, and x_m is the mean of the actual daily-mean temperatures (cf. Cook et al. 1994). These statistics and plots of residuals were carefully scrutinized to identify and eliminate any remaining problematic daily-mean temperature observations by running the interstation screening routine again on any suspect daily data. Table 3 summarizes the final calibration and verification results after all problematic data had been purged from the datasets. The mean CE was above 0.86 for all station segments (Table 3). Weakest models were based on the most distant stations (Fort Gibson, Oklahoma, and Jefferson Barracks, Missouri), which were used only when there were no closer alternatives.

9) DERIVATION OF THE FINAL REGRESSION MODELS

Final regression models were derived using the entire period of overlap after screening with forward and backward calibration and verification was completed. The station data were used for reconstruction in the order presented in Table 4. Most of the daily-mean temperature data used in the reconstruction from 1828 to 1893 were derived from nearby stations in northeastern Kansas (Fig. 1 and Table 4). The lower-quality models from Fort Gibson and Jefferson Barracks, the closest stations available in the 1820s–50s, were needed to estimate 1882 out of 23 925 days during the historical reconstruction period from 1828 to 1893. The variance explained by

TABLE 4. Final regression models were calibrated on the entire common period once all influential outliers had been purged from the datasets. The stations were used preferentially for reconstruction by the order listed below (1–10; N denotes the sample size; other abbreviations as in Table 1). The weakest regression models were derived for the most distant historical observations at Fort Gibson and Jefferson Barracks (each daily-mean temperature estimate, SE, and station used is available online at http://www.uark.edu/dendro/kansas/).

Order	Station segment	Low N	High N	Mean N	Low R^2	High R^2	Mean R^2	SE (°C)
1	Fort Riley, KS 1	54	79	64	0.94	0.99	0.97	0.92
2	Manhattan, KS 2	33	64	50	0.93	0.99	0.97	0.80
3	Leavenworth, KS 1	71	113	92	0.93	0.98	0.96	1.00
4	Leavenworth, KS 2	26	36	30	0.91	0.98	0.97	0.92
5	Fort Leavenworth, KS 1	66	89	77	0.90	0.98	0.95	1.09
6	Fort Scott, KS 1	28	49	37	0.89	0.98	0.96	0.85
7	Fort Gibson, OK 1	74	102	90	0.85	0.97	0.93	1.19
8	Fort Leavenworth, KS 2	19	32	25	0.82	0.98	0.93	1.13
9	Fort Gibson, OK 2	59	85	73	0.77	0.96	0.89	1.33
10	Jefferson Barracks, MO 1	25	54	41	0.77	0.98	0.90	1.30

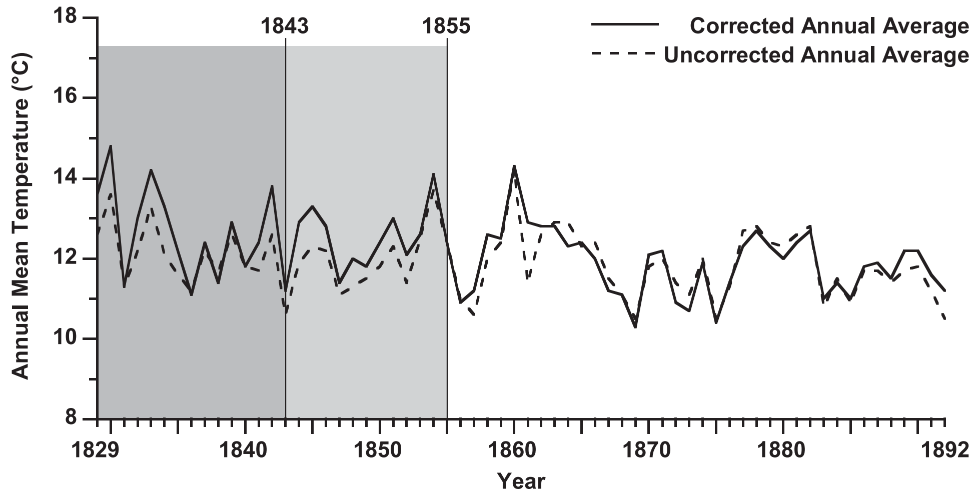


FIG. 4. Daily-mean temperatures based on fixed hourly observations during the historical period (1828–92) have been corrected to be compatible with daily means calculated from maximum and minimum temperatures during the modern period (1893–2009). These data have also been adjusted for other nonclimatic discontinuities (e.g., poorly exposed thermometer, station relocation, changes in observing time). Corrected annual-mean temperatures shown here were 0.26°C warmer on average than the uncorrected data (annual average, $P < 0.0001$). Significant differences between the corrected and uncorrected data were detected in all seasons ($P < 0.05$). Uncertainty increases in the reconstruction prior to 1855 and by an additional amount prior to 1843 (see section 2f for further discussion). Increasing gray shading indicates increasing levels of uncertainty.

these models was highest in the winter season, but it never fell below $R^2 = 0.77$ (Table 4).

Most of the regression models had mean sample sizes of at least 30, but one suite of models associated with the second Fort Leavenworth segment had small sample sizes (Table 4). Although the R^2 values were high for these models, only 5 of 36 models could be calibrated and verified. This segment of Fort Leavenworth also spans the 1842–43 period, when there was a fundamental change in the observing methodology and instrumentation [section 2b(7)]. Therefore, uncertainty in the reconstructed daily-mean temperature at Manhattan increases prior to 1843.

c. *Significance of screening and correcting the daily historical data*

Failure to rigorously screen and correct these daily meteorological data would result in a significant cold bias to the annual (Fig. 4) and seasonal mean temperature data. The uncorrected series shown in Fig. 4 was calculated using the same regression-based methodology and same station segments, but with no correction for time of observation, diurnal averaging, or homogeneity and no interstation screening. Note the large difference of 1.5°C between the corrected and uncorrected annual-mean temperatures in 1861 (Fig. 4). Figure 3 illustrated a significant cold bias between Fort Riley, Kansas, and other nearby station data during the last four months of 1861, and those problematic data were purged during the interstation screening phase of the reconstruction. The uncorrected series was calculated using the anomalous Fort Riley data. Thus, it is likely that these anomalous data introduced a significant cold bias in the annual-mean temperature for 1861. The uncorrected discontinuities and the poorer-quality data within the uncorrected dataset introduce biases in the regression relationship between station segments, and these biases generally increase as the reconstruction proceeds backward to 1828.

d. *Reconstruction of the modern record*

The daily-mean temperature data from Manhattan, Ottawa, Atchison, and Emporia, Kansas, used to reconstruct the Manhattan record from 1 January 1893 to 28 February 2009 were obtained from the Global Historical Climatology Network (GHCN; Peterson and Vose 1997). Manhattan, Ottawa, and Atchison are USHCN stations, which is a subset of the GHCN (Peterson and Vose 1997). Emporia is the lone station that was used in the reconstruction but not classified as USHCN. Minneapolis, Kansas, was well correlated, but it has a large and probably artificial shift in mean temperature in the 1890s and was not used for this reconstruction.

Ottawa, Atchison, and Emporia were first regressed on the modern daily data at Manhattan in the order listed using the same interstation screening and every third day per month forward, backward, and final regression modeling routines as detailed in sections 2b(8) and 2b(9). The R^2 and CE values during this phase of the reconstruction ranged from 0.93 to 0.99 and from 0.91 to 0.99, respectively. These routines developed a continuous record of daily-mean temperature for Manhattan running from 1 January 1893 to 28 February 2009. Daily data (available online http://www.uark.edu/dendro/kansas/) indicate which station was used for each day.

Various discontinuities such as time of observation changes, station movements, and changes in the environment around the station remain in the reconstructed modern daily data, but homogenized monthly-mean temperature data are available from version 2 of the USHCN, which improves upon version 1 with more effective station-specific homogeneity adjustments (Menne et al. 2009). Thus, USHCN version 2 for Manhattan running from January 1895 to February 2009 were obtained and used as a homogenous reference series to correct the daily data. Differences between the monthly averages of the raw daily data and the corrected monthly values from the USHCN version 2 were computed, which yielded monthly correction values, but directly applying these corrections could introduce discontinuities at the beginning and end of each month. Thus, the raw daily data were adjusted by interpolating between the monthly correction values (cf. Moberg et al. 2002; Vincent et al. 2002). Adjustments were different for each month and are summarized by decade in Table 5. Note that these homogenous data from USHCN version 2 are only available back to 1895. This left two years, 1893 and 1894, that could not be adjusted. However, metadata from the two stations that cover 1893 and 1894, Atchison and Emporia, were carefully examined and no known discontinuity occurred in either station during this period of time (Williams et al. 2006; National Climatic Data Center 2008).

No specific corrections for urban heat island were applied to the USHCN version 2 dataset, but the methodology used to homogenize the dataset appears to account for gradual changes in the environmental conditions around the station (Menne et al. 2009). Furthermore, the microscale environment can influence the magnitude of urban heat island effects on temperature time series and "park cool islands" have been observed inside the mesoscale urban environment (Peterson 2003). Metadata on the Manhattan station provided in the USHCN (Williams et al. 2006) and by Doty (2005) suggest that the station was located in well-exposed areas on grass away from large buildings and industry from 1895 to the present. Today, the station is near the north edge of the Kansas State University campus in an open grassy area and unlikely to have suffered major urban warming.

TABLE 5. Each daily-mean temperature in the Manhattan record from 1895 to 2009 was adjusted on a monthly basis relative to the homogenous monthly-mean temperature data at Manhattan available from USHCN version 2 (Menne et al. 2009). A summary of the adjustments (°C) is presented by decade. These adjustments take into account all nonclimatic biases such as time of observation, station movement, and gradual changes in the environment around the station. The most recent movement of the station occurred on 15 May 1989, and no changes have occurred since that time (Doty 2005).

Decade	Min	Mean	Max
1895–99	−1.44	0.32	2.11
1900–09	−0.88	0.44	1.69
1910–19	−1.61	−0.06	1.52
1920–29	−0.84	0.09	1.13
1930–39	−1.39	0.12	1.43
1940–49	−0.94	0.17	1.75
1950–59	−1.95	−0.04	0.78
1960–69	−0.64	0.19	1.24
1970–79	−0.42	0.31	1.65
1980–89	−1.24	0.11	1.18
1990–99	−1.30	−0.07	1.31
2000–09	−0.94	0.17	2.14

e. *Attachment of the historical and modern daily-mean temperature data*

The reconstructed historical dataset overlaps the modern dataset for approximately 11 months in 1893 (Fig. 5). This overlap was used to make a quantitative comparison between the historical and modern daily-mean temperature time series. However, Fort Riley was the sole historical record available for 1893 and could not be thoroughly screened during the reconstruction of the historical dataset. Thus, the Fort Riley data were first assessed relative to other modern station data from the city of Leavenworth and Independence that were not used to reconstruct the modern temperature record to identify any problematic segments. The results show that Fort Riley lost variance relative to other stations from late September into November; therefore, those data in the historical reconstruction for 1893 were removed from the dataset. A two-tailed paired t test was then run on the approximate 10 months of remaining overlap between the historical and modern daily data in 1893 and no significant difference was detected between the two datasets ($P = 0.6862$; Fig. 5).

Based on the examination of the overlap between the historical and modern datasets, the historical data for 1893 were eliminated from the reconstruction and the modern data were attached to the end of the historical data at 1 January 1893. No significant discontinuities were noted in the Independence record from 1 January 1885 through 31 December 1909, and a cotton region shelter was also in use (Williams et al. 2006). Linear regression

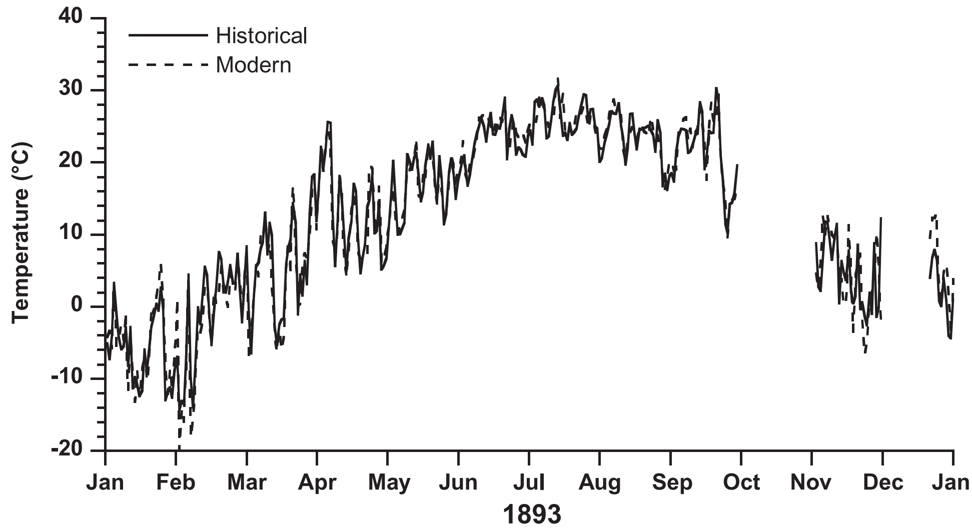


FIG. 5. Historical Manhattan was reconstructed forward to 31 Dec 1893 and modern Manhattan was reconstructed backward to 1 Jan 1893. An approximate 10 months of overlap (note the gaps in October and December) were then examined, and no significant difference was found between the two datasets ($P = 0.6862$). The historical data for 1893 were then eliminated from the database and the modern dataset was attached to the end of the historical dataset on 1 Jan 1893.

lines fit to the slopes of the Independence and the reconstructed Manhattan annual-mean temperature data were compared from 1885 through 1909, and no significant difference between the two slopes was detected ($P = 0.9431$). A difference series between the annual means at Independence and Manhattan was also constructed, and a two-tailed t test between the 1885–92 and 1893–1909 differences was not significant ($P = 0.297$).

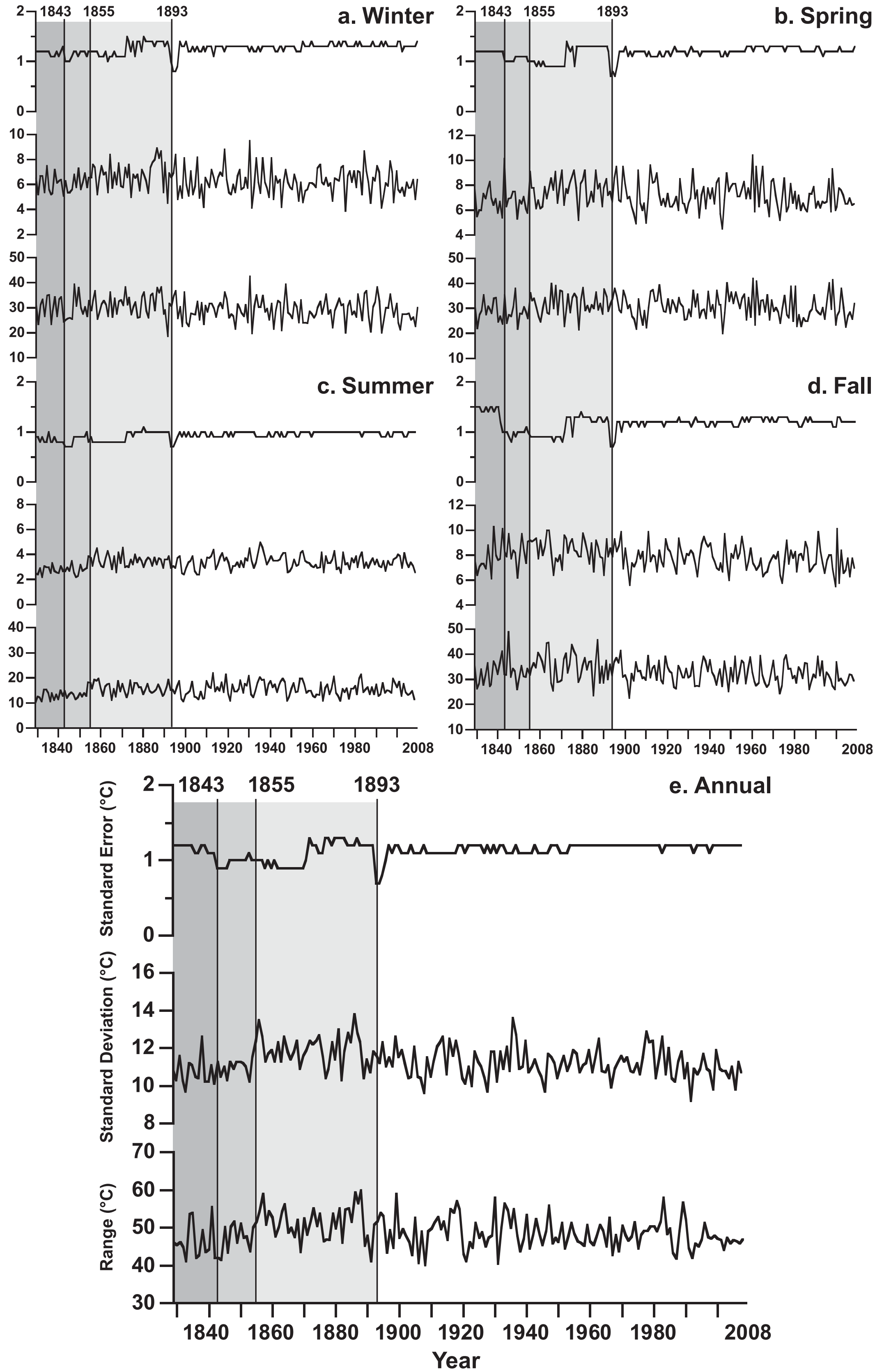
f. The consistency of the daily-mean temperature reconstruction

Uncertainty remains in the reconstruction because of nineteenth-century changes in instrumentation, procedures, and undocumented station movements, in spite of the screening, testing, and adjustments applied to the daily observations. This remaining uncertainty is difficult to quantify because of the lack of other nineteenth-century temperature records for the region and the limited temporal overlap between the temperature records that are available. The greatest uncertainties appear to remain at 1893, when the modern and historical records overlap briefly (i.e., 10 months); 1855, when there was a system-wide change in procedures (Darter 1942); and 1843, when there was a system-wide change in instrumentation and procedures (Lawson 1855; Darter 1942). Some insight into the internal consistency of the daily temperature reconstructions may be gained by an examination of the standard errors of the regression estimates, the standard deviations of the daily temperature data used to compute seasonal and annual temperature averages, and the range of daily temperatures included in these averages over the past 180 yr (Fig. 6).

The standard errors are stable during the twentieth century, decline sharply from 1893 to 1895 when the reconstruction is based on a long calibration period [1896–2009; the modern Manhattan record was reconstructed with uncorrected daily station data and then homogenized using the corrected monthly USHCN data (section 2d)], and are slightly elevated from 1872 to 1892 (Figs. 6a–e). The sharp decline in standard errors at 1872 (Fig. 6) is largely due to the use of more proximate stations for the reconstruction of Manhattan temperature (Table 2). Standard errors increase before 1843, partly because of the incorporation of estimates from more distant stations.

The standard deviations and range of the daily temperatures included in the seasonal and annual temperature reconstructions do not indicate any glaring inconsistencies from 1854 to 2009 (Figs. 6a–e). Thus, the link between the historical and modern data at 1893, although short, appears to be reasonable.

The variance of the reconstruction is suppressed before 1854, especially in summer (Figs. 6a–e). This is likely related to protected exposures, discontinuities, and poorer-quality data. The suppressed variance only appears once Fort Leavenworth is the main station used (i.e., 1 July 1828 to 31 October 1853). Analyses of the interhourly temperature range [section 2b(4)] and homogeneity adjustments [section 2b(5)] at Fort Leavenworth revealed small ranges and positive adjustments of 1°C or more to the afternoon temperatures from 1


a. Winter
b. Spring
c. Summer
d. Fall
e. Annual
1843
1855
1893
Standard Error (°C)
Standard Deviation (°C)
Range (°C)
1840
1860
1880
1900
1920
1940
1960
1980
2008
Year

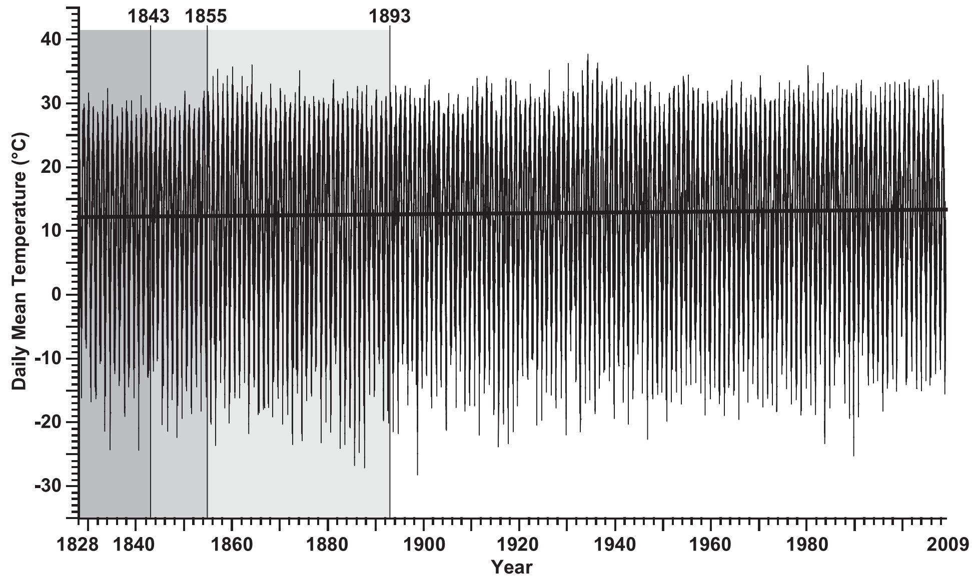


FIG. 7. All 65 987 daily-mean temperatures estimated from 1 Jul 1828 to 28 Feb 2009 are illustrated for Manhattan [0.06° ± 0.01°C decade^{-1} ($P < 0.0001$)]. The 95% confidence interval estimates are not shown in the figure, but are presented on a Web site (available online at http://www.uark.edu/dendro/kansas/). The confidence interval was derived from the regression SE. Confidence intervals for daily-mean temperatures observed at Manhattan were calculated by regressing Manhattan daily data on the reconstruction from 1895 to 2009. Transitions in the quality of the data occur at 1843, 1855, and 1893 and are indicated here and in Figs. 8–13 by vertical lines and increasing shades of gray to denote increasing uncertainty in the reconstruction (see section 2f).

January 1838 to 31 December 1852 (not shown). Such adjustments might be consistent with a northward exposure of the thermometer, which was a common practice in the U.S. during the nineteenth century, and can result in a record that is cool biased, especially during the afternoon (Chenoweth 1992). Larger temperature ranges were observed at Fort Leavenworth from 1830 to 1837, and adjustments for exposure indicated that the thermometer may have been exposed in a southerly direction, perhaps on a south wall, because the afternoon temperatures were lowered and the morning temperatures were increased upon adjustment, and the evening temperatures had to be reduced (suggesting heat retention by a building). The standard deviation and range also appear to be less suppressed from 1830 to 1837, except in the summer (Figs. 6a–e). An overprotected thermometer at Fort Leavenworth seems plausible from 1828 to 1829, when standard deviations and ranges were again suppressed, except during the winter season (Figs. 6a–e). A comparison of the summer and annual temperature ranges between the uncorrected and the final reconstruction showed an average increase in the summer and annual temperature ranges by 2.9° and 4.0°C, respectively.

We use the standard error of the regression models as a first-order estimate of the uncertainty in the reconstructions associated with our station network. The deeper uncertainties associated with hidden changes in procedures and instruments are more difficult to represent and are indicated in Figs. 4 and 6–13 by increasing levels of gray shading. The analyses of standard deviations, ranges, and exposure adjustments would suggest that the bias is greatest in the summer and lowest in the winter. This inference is supported by an analysis of the statistical distribution of the daily-mean temperature

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FIG. 6. Time series of the SEs of the (top) regression estimates, (middle) standard deviations, and (bottom) range of daily-mean temperature values for the seasonal and annual series are plotted and indicate potential problems in variance structure of the reconstruction that may remain at key time periods (i.e., 1843, 1855, 1893; denoted with increased gray shading to represent increased uncertainty). Changes in the SEs are a function of the distance between stations used for temperature reconstruction, sample size, and data quality (e.g., the estimates for 1893–95 are based on a long calibration period). The suppressed variance before 1854, particularly (c) in the summer season, may be due to instrumentation and methodological changes that remain uncorrected in the reconstructions.

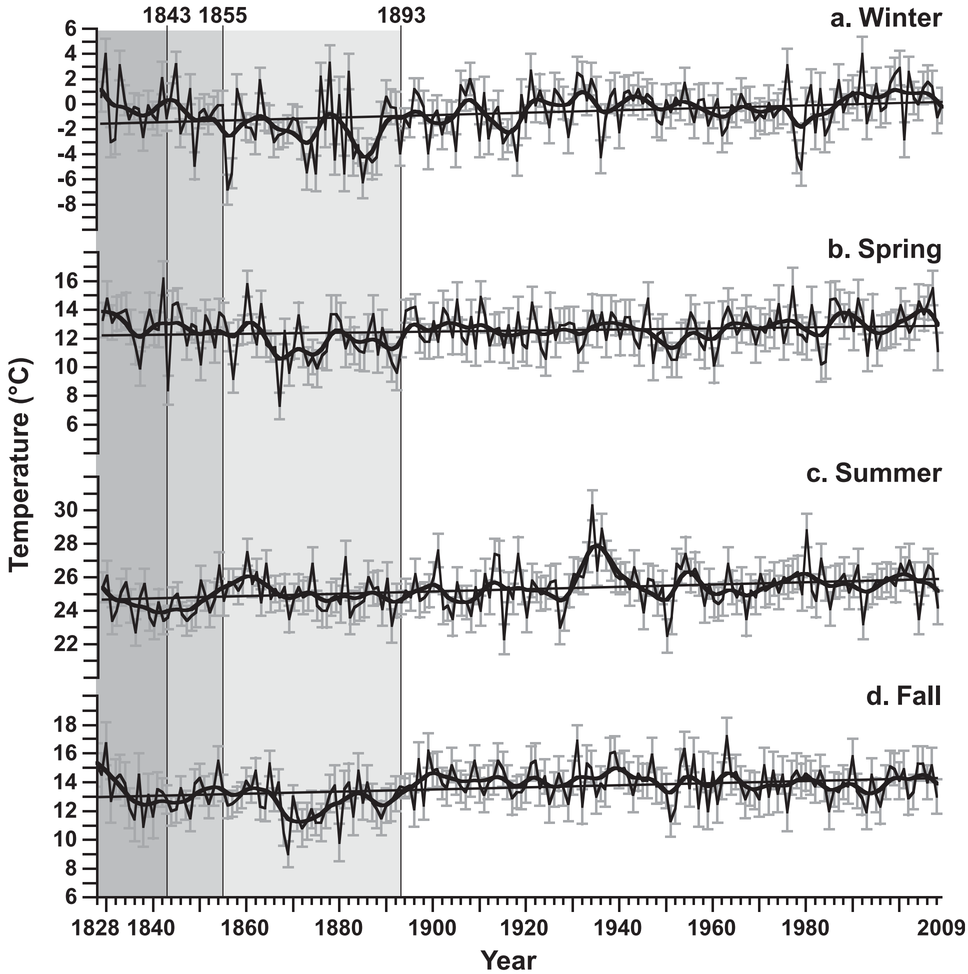

FIG. 8. (a) Winter, (b) spring, (c) summer, and (d) fall mean temperatures with approximate 95% confidence level estimates and 10-yr cubic smoothing splines. The 95% confidence interval estimates were derived by seasonally averaging the 95% confidence level associated with each daily-mean temperature and are therefore conservative, because the averaging is likely to narrow the confidence ranges. Positive linear trends were detected in all seasons [$+0.10° \pm 0.03°C$ decade^{-1} in winter ($P = 0.0010$), $+0.04° \pm 0.02°C$ decade^{-1} in spring ($P = 0.0619$), $+0.07° \pm 0.02°C$ decade^{-1} in summer ($P = 0.0001$), and $+0.07° \pm 0.02°C$ decade^{-1} in fall ($P = 0.0001$)].

data on a seasonal and annual basis, comparing the 27-yr periods 1828–54 and 1901–27 (not shown). The overall variance was lower during the 1828–54 summer season, but the variance, skewness, and kurtosis were similar for the other seasons during the two 27-yr periods. Because the temperature extremes tend to be more sensitive to these measurement uncertainties than daily, seasonal, or annual-mean values (Chenoweth 1993; Parker 1994; van der Meulen and Brandsma 2008; Brandsma and van der Meulen 2008), we have reasonable confidence in the seasonal and annual means back to 1828. Reconstructed seasonal means and extremes are presented prior to 1855, but the extrema are likely to be biased by uncorrected problems with the observations, especially during the summer season.

g. *Analysis of the daily-mean temperature reconstruction*

Daily-mean temperature, seasonal means, annual means, heating and cooling degree-days, the warmest and coldest days of the year, counts of seasonal and annual extremes, and counts of cold waves and heat waves are plotted in Figs. 7–13 with the years 1843, 1855, and 1893 highlighted to denote the years when uncertainty increases, as described in section 2f. Confidence intervals were estimated for all daily-mean temperature values and all other derived time series shown herein (see figure captions). All linear trends were examined for statistical significance by testing whether the slope was statistically different from zero, and the standard error

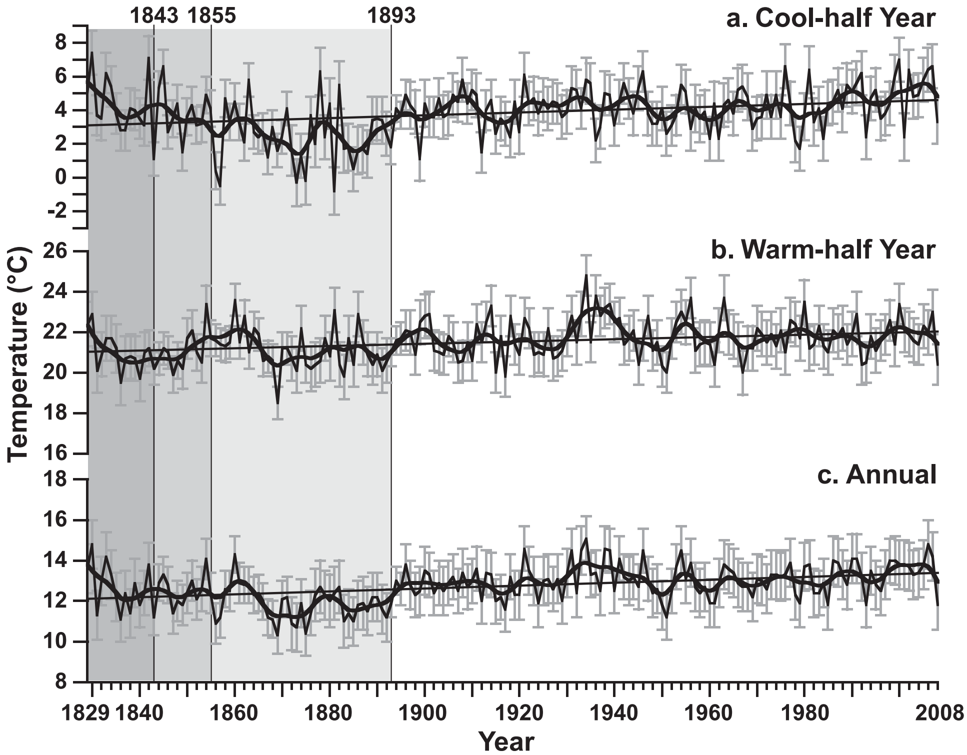

FIG. 9. Mean temperatures for the (a) cool (NDJFMA) and (b) warm (MJJASO) halves of the year and (c) annual-mean temperatures are plotted with approximate 95% confidence level estimates and 10-yr cubic smoothing splines. The 95% confidence interval estimates were derived by seasonally or annually averaging the 95% confidence level associated with each daily-mean temperature and are therefore conservative. Significant linear trends were detected in all three time series [cool = +0.08° ± 0.02°C decade^{-1} (P = 0.0001), warm = +0.06° ± 0.01°C decade^{-1} (P = 0.0001), and annual = +0.07° ± 0.01°C decade^{-1} (P < 0.0001) or +1.27° ± 0.23°C for the change in annual-mean temperature from 1829 to 2008].

of the slope estimate was used to approximate the 95% confidence interval. The 10-yr cubic smoothing splines were fit to the data in Figs. 8–11 using program FMT in the Dendrochronology Program Library (Cook and Peters 1981; Holmes 2008) to highlight the decadal-scale variations in each time series.

The 180-yr reconstruction of daily-mean temperature for Manhattan is presented (available online at http://www.uark.edu/dendro/kansas/), along with the standard errors and station names associated with all daily-mean temperature estimates. The raw station observations used for the reconstruction are also presented at the Web site. All evaluations, corrections, modeling, and analyses were performed using a computer program written in Microsoft Visual Basic.NET, Historical Observation Tools (HOB Tools on Web site).

3. Results

a. Daily means

Warming has been detected in the reconstructed temperature data for eastern Kansas at daily to centennial time scales and in various derived quantities. All 65 987 daily observations are plotted in Fig. 7 along with a linear regression illustrating the significant positive trend of 1.27° ± 0.23°C based on the annual-mean temperature for calendar years from 1829 to 2008 (Fig. 9). These data illustrate the strong annual cycle in daily-mean temperature over eastern Kansas, which often exceeded 45°C. The daily-mean temperature is skewed by cold winter extremes, and the annual cycle of extremes appears to have narrowed after 1990 (Fig. 7). Note the warm daily extremes during the 1930s Dust Bowl drought and mid-nineteenth-century drought (Fig. 7).

b. Seasonal and annual means

Linear trend lines fit to the seasonal and annual-mean temperatures reveal warming in all four seasons (Fig. 8), in the cool and warm halves of the year, and in the annual-mean temperature (Fig. 9). Winter mean temperatures have increased 1.75° ± 0.52°C since the winter of 1828/29 (P = 0.0010; Fig. 8a). The coldest winter in the reconstruction was the ''long, cold winter'' of 1855/56 [Ludlum 1968; December–February (DJF) mean of

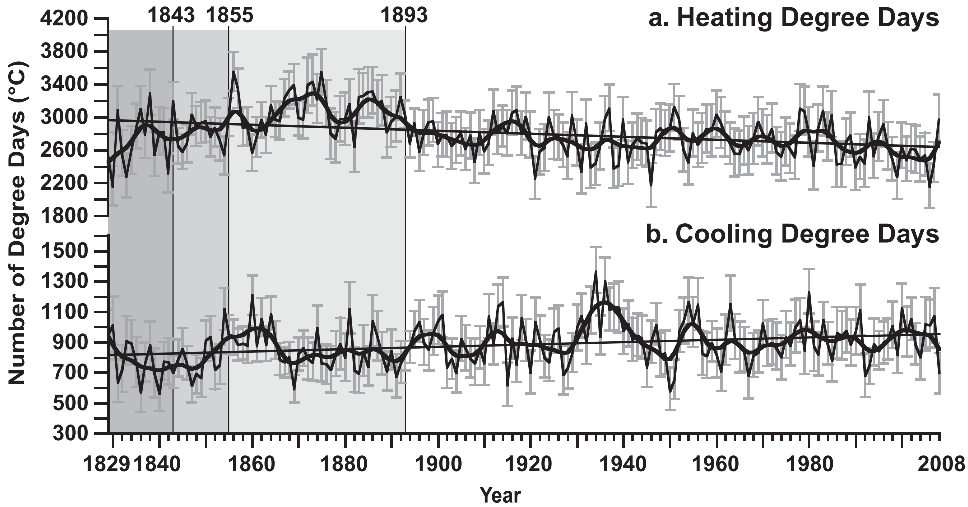

FIG. 10. HDD and CDD [base temperature = 18°C (65°F)] provide a concise intensity scale for cold winters and warm summers, respectively. Cold winter intensity has declined more sharply than hot summers have increased since 1829 [−18.1 ± 3.7 HDD per decade ($P < 0.0001$) vs +7.8 ± 2.1 CDD per decade ($P = 0.0002$)]. The approximate 95% confidence intervals and 10-yr cubic smoothing splines are also shown. The 95% confidence intervals were approximated by first deriving a high and low time series using the upper and lower ends of the temperature confidence intervals. The calculations for HDD and CDD were then run on these two additional time series to estimate the 95% confidence level around each annual degree-day value.

−6.8° ± 1.2°C], but this winter was within the standard errors of other notably cold winters in 1849, 1857, the 1880s, and the late 1970s. Note also the cold period in the early 1870s, which was followed by pronounced variability in the late 1870s and early 1880s. Winter mean temperatures were low through the remainder of the 1880s, when seven consecutive winters averaged below normal from 1882/83 to 1888/89 (Fig. 8a).

Spring mean temperatures have warmed by 0.70° ± 0.38°C since 1829 ($P = 0.0619$; Fig. 8b). The five coldest springs all occurred in the nineteenth century (1867, 1843, 1857, 1892, and 1869; Fig. 8b). The springs of 1842, 1860, 1977, 2007, and 1910 were the five warmest springs in the 180-yr reconstruction (Fig. 8b). The year 1860 was not only anomalously warm, but it was also one of the worst drought years in the history of the Great Plains

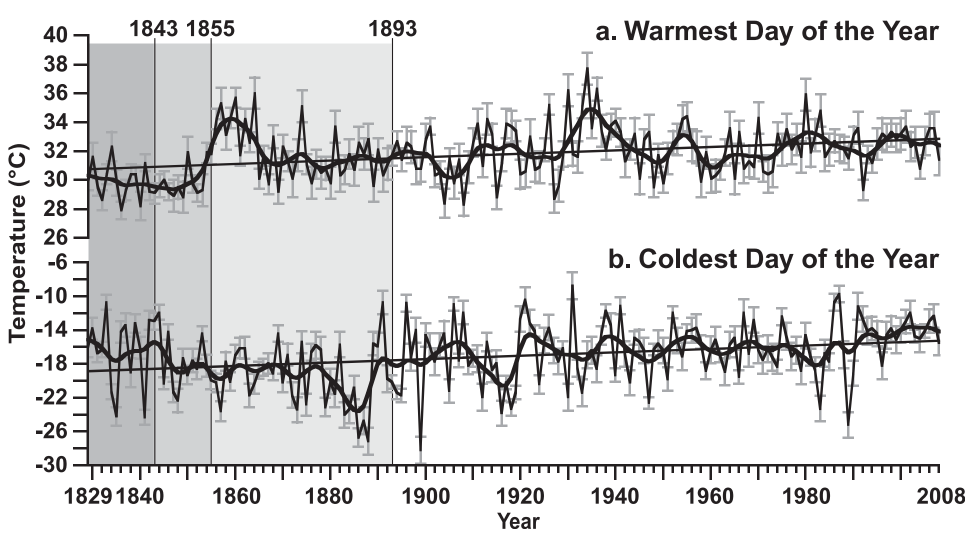

FIG. 11. The temperatures of the (a) warmest and (b) coldest days of the year have increased significantly from 1829 to 2008 [0.12° ± 0.03°C decade^{-1} ($P < 0.0001$) and 0.20° ± 0.05°C decade^{-1} ($P < 0.0001$), respectively]. The approximate 95% confidence intervals, defined as the interval associated with each warmest and coldest day of the year, and 10-yr cubic smoothing splines are also shown.

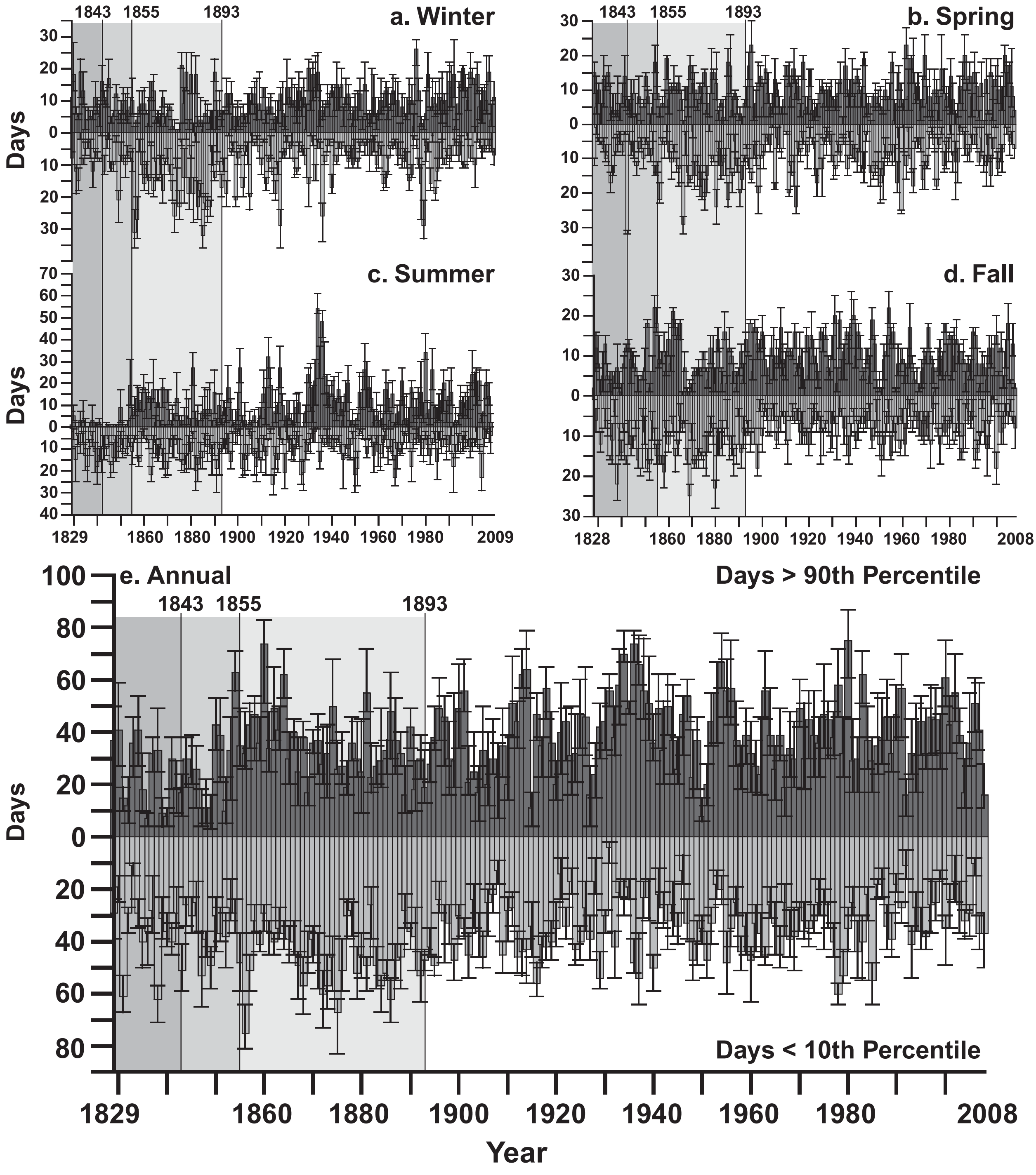

FIG. 12. Extremely warm days have increased over the past 180 yr [black bars; (a) +0.20 ± 0.07 days decade^{-1} in winter (P = 0.0059), (b) +0.12 ± 0.07 days decade^{-1} in spring (P = 0.1073), (c) +0.55 ± 0.12 days decade^{-1} in summer (P < 0.0001), (d) +0.09 ± 0.08 days decade^{-1} in fall (P = 0.2429), and (e) +0.77 ± 0.20 days decade^{-1} annually (P = 0.0002)]. Extremely cold days have declined over the past 180 yr [gray bars, scale inverted; (a) −0.30 ± 0.10 days decade^{-1} in winter (P = 0.0024), (b) −0.18 ± 0.09 days decade^{-1} in spring (P = 0.0379), (c) −0.16 ± 0.08 days decade^{-1} in summer (P = 0.0416), (d) −0.27 ± 0.06 days decade^{-1} in fall (P < 0.0001), and (e) −0.66 ± 0.17 days decade^{-1} annually (P = 0.0001)]. These percentiles were calculated seasonally relative to the entire period of record (1 Jul 1828–28 Feb 2009). The approximate 95% confidence intervals are also shown, and they were calculated in the same way as the HDD and CDD in Fig. 9.

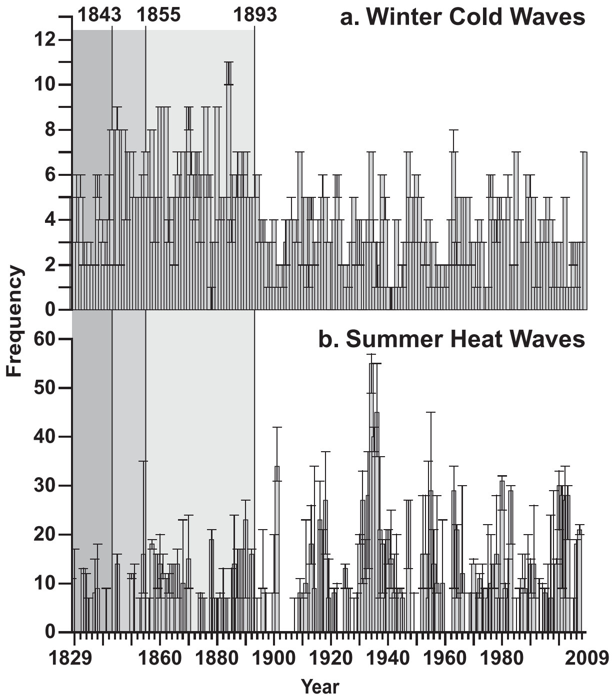

FIG. 13. (a) Winter cold waves and (b) summer heat waves are plotted with approximate 95% confidence intervals. The confidence intervals were calculated in the same way as the HDD and CDD in Fig. 9. Significant linear trends were detected in both of these metrics [-0.14 ± 0.03 decade^{-1} ($P < 0.0001$) and $+0.49 \pm 0.14$ decade^{-1} ($P = 0.0008$), respectively].

(Flora 1948; Dodds et al. 2009). The high temperatures, evaporation rates, dry conditions, and high winds of the spring and summer in 1860 favored the development of intense dust storms over Kansas where ''a person could scarcely be seen one hundred yards'' (Malin 1946). The drought of 1860 severely impacted the booming settlement in Kansas, and it may have been a factor in the mass migration of settlers out of the state (Bark 1978).

Summers have warmed by 1.25° ± 0.31°C since 1829 ($P = 0.0001$; Fig. 8c). The amazing decade-long thermal extreme over Manhattan during the 1930s Dust Bowl drought dominates the time series. In fact, the largest daily, seasonal, annual, and decadal temperature excursions in the entire reconstruction occurred during the 1930s (Figs. 7–13). The coldest summer occurred in 1915 [June–August (JJA) mean 22.3° ± 0.9°C; Fig. 8c].

Autumn over Manhattan has warmed by 1.30° ± 0.34°C since 1828 ($P = 0.0001$; Fig. 8d). The coldest single fall season occurred in 1869 [September–November (SON) mean 9.0° ± 0.9°C; Fig. 8d] during a decade-long cool period in the late 1860s and early 1870s. The fall of 1880 was also very cold and included an early onset to winter leading into the ''snow winter'' of 1880/81 (cf. Laskin 2004). The warmest autumn occurred in 1963 (SON mean 17.2° ± 1.3°C; Fig. 8d).

The means for the cool and warm halves of the year are presented in Fig. 9 along with the overall annual-mean temperature. The annual-mean temperature has increased 1.27° ± 0.23°C ($P < 0.0001$), but more warming has occurred in the cool season than in the warm season [1.51° ± 0.38°C ($P = 0.0001$) versus 0.98° ± 0.25°C ($P = 0.0001$), respectively]. The warmest year in the reconstruction was 1934 (15.1° ± 1.1°C), and the Dust Bowl dominates the warm season and annual means (Figs. 9b,c). However, 1934 was also within the standard errors of other warm years, including 2006, 1830, 1938, and 1921. The coldest annual-mean temperatures in the reconstruction occurred in the late 1860s–early 1870s and 1880s–early 1890s (Fig. 9c).

The significance of linear trends can be sensitive to the time period assessed and to large anomalies such as the hot summers of the 1930s and cold winters of the 1880s. All seasonal and annual means show significant warming since 1843 and since 1855 ($P < 0.002$ and $P < 0.03$, respectively), when there is less uncertainty in the quality of the reconstruction. The seasonal and annual means also reveal a fundamentally cooler nineteenth century with secular warming in the twentieth and twenty-first centuries (two-tailed t tests comparing 1829–99 with 1900–2008, $P < 0.05$ for all seasonal and annual means). In fact, annual-mean temperatures over Manhattan show significant cooling from 1829 to 1899 ($P = 0.0290$; Fig. 9c). Warming was detected in the summer season during the same time period, but this summer warming was not statistically significant ($P = 0.20$; Fig. 8c).

Warming in annual-mean temperatures at Manhattan has been stronger over the last 40 years than from 1829–1968 [Fig. 9c; 0.21° ± 0.10° decade^{-1} versus 0.07° ± 0.02°C decade^{-1}, respectively (both slopes significantly different from zero, $P < 0.05$)]. The recent warming has been confined to the cold half of year [November–April (NDJFMA)], which has warmed at a rate of 0.44° ± 0.18°C decade^{-1} since 1969 ($P = 0.0189$; Fig. 9a). This recent acceleration of the warming driven mostly by cool season temperatures has been attributed to anthropogenic forcing in the global temperature data (Trenberth et al. 2007).

The Baker et al. (1985) monthly record for Minnesota was not as carefully screened and corrected for nonclimatic biases as this new daily record for Manhattan, but it provides some interesting comparisons. The Kansas and Minnesota annual-mean temperature records both exhibit cooling during the nineteenth century and secular warming from the late nineteenth century into the twentieth century (not shown). The Minnesota record ends in 1982, but warming in annual-mean temperature over

Minnesota from 1829 to 1982 was very similar to the warming detected at Manhattan for the same time period [$+0.08° \pm 0.02°C\ \text{decade}^{-1}$ versus $+0.07° \pm 0.02°C\ \text{decade}^{-1}$, respectively (both $P = 0.0001$)]. This suggests that portions of the nineteenth-century Fort Snelling data will be useful, but the record is also subject to the same measurement and observation issues confronting other nineteenth-century records with few nearby stations available to construct a homogeneous time series.

c. Heating and cooling degree-days

Annual heating and cooling degree-days can be used as proxies for the strength of the cold and warm seasons, respectively (Fig. 10). Heating degree-days (HDD) and cooling degree-days (CDD; both in °C) are defined as follows:

$$\text{HDD} = \sum_{\text{Annual}} (18 - \text{Daily Mean Temperature})$$

$$\text{CDD} = \sum_{\text{Annual}} (\text{Daily Mean Temperature} - 18).$$

These data show a decline of 324.6 ± 67.4 ($P < 0.0001$) in HDD and an increase of 139.1 ± 37.0 ($P = 0.0002$) in CDD since 1829. The decline in HDD was more significant since 1855 [503.0 ± 65.7 ($P < 0.0001$)], but warming trends in CDD were not significant since 1855 ($P = 0.0723$). By this metric, the top 10 cold seasons were all in the nineteenth century, with the coldest occurring in 1856 [3551 ± 237 (~95% confidence interval = +240, −229) HDD; Fig. 10a]. The late 1860s–early 1870s and 1880s–early 1890s were characterized by persistently high HDD similar to the cold season means (Fig. 10a versus Fig. 9a). These intense cold seasons have declined dramatically, and the five lowest HDD included 2006 [2163 (~95% confidence interval = +278, −259) HDD; Fig. 10a].

The most intense warm seasons with the highest CDD were during the Dust Bowl of the 1930s [e.g., 1365 (~95% confidence interval = +165, −141) days in 1934; Fig. 10b]. The overall positive trend in CDD has been highly significant since 1829, but it has been less dramatic than the negative trend in HDD, because that warming in eastern Kansas has been more intense during the cold season (Figs. 9, 10). The lowest quantity of CDD was in 1840 [563 (~95% confidence interval = +137, −114); Fig. 10b], during the height of an evidently moist and cool period, when the High Plains grasslands were lush and teeming with bison (West 1995; Fye et al. 2003).

d. Daily-mean temperature extrema of the past 180 yr

The warmest and coldest single days of each year from 1829 to 2008 are plotted separately in Fig. 11. A linear trend line fit to the warmest day of the year time series exhibits significant overall warming of $2.09° \pm 0.45°C$ since 1829 ($P < 0.0001$; Fig. 11a). Extremely warm days were less common before 1850 (Fig. 11a), which might be consistent with higher atmospheric moisture levels during the pluvial conditions reconstructed with precipitation-sensitive tree-ring data (Fye et al. 2003). However, changes in observation methodology occurred prior to 1855, and temperature extremes are much more sensitive than means to such changes (Chenoweth 1993; Parker 1994; van der Meulen and Brandsma 2008; Brandsma and van der Meulen 2008). No significant trend was detected in the warmest day of the year time series from 1855 to 2008 ($P = 0.2431$), but this trend was likely influenced by the anomalously warm temperatures during the mid-nineteenth-century drought. Significant warming was detected from 1865 to 2008 ($P = 0.0027$). The warmest day in the reconstruction occurred during the height of the Dust Bowl on 8 August 1934 [daily mean of $37.7° \pm 1.1°C$ ($99.9° \pm 2.0°F$); Fig. 11a], but this warm day was within the standard errors of other extremely warm days during the 1930s Dust Bowl, including 1936, when the most intense heat wave in the modern instrumental record occurred across the United States (Burt 2004). Daily maximum temperatures over 48.9°C (120°F) were recorded in Kansas and across the Great Plains during the summer of 1936 (Burt 2004).

The temperature of the coldest day of the year has warmed at approximately 1½ times the rate of the warmest day of the year since 1829, and it is the strongest warming detected in any of the data reported in this study ($3.60° \pm 0.94°C$, $P = 0.0001$; Fig. 11b). The trend is even stronger for 1855–2008 ($5.17° \pm 0.95°C$, $P < 0.0001$; Fig. 11b), when less uncertainty exists in the quality of the daily-mean temperature data. Ludlum (1968) described the occurrence of the two most severe outbreaks of arctic air in the nineteenth century, which correspond to 2 of the top 10 coldest days in this new reconstruction for eastern Kansas. The first occurred on 7 February 1835, when the 0700 LT temperature at Fort Leavenworth stood at −31.9°C. The reconstructed daily-mean temperature for 7 February 1835 was $-24.2° \pm 1.1°C$ (Fig. 11b). Ludlum (1968) suggested that snow-covered ground across a large part of the Midwest limited the modification of the arctic air mass as it plunged southward. Thus, when the arctic express reached the South on 8 February 1835, it brought the −17.8°C (0°F) isotherm to near the Gulf of Mexico (Ludlum 1968). This outbreak of extreme cold was exceeded by another extremely cold episode in Kansas on 11 February 1899, when the daily-mean temperature was $-28.2° \pm 1.6°C$ (Fig. 11b) and the −17.8°C (0°F) isotherm again approached the Gulf Coast (Ludlum 1968). Note also that the variance of this coldest day of year time series appears to have attenuated in the late twentieth century, with the exception of the 1980s, when another one of the coldest days in the reconstruction occurred (22 December 1989; reconstructed daily mean of $-25.2° \pm 1.5°C$; Fig. 11b).

The number of days colder than the 10th percentile and warmer than the 90th percentile are counted and plotted on a seasonal and annual basis in Fig. 12. Extreme warm days during the winter have increased 3.6 ± 1.3 days and extreme cold days have decreased 5.4 ± 1.8 days since 1829 ($P = 0.0059$ and $P = 0.0024$, respectively; Fig. 12a). The highest frequency of extremely cold days in the winter occurred in 1885, when 32 days registered daily-mean temperatures below $-10.1°C$ (the 10th percentile; ~95% confidence interval = +4,−3; Fig. 12a). The large winter temperature depression in the 1880s has been unmatched for the number of cold extremes (Fig. 12a) and for the run of coldest days of the year (1883–88; Fig. 11b). These cold winters may partially reflect global cooling associated with the eruption of Krakatau in 1883 (Simkin and Fiske 1983; Robock 2000), even though Shindell et al. (2004) do not detect consistent and significant cooling over the central United States following volcanic eruptions in empirical and modeling analyses.

The winters of the 1880s were famous for destructive blizzards, which decimated the cattle industry and severely impacted many homesteads (Mattison 1964; Wheeler 1991). One of the coldest single days in eastern Kansas occurred on 15 January 1888 (reconstructed daily-mean temperature of $-27.1° \pm 1.6°C$; $-16.8° \pm 2.9°F$), following the passage of an intense arctic cold front and one of the greatest blizzards in American history. This blizzard reached Manhattan on 12 January 1888 with temperatures rapidly falling from 2.4°C (36.3°F) at 1300 LT to −16.5°C (2.3°F) by 2000 LT. The city of Leavenworth, Kansas, recorded extreme winds up to 16.1 m s^{-1} (36 mph). This notorious event is known as "the Schoolchildren's Blizzard" because over 100 children perished in the sudden whiteout conditions and extreme cold trying to return home from school across Dakota Territory and Nebraska (Laskin 2004). The fresh snowcover increased the radiational cooling as the arctic air mass settled over Kansas, and by 0600 LT 15 January temperatures at Manhattan registered −32.5°C (−26.5°F).

The modern winters closest to the extraordinary nineteenth-century winters occurred during the 1977–78 regime shift in the northern Pacific (Ebbesmeyer et al. 1991), when the westerlies were displaced anomalously southward across central and eastern North America (Harnack 1980). All-time record minimum temperatures were set at many short instrumental stations in 1977/78; for many areas, February 1978 was the coldest on record (National Oceanic and Atmospheric Administration 1978).

Extremely warm days in the spring have increased 2.1 ± 1.3 days and cold days have decreased 3.2 ± 1.5 days since 1829 ($P = 0.1073$ and $P = 0.0379$, respectively; Fig. 12b). The highest number of cold spring days occurred in 1843 (32 ± 1 days; Fig. 12b), when daily-mean temperatures were near or below freezing for the entire month of March. Much of the central and eastern United States shared the frigid March air in 1843, when temperatures were 5°–11°C below normal on the Gulf Coast to over 17°C below normal in the northern Plains (Rosendal 1970; Nielsen-Gammon and McRoberts 2009) and frost damaged tree rings were recorded in Texas (Stahle 1990). Reconstruction and analysis of synoptic-scale weather maps suggest that a persistent southern storm track prevailed during this month. Low pressure systems tended to develop in the Gulf of Mexico, which also brought snowstorms and frigid arctic air to the South (Nielsen-Gammon and McRoberts 2009). The cold spring of 1843 occurred in the wake of a relatively mild January across the central and eastern United States (Ludlum 1968), when daily-mean temperatures in eastern Kansas were above freezing for 12 consecutive days.

Reconstructed extremes in the summer show an increase in warm days of 9.9 ± 2.2 and a decrease in cold days of 2.9 ± 1.4 since 1829 ($P < 0.0001$ and $P = 0.0416$, respectively; Fig. 12c). The largest count of extremely warm days occurred in 1934 [54 (~95% confidence interval = +7, −2) days; Fig. 12c]. The 1930s Dust Bowl dominates the series, but the 1850s, 1860s, 1910s, 1950s, and 1990s also contained persistently warm summers (Fig. 12c).

Extremely warm days in the fall have increased 1.6 ± 1.4 days and cold days have decreased 4.8 ± 1.1 days since 1828 ($P = 0.2429$ and $P < 0.0001$, respectively; Fig. 12d). The highest number of fall warm days occurred in 1954, when 22 ± 4 days of recorded daily means exceeded 23.9°C (the 90th percentile; Fig. 12d). A higher frequency of extreme cold days in the fall occurred in the nineteenth century than in the twentieth and early twenty-first centuries (Fig. 12d).

Annually, extreme warm days have increased by 13.8 ± 3.6 and extreme cold days have decreased by 11.8 ± 3.1 since 1829 ($P = 0.0002$ and $P = 0.0003$, respectively; Fig. 12e). The highest number of warm days in this reconstruction occurred in 1980, when 75 days were above 26.7°C (the 90th percentile; ~95% confidence interval = +12, −14; Fig. 12e), but 1860, 1934, and 1936 also recorded 70 or more extremely warm days. The highest number of cold extremes occurred in 1856, which included daily data during the "long, cold winter" of 1855/56 and another cold winter in 1856/57 (Fig. 7a; Ludlum 1968).

Very few warm days were observed in the 1830s and 1840s, especially during the summer (Fig. 12c). Such observations might be consistent with the probable north-wall exposure detected in the reconstructed Manhattan record from 1838 to 1853. Afternoon temperatures associated with such exposures typically run cooler than standard cotton region shelters (Chenoweth 1992). Upward adjustments were performed on the afternoon temperature data, which inflated the standard deviation and variance in the earlier part of the record (see section 2f). However, such adjustments may have been too conservative. Warming was statistically significant in all seasonal and annual cold extremes since 1855, but only in summer and winter warm extremes since 1855 ($P < 0.05$).

e. *Winter cold waves and summer heat waves*

The number of winter cold waves and summer heat waves are counted and plotted in Fig. 13. The quantity of cold waves during any given winter season was calculated by summing the number of 24-h daily-mean temperature depressions that exceeded 8.3°C (top 10% of all 24-h daily-mean temperature depressions in winter). The results show a decline in winter cold waves of 2.6 ± 0.5 since 1829 and a decline of 3.0 ± 0.6 since 1855 (both $P < 0.0001$; Fig. 13a). The highest number of cold waves occurred in 1884, when 11 ± 1 separate days recorded a change in daily-mean temperature of over −8.3°C associated with the passage of cold fronts (Fig. 13a). The strongest cold wave in the reconstructed Manhattan record occurred in 1876, when the daily-mean temperature plummeted by 22.1°C from 13.8° ± 1.4°C to −8.3° ± 1.2°C from 8 to 9 January.

A heat wave was defined as ≥7 consecutive days during the summer with daily-mean temperatures above the 75th percentile (27.8°C). The total number of heat wave days were then summed to estimate heat wave intensity each year (e.g., if two heat waves occurred and one lasted 7 days and the other 10, then the heat wave index = 17). Summer heat waves have increased by 8.7 ± 2.6 days since 1829 ($P = 0.0008$; Fig. 13b), but this trend could be accentuated by the minimal summer extremes of the 1830s and 1840s. The positive trend was less significant since 1855 ($P = 0.0593$). The top three most intense heat wave years occurred during the 1930s Dust Bowl, but other concentrations of large heat wavenumbers occurred in the 1850s, 1860s, 1910s, 1950s, late 1970s–early 1980s, and the late 1990s–early 2000s (Fig. 13b).

4. Conclusions

The new reconstruction extends the Manhattan daily-mean temperature record into the early nineteenth century and documents dramatic temperature change over the continental interior of North America for the past 154–180 yr. The Manhattan daily-mean temperature record now extends with good confidence back to 1 July 1855 and with more uncertainty concerning instrumentation and procedural changes back to 1 July 1828. This new daily-mean temperature record running from 1 July 1855 to 28 February 2009 is currently the longest continuous and corrected record of daily-mean temperature published in the Americas, but other longer records await recovery and reanalysis from archives across North America. The new Kansas data indicate a fundamentally cooler nineteenth century and significant secular warming in all seasons, extremes, and various derived quantities in the twentieth and early twenty-first centuries. The sharpest warming was detected in the coldest day of the year, the winter mean, and in the annual count of daily-mean temperature extremes above the 90th percentile. The extremely cold winter temperatures of the 1870s and 1880s and the extreme summer warmth of the 1930s dominate the 180-yr reconstruction.

The approximate 95% confidence intervals estimated for the reconstruction are based only on the standard error of the regression models and do not reflect other uncertainties that are embedded in these data. These potential uncertainties include the attachment of the historical and modern records at the brief overlap in 1893; undetected changes in nineteenth-century instrumentation, instrument exposure, and procedures in 1855; and the system-wide change in instrumentation in 1843. Quantifying these uncertainties remains a significant challenge because of the limited availability of early-nineteenth-century temperature measurements. The greatest uncertainty likely lies with the daily-mean temperature extrema, especially for the summer season.

We took an empirical approach to the potential discontinuities identified in these historical observations, where data before and after a suspected discontinuity were evaluated with detailed visual inspection of the reconstructed daily-mean temperature data and a comparative analysis with a nearby station free of potential discontinuity (including visual inspection and *t* tests for changes in the mean of the daily-mean temperature difference between the two stations). Observations that did not exhibit significant statistical change or erratic behavior across a potential boundary were joined as a single time series for final reconstruction. These analyses retain a continuous Fort Leavenworth daily-mean temperature series from 1 July 1828 to 31 August 1845 (Table 2), which may not be realistic, considering the frontier conditions under which the observations were made. Comparative analysis of the early Fort Leavenworth record is complicated by the lack of nearby stations (Fort Gibson and Jefferson Barracks were the nearest available stations, both of which are nearly 400 km from Fort Leavenworth). Other methods might be used to further evaluate the true homogeneity of Fort Leavenworth and other early records, including detailed investigation of other recorded weather information at the site, comparison with contemporaneous diary accounts, large-scale synoptic evaluation, and historical analysis of the personnel responsible for the observations. Nevertheless, the current reconstruction is offered as one possible interpretation of the daily temperature history for eastern Kansas during the mid-nineteenth century, and the raw digitized observations are presented online to facilitate further analysis.

Daily temperature data have recently been used as sensitive indicators of climate change at the continental and global scale. Alexander et al. (2006) and Peterson et al. (2007) both note dramatic warming in indices derived from daily temperature data such as the frequency of warm and cold days and warmest and coldest temperatures of the year. The long daily-mean temperature record now available for eastern Kansas has been used to extend these climate change metrics into the mid-nineteenth century to provide a much longer perspective on twentieth- and twenty-first-century warming. The successful reconstruction of daily-mean temperature into the mid-nineteenth century is testimony to the careful thermometer measurements made by most nineteenth-century observers.

A quantitative methodology was used to reconstruct daily-mean temperature for Manhattan from early thermometer observations. These screening and correction routines are imperative to maximize the quality of these records and permit the computation of daily, monthly, seasonal, and annual temperature trends and extremes. A toolkit of computer programs has also been developed for the efficient implementation of these screening and correction procedures (available online at http://www.uark.edu/dendro/kansas/).

The NOAA Climate Database Modernization Program has recovered a number of daily temperature records dating into the early nineteenth century (Dupigny-Giroux et al. 2007), and these data await careful screening, correction, and reanalysis. Many other instrumental and documentary temperature records are available in archives across the United States (e.g., the National Archives, Library of Congress, and local state archives). It might be possible to use these early weather recording stations to develop daily-mean temperature records during the mid- to late-nineteenth century for most climate regions of the United States, which would provide a valuable preindustrial perspective on temperature means, extremes, and their forcings in a pre-CO_2 enriched world.

Acknowledgments. This research was sponsored by the National Science Foundation [BCS-0622894 (DJB), ATM-0400713 and ATM-0753399 (DWS), and BCS-0349986 (CJM)] and Jeanne and Wayne Erickson. We thank P. Jones, M. K. Cleaveland, R. D. Griffin, and three reviewers for the critical reading of our initial manuscript and for the many valuable comments that have significantly improved the reconstruction and discussion.

APPENDIX

Adjusting Modern Hourly Data and Calculating the Historical Daily-Mean Temperature

Modern hourly temperature data were used to provide a rigorous framework to assess the historical fixed hourly temperature readings and calculate daily-mean temperatures in the historical period that would be compatible with the modern daily means calculated from minimum and maximum temperatures. All modern hourly temperature data were transformed into nineteenth-century equivalents to directly compare a 1400 LT observation in the modern period with a 1400 LT observation in the nineteenth century (or any other hour). The first step in this process was to derive the solar time correction (STC; in minutes) based on the station location within a particular time zone. Equation (A1a) was used for stations in the west half of the time zone (negative correction required):

$$\mathrm{STC} = -30(S_{\mathrm{lon}} - M_{\mathrm{lon}})(W_{\mathrm{lon}} - M_{\mathrm{lon}})^{-1}. \quad \text{(A1a)}$$

Equation (A1b) was used for stations in the east half of the time zone (positive correction required):

$$\mathrm{STC} = 30(M_{\mathrm{lon}} - S_{\mathrm{lon}})(M_{\mathrm{lon}} - E_{\mathrm{lon}})^{-1}, \quad \text{(A1b)}$$

where S_{lon} is the station longitude, M_{lon} is the longitude for the middle of the time zone, W_{lon} is the longitude for the western edge of the time zone, and E_{lon} is the longitude for the eastern edge of the time zone (all in degrees). No solar time correction was necessary for Signal Service observations, because they were instructed to take observations at Washington time (Darter 1942). For these Signal Service records, the value for STC in subsequent equations was zero, and one hour was subtracted from the observation times (correction to central time).

Once the solar time correction was calculated, the hourly data (1961–95) were transformed for exact time of observation compatibility with the nineteenth-century data observations. It was assumed that all hourly temperatures from 1961 to 1995 were observed at 20 min before the hour. The hourly data were converted to the top of the hour and to solar time with Eq. (A2a), if the solar time correction was >20 min and a sunrise fixed observation was not required:

$$T_{\mathrm{adj}} = T_{\mathrm{hr}}(T_{\mathrm{hr}} - T_{\mathrm{phr}})(\mathrm{STC} - 20)(60)^{-1}. \quad \text{(A2a)}$$

Equation (A2b) was used if the solar time correction was ≤20 min and a sunrise fixed observation was not required:

$$T_{\mathrm{adj}} = T_{\mathrm{hr}} + (T_{\mathrm{nhr}} - T_{\mathrm{hr}})(20 - \mathrm{STC})(60)^{-1}, \quad \text{(A2b)}$$

where T_{adj} is the temperature after the adjustment to the top of the hour and solar time, T_{hr} is the specific hour's temperature, T_{phr} is the previous hour's temperature, T_{nhr} is the next hour's temperature, and STC is in minutes.

If the historical temperature observations were made at sunrise (e.g., during parts of the 1840s and 1850s; Lawson 1855), then the hourly temperature data from 1961 to 1995 were adjusted to sunrise using Eqs. (A2c)–(A2g) instead of Eqs. (A2a) and (A2b). Equations (A2c) and (A2d) for sunrise observations were used if the solar time correction was >20 min:

$$\mathrm{TS}_{\mathrm{adj}} = T_{\mathrm{shr}} - (T_{\mathrm{shr}} - T_{\mathrm{phr}})(\mathrm{STC} - 20)(60)^{-1} \quad \text{and} \quad \text{(A2c)}$$

$$\mathrm{TN}_{\mathrm{adj}} = T_{\mathrm{nhr}} - (T_{\mathrm{nhr}} - T_{\mathrm{shr}})(\mathrm{STC} - 20)(60)^{-1}. \quad \text{(A2d)}$$

If the solar time correction was ≤20 min, then Eqs. (A2e) and (A2f) were used:

$$\mathrm{TS}_{\mathrm{adj}} = T_{\mathrm{shr}} + (T_{\mathrm{nhr}} - T_{\mathrm{shr}})(20 - \mathrm{STC})(60)^{-1} \quad \text{and} \quad \text{(A2e)}$$

$$\mathrm{TN}_{\mathrm{adj}} = T_{\mathrm{nhr}} + (T_{2\mathrm{hr}} - T_{\mathrm{nhr}})(20 - \mathrm{STC})(60)^{-1}. \quad \text{(A2f)}$$

Finally, Eq. (A2g) was used to adjust the temperature data from the top of the hour (solar time) to sunrise (solar time):

$$T_{\mathrm{sunrise}} = \mathrm{TS}_{\mathrm{adj}} + (\mathrm{TN}_{\mathrm{adj}} - \mathrm{TS}_{\mathrm{adj}})S_{\mathrm{min}}(60)^{-1}. \quad \text{(A2g)}$$

In Eqs. (A2c)–(A2g), T_{sunrise} is the temperature completely adjusted to sunrise, $\mathrm{TS}_{\mathrm{adj}}$ is the sunrise hour temperature adjusted to the top of the hour and to solar time, $\mathrm{TN}_{\mathrm{adj}}$ is the next hour's temperature adjusted to the top of the hour and to solar time, T_{shr} is the sunrise hour temperature (i.e., the final observation before sunrise), T_{phr} is the previous hour's temperature, T_{nhr} is the next hour's temperature, $T_{2\mathrm{hr}}$ is the temperature two hours following the sunrise hour, STC is in minutes, and S_{min} is the minute in which sunrise occurs.

Identical daily-mean temperatures can be computed from fixed hourly observations (e.g., 0700, 1400, and 2100 LT) and from maximum–minimum temperatures by using modern data to calculate an average difference between these two estimates of the daily mean in the relevant calendar month. The difference was then scaled according to the ratio of the range between morning and afternoon temperatures on the target historical day R_{hf} and the modern average range from the equivalent fixed hourly observations in the same calendar month R_{mf}:

$$C = (M_{\mathrm{mm}} - M_{\mathrm{mf}})(R_{\mathrm{hf}})(R_{\mathrm{mf}})^{-1}, \quad \text{(A3)}$$

where M_{mm} is the average modern daily-mean temperature from maximum and minimum values and M_{mf} is the average modern daily-mean temperature from fixed hourly observations. All modern fixed hourly temperatures were first converted to nineteenth-century equivalents using Eqs. (A1a)–(A2g). Then the correction C was applied; it accounts for both the normal diurnal cycle in the given calendar month and for day-to-day variations in diurnal range arising from weather variations (e.g., cloudiness) in the historical record. The final daily-mean temperature was then calculated by

$$T_{\mathrm{final}} = (T_{\mathrm{am}} + T_{\mathrm{pm}} + T_{\mathrm{eve}})(3)^{-1} + C, \quad \text{(A4)}$$

where T_{am} is the morning temperature, T_{pm} is the afternoon temperature, T_{eve} is the evening temperature, and C is the correction value that adjusts the historical daily means for compatibility with modern daily means.

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