Trends in Twentieth-Century Temperature Extremes across the United States

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ABSTRACT

A long-term, homogeneous set of daily maximum and minimum temperature data representing a subset of daily U.S. Historical Climatology Network stations is used to analyze trends in extreme temperature occurrence across the contiguous United States. Time series of various lengths are analyzed, with the longest spanning the period 1900–96. Trends in the annual occurrence of extreme maximum and minimum temperatures (e.g., values greater than the 90th, 95th, or 99th percentile) are strongly influenced by high exceedence counts during drought periods in the 1930s and 1950s. Peaks in exceedences during these years result in predominantly decreasing warm exceedence trends across the country during the 1930–96 period. This is uncharacteristic of recent years (1960–96) in which a large majority of stations show increases in warm extreme temperature exceedences. Significant increases in warm minimum temperature exceedences are found at nearly one-third of the stations during this period. Multiday warm temperature exceedence runs also show strong increases during this more recent period. The most rapid increases in high maximum and minimum temperature extremes occur at stations classified as urban, by satellite land use information.

Trends in the annual occurrence of extremely cold maximum and minimum temperatures display an analogous decrease during the 1960–96 period. Here again, there is a distinct shift in the number of decreasing trends between the 1950–96 and 1960–96 periods. Based on starting decades prior to 1960, there is not a strong tendency for either increasing or decreasing trends. The period 1910–96 is an exception, with almost all stations exhibiting decreasing cold extreme occurrence trends. The extreme cold exceedence trends during the 1960–96 period are also influenced by urbanization, but to a lesser degree than the warm extremes.

1. Introduction

Attempts to characterize trends in temperature extremes have been plagued by the lack of long-term, high-quality daily datasets. Recently, Easterling et al. (1999) presented long-term daily data from a subset of the monthly Historical Climatology Network (HCN) stations. However, these series are neither serially complete, nor do they incorporate adjustments for nonclimatic inhomogeneities, such as station relocations and observation time differences, which are available for the corresponding monthly data (Karl et al. 1990). Despite an increased interest in the temporal variation of temperature extreme occurrences by groups such as the International Panel on Climate Change (IPCC), the unavailability of high-quality daily data has led to inconsistencies in describing time-dependent changes in both warm and cold temperature extremes.

Easterling et al. (2000) gives an overview of the literature related to temporal variations in temperature

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extremes. In many cases, these studies have focused on 0°C as an extreme cold temperature threshold. Cooter and LeDuc (1995) show an 11-day shift in the start of the frost-free season in the northeastern United States from 1950 to the mid-1990s. Several national studies show similar trends toward fewer days with minimum temperatures <0°C in Australia, and New Zealand (Plummer et al. 1999), Europe (Heino et al. 1999), Canada (Bonsal et al. 2001), China, and the United States (Easterling et al. 2000). Preliminary findings with respect to the United States show a slight downward trend in the number of days below freezing during the 1910-98 period (Easterling et al. 2000). However, the trends exhibit considerable regional variability. Trends in spring mean minimum temperature (Plantico et al. 1990) show some agreement with the reported decreases in below-freezing temperatures. Like the freezing-day trends, there is considerable regional variability in the character of the mean minimum temperature series.

Using a more extreme cold minimum temperature threshold of -15.0° C, DeGaetano (1996) showed decreasing trends in exceedence days at a set of 22 primarily rural northeastern U.S. stations over the 1959–

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93 time period. Significant ($\alpha = 0.10$) trends were present at nearly 50% of the sites. Similar results were obtained for Canada using the 1st, 5th, and 10th percentiles of daily minimum temperature (Bonsal et al. 2001). Kunkel et al. (1999), however, found little evidence for an overall trend in days with temperatures below the 1.5% probability threshold, despite peaks in the number of occurrences during the early 1960s and late 1970s. Likewise, they showed no trend in the annual occurrence of 4-day cold spells. Addressing cold maximum temperatures ($\leq 0.0, -6.7, \text{ and } -12.2^{\circ}$ C), De-Gaetano (1996) showed significant increases in these extremes at the northernmost sites in his sample.

Trends in warm extremes have tended to be more pronounced than those for cold extremes, but still it has proven difficult to characterize the behavior of these trends on a national or regional level. Bonsal et al. (2001) find little evidence for a consistent change in extreme maximum temperatures (>90th, 95th, and 99th percentile) across Canada during the entire or last half of the twentieth century. Over the 1910–98 time period, Easterling et al. (2000) report that exceedences of the 32.2°C threshold show slight downward trends across the United States. A more notable feature of this time series, however, is the relatively large number of exceedences that characterize the 1930s and 1950s drought years.

Kalkstein and Davis (1989) also highlighted the number of extreme temperatures that occurred in the 1930s. However, using a threshold equal to the 98.5th percentile, they found no exceedence trend over the 1931–96 period. Similarly, Kunkel et al. (1999) found no overall trend in 4-day heat waves with temperatures exceeding the 10-yr recurrence interval value. At the 22 rural northeastern stations studied by DeGaetano (1996), daily temperatures above the 90th percentile tended to decline from 1951 through 1993. DeGaetano attributed these trends to changes in the attributes of the individual stations.

Although these studies are in general agreement, Gaffen and Ross (1998) examined trends in extreme apparent temperatures and found increases in the number of days exceeding the 85th percentile over the period from 1949–95. Balling and Idso (1990) studied trends in high summer temperatures and found an increasing trend over the 1948–87 period. These differences can be attributed to the the exclusion of the 1930s in Gaffen and Ross's and Idso and Balling's studies, a potential urban influence at the stations used by Gaffen and Ross, and water vapor trends (Ross and Elliot 1996).

When extremely warm minimum temperatures (i.e., values ≥ 23.8 , 21.1, and 18.3°C) were considered, DeGaetano (1996) found significant increases at more stations than can be expected by chance. Bonsal et al. (2001) found a similar pattern at Canadian stations. This disparity in results between extremely warm maximum and minimum temperatures was also found for monthly extremes by Karl et al. (1991). They examined changes

in the warmest temperature recorded in a given year or month for the United States and the former Soviet Union. Although a small upward trend in maximum temperature was found, strong increases in minimum temperature extremes characterized the 1951–89 period. Mean temperatures also display this characteristic across the United States.

It is likely that the absence of a high-quality, longterm homogeneous set of daily maximum and minimum temperature data has contributed to these contrasting results. Using the recently developed Daily Historical Climatology Network for Extreme Temperature (HCN-XT) dataset (DeGaetano and Allen 2002), extreme temperature trends are analyzed for stations in the contiguous United States. In analyzing these trends, we pay particular attention to the data quality and periods-ofrecord issues that may have influenced the previous temperature extreme studies. We also investigate the influence of urbanization by providing separate analyses based on the urbanization classification provided in the HCN-XT dataset.

2. Data and data preparation

While a complete description of the methods used to adjust and develop the HCN-XT dataset is given by DeGaetano and Allen (2002), a brief review of these procedures is given here to provide some context for the subsequent results. The annual extreme temperature exceedence series that form the basis of this study were constructed for a 361-station subset of the Daily U.S. Historical Climatology Network (Easterling et al. 1999). These stations were selected to limit missing data to <10% of the possible daily observations. In addition, although the number of station relocations and instrument changes at the retained stations was not specifically minimized, periods with constant station attributes were generally required to be ≥ 10 yr in length. This length facilitated subsequent adjustments for nonclimatic discontinuities. The majority of station records begin between 1930 and 1950. Records begin prior to 1930 at 163 sites.

Extreme thresholds at each station were set at the 99th, 95th, 90th, 10th, 5th, and 1st percentiles of all daily maximum (and separately minimum) temperatures within the longest homogeneous subseries. Since threshold exceedence count data are truncated at zero, a percentile threshold characteristic of the warmest part of the record may result in no exceedences in the majority of the cooler years. Clearly, this would skew any trend that may have been present. The potential for this problem was reduced by using the longest period with no nonclimatic discontinuities, rather than the most recent, as the base for computing the extreme thresholds. The choice of base period may change the number of exceedences in given year (i.e., the intercept of the timedependent regression is altered). However, it has no effect on the magnitude or character of any temporal



FIG. 1. Map of 95th percentile (a) extreme max and (b) extreme min temperature thresholds. The 5th percentile (c) extreme max and (d) extreme min temperature threshold maps are also given. The 95th percentile isotherms are drawn at $2.2^{\circ}C$ (4°F) intervals, while the isotherm interval for 5th percentiles is $4.4^{\circ}C$ (8°F) due to the greater spatial variability of the cold extremes.

trends that may be present in the time series (i.e., the slope is unaffected).

Although temperature extremes tend to be confined to a specific season, the use of annual series percentiles eliminated the need to select arbitrary beginning and ending dates for seasons. Thus, on average the 5th and 95th percentiles are exceeded about 18 times per year, with exceedences of the 95th percentile confined mainly to summer months and temperatures below the 5th percentile occurring predominantly in winter months. Figure 1 shows the geographic pattern of extreme threshold temperatures across the United States.

a. Missing data estimation

Missing daily observations are inevitable in the climate record and introduce a source of uncertainty when tallying annual extreme threshold exceedences. In mean series, the influence of random missing observations is minimized by the averaging process. Since this is not the case with extreme counts, missing values were estimated based on the methods of Allen and DeGaetano (2001). The method is a variation of a least squares regression approach. It focuses on obtaining accurate estimates of annual extreme temperature exceedence counts, as well as counts of consecutive exceedences, while limiting the estimation error associated with each individual value. For example, using cold minimum or warm maximum temperatures the median percentage of correctly estimated exceedences was 97% and the median percentage of correctly identified consecutive exceedences was 98%. The more conventional data estimation routines (e.g., DeGaetano et al. 1995; Eischeid et al. 2000) tend to underestimate both exceedence and consecutive exceedence counts. Using these procedures, estimated single and consecutive exceedence counts were generally less than 80% of those that actually occurred. Despite the fact that the Allen and DeGaetano (2001) method is tuned to estimate exceedence counts, the estimation accuracy of individual daily maximum or minimum temperatures is similar to that of previous estimation procedures.

b. Observation time adjustment

The effect of observation time bias on monthly and annual temperature exceedence counts is analogous to its influence on average temperature (Karl et al. 1986). DeGaetano and Allen (2002) illustrate this bias for cold and warm extremes of maximum and minimum temperature and describe the adjustment procedure used in the current analysis for daily exceedences.

Using hourly data to simulate daily observations based on different observation times, DeGaetano and



FIG. 2. Representative patterns of observation time bias relative to a midnight-to-midnight observation for ≥ 2 (open symbols) and ≥ 3 day (solid symbols) extreme temperature runs based on (a) max temperature and (b) min temperature. Squares correspond to warm extremes (≥ 95 th percentile) and circles denote cold extremes (≤ 5 th percentile).

Allen (2002) show that 75% of the adjusted monthly 90th percentile exceedence counts fall within ± 1 day of the observed values. Similar error statistics result for the other extreme percentiles. These results fail to consider that separate observation time adjustment equations are required for counts of consecutive day extreme temperature exceedences. Figure 2 shows the pattern of bias associated with ≥ 2 and ≥ 3 day extreme temperature runs. As with single-day occurrences, afternoon observation times produce more consecutive warm maximum temperature exceedences and fewer consecutive cold maximum temperature runs than would occur based on a calendar-day observation schedule (Fig. 2a). For consecutive occurrences of extreme minimum temperatures, morning observation hours, on average, produce fewer warm exceedence runs and more cold exceedence runs than would have occurred if a midnight-to-midnight observation schedule was used (Fig. 2b).

Opposed to the monthly adjustments for threshold

TABLE 1. Hourly stations used to develop and validate the observation time adjustment equations.

| Development Stations | Validation Stations |
|----------------------|---------------------|
| Brownsville, TX | Asheville, NC |
| Cape Hatteras, NC | Billings, MT |
| Carabou, ME | Corpus Christi, TX |
| Fort Myers, FL | Flagstaff, AZ |
| New Orleans, LA | Fresno, CA |
| Pocatello, ID | Los Angeles, CA |
| Quillayute, WA | Miami, FL |
| Sacramento, CA | Mobile, AL |
| San Diego, CA | Omaha, NE |
| St. Louis, MO | Phoenix, AZ |
| Salt Lake City, UT | Portland, ME |
| Tucson, AZ | San Francisco, CA |

exceedences presented by DeGaetano and Allen (2002), the consecutive (≥ 2 and ≥ 3 day) extreme occurrence counts were adjusted on an annual basis. This change in temporal resolution was necessary due to the smaller number of consecutive day events. Based on the annual counts it was also possible to restrict the adjustments to observation categories (i.e., morning, afternoon, and midnight) rather than individual predictand hours as was the case with the single-day events (DeGaetano and Allen 2002). Thus, for a specific extreme (e.g., cold maximum temperatures) and minimum run length (e.g., ≥ 3 days), a set of eight equations was required to convert between the three observation time categories (Karl et al. 1986). Although it was possible to use the same set of adjustment equations for different extreme thresholds (e.g., the 90th or 99th percentiles), separate adjustment equations were required for ≥ 2 and ≥ 3 day runs. Although not relevant to the present study, the influence of observation time bias diminishes for run lengths greater than 5 days. Adjustments were applied to all years with nonzero single-day exceedences.

The adjustment equations were based on pool of six potential predictors that included the original and new observation hour, the number of days exceeding the extreme threshold, annual counts of ≥ 2 and ≥ 3 day extreme occurrences, and the number of extreme events. An event was defined as a run of one or more days exceeding the extreme threshold, separated by at least one day on which the temperature fell below the threshold. Predictors were eliminated from the final regression equations using a backward elimination procedure when their regression coefficient was not statistically different from zero ($\alpha = 0.10$).

The regression equations were developed and evaluated using independent sets of simulated daily observations representing the relevant observation hours. Hourly data from 12 sites (Table 1) for the period 1985– 95 were used for these simulations. Figure 3 shows the results of these evaluations for high and low maximum and minimum temperature extremes. Each box plot summarizes the difference between 330 annual exceedence count pairs. When rounded to the nearest day, the me-



FIG. 3. Box plots of observation time bias adjustment errors for 12 independent stations for (a) 95th percentile max temperature, (b) 95th percentile min temperature, (c) 5th percentile max temperature and (d) 5th percentile min temperature. Whiskers denote the 95th percentile. The gray band indicates errors that, when rounded, equal zero.

dian adjustment errors are zero in all cases, indicating that the regression-based adjustments have eliminated the biases present in Fig. 2. In the majority of cases, the adjustment errors within the interquartile range also round to zero. In general, the variability of adjustment errors is greater for minimum temperature than for maximum temperature. This was also the case for the daily temperature extreme exceedences given by DeGaetano and Allen (2002). There is also a tendency for larger absolute differences when ≥ 2 consecutive-day events are considered as opposed to ≥ 3 day runs. On average there are 2 times more ≥ 2 day events than ≥ 3 day events in a given year.

c. Nonclimatic inhomogeneities

The methods of Allen and DeGaetano (2000) were used to test and potentially adjust each documented station relocation or instrument change for a nonclimatic discontinuity. Potential inhomogeneities were identified using the HCN station history file. Based on these metadata, it was possible to identify changes in station

d. Urban classification

For some of the subsequent analyses the homogenized exceedence series were grouped based on the degree of urbanization of the observation site. For this purpose, urban, suburban, and rural stations were identified based on the methods of Owen et al. (1998). The set of 361 stations was fairly evenly divided among the three categories with 136 urban, 99 rural, and 126 suburban stations.

3. Statistical methodology

A first-difference series test was used to detect the sign and significance of trends in the homogenized extreme exceedence series. Separate tests were run using series starting dates ranging from 1900 to 1970 in increments of 10 yr. All series ended in 1996. Trend analysis followed the methods of Karl and Williams (1987). In this approach, the exceedence series were first standardized and then a first-difference series was formed by subtracting the value of the 10-yr running mean centered on year *i* from the value centered on year *i* + 1. A desirable quality of such a test is that all observations are weighted equally, eliminating the overemphasis of observations at the beginning and end of the time series, which is characteristic of least squares regression.

As a comparison, each trend was also evaluated for sign and significance using the nonparametric Kendall and Stuart (1977) test. All possible observation pairs (x_a, x_b) with a < b were identified and a tally (*K*) made of those pairs for which $x_a < x_b$. A large *K* is indicative of an increasing trend, while a small *K* corresponds to a decreasing trend. Statistical significance is based on the value:

$$\tau = \frac{4K}{N(N-1)} - 1$$
(1)

In both cases Monte Carlo techniques were used to assess the statistical significance of the computed test statistics. Because a priori knowledge concerning the direction of each trend did not exist, the use of twotailed statistical significance was required. The randomization procedure also destroyed any serial correlation that may have been present in the original time series. This, however, did not compromise the tests as the series were generally associated with lag-1 autocorrelations near 0.05.

Although the Kendall–Stuart test follows the normal distribution, allowing tabulated values to be used to as-

sess statistical significance, resampled distributions were used for this purpose to facilitate subsequent field significance testing. To evaluate the field significance of the individual tests, an identical reordering of years was used at each station, owing to the relatively high degree of spatial correlation in the exceedence counts. Based on the resampled series, test statistics were calculated simultaneously for each station, and a count made of the number of stations at which this new randomized t statistic was associated with a specific trend (i.e., increasing or decreasing, significant increase or decrease, etc.). This provided an empirical distribution of the number of specific trends against which the original nonrandomized result could be compared.

The series were also examined for the most significant trend changepoint using a method presented by Solow (1987). Using this approach the null hypothesis of no change in trend throughout the time series can be tested. Rejection of the null hypothesis indicates that the time series is better represented by two distinct linear trends. Solow (1987) referred to the year in which a significant change in trend was detected as the changepoint.

As a means of summarizing the collective behavior of the exceedence series over specific geographic areas or urbanization categories, composite series were developed using a procedure akin to the first difference method of Peterson et al. (1998). An unweighted average of these annual first differences was then computed over the area or category of interest. The cumulative sum of the area (or urbanization category) averaged first-difference series was then calculated to obtain the composite series. Although Peterson et al. (1998) chose to scale this final series such that each value represented the difference from the original time series at time t = 0, we have chosen to use the average count in the most recent year.

4. Results

a. Warm extremes

Collectively, based on 95th-percentile exceedences, the number of increasing and significant increasing trends outnumber the respective decreasing trends for exceedences of warm thresholds. However, it is not until the 1950–96 period that increasing trends are apparent at the majority of stations (Table 2). The post-1950 periods are characterized by the highest percentages of nonsignificant increasing trends, with increases in high extreme maximum and minimum temperatures occurring at over two-thirds of the stations (Table 2). The most recent decades are also nearly devoid of significant decreasing trends.

Using earlier starting decades, the percentages of increasing and decreasing trends are similar, with most periods showing both more significant increasing and decreasing trends than would be expected by chance (Table 2). In the 1930–96 period 70% of the stations

| | Μ | lax ten | nperatu | ire | M | | | | |
|--------|-------|---------|-----------------|-----------------|-------|-------|-----------------|-----------------|----------------|
| Begin- | All o | cases | Signi | ficant | All o | cases | Signi | ificant | Avail- able |
| decade | Inc | Dec | Inc | Dec | Inc | Dec | Inc | Dec | stations |
| 1900 | 65 | 35 | 32° | 19 ^b | 63 | 34 | 40 ^c | 14 ^b | 35 |
| 1910 | 53 | 47 | 28° | 17 ^b | 70 | 31 | 26° | 6 | 81 |
| 1920 | 64 | 36 | 24° | 3 | 71 | 31 | 29° | 12ь | 117 |
| 1930 | 30 | 70 | 12ь | 38° | 41 | 59 | 17° | 34° | 178 |
| 1940 | 47 | 53 | 16 ^b | 8 ^a | 53 | 47 | 21° | 13ь | 219 |
| 1950 | 45 | 55 | 17 ^b | 12ь | 61 | 39 | 23° | 11 ^b | 357 |
| 1960 | 77ª | 23 | 22° | 1 | 74ª | 26 | 34° | 4 | 358 |
| 1970 | 74 | 26 | 20 ^c | 2 | 70 | 30 | 22° | 3 | 359 |

exhibit decreasing high extreme maximum temperature trends. This period-dependent behavior is strongly influenced by peaks in 95th-percentile maximum and minimum temperature exceedences in the 1930s and to some extent the 1950s.

Focusing on the periods 1930–96 and 1960–96 shows that during the longer period, significant increasing high extreme occurrence trends are predominantly confined to extreme western, eastern, and southern locations (Figs. 4a, 5a). There is also a tendency for the significant negative trends to be clustered along the Rocky Mountains and in the Midwest. During the more recent period, the significant increasing trends are fairly widespread across the country, with a conspicuously low number of significant trends in the area between the Mississippi River and western Rocky Mountains (Figs. 4b, 5b). This lull is particularly evident when maximum temperature extremes are considered. Similar results (not shown) were obtained based on the Kendall–Stuart test.

This dichotomy in trend behavior between the two periods, indicates the presence of a trend changepoint sometime after 1930. Indeed, when applied to the 1930– 96 series, the two-phase regression model indicated that a significant ($\alpha < 0.01$) number of both the high extreme maximum and minimum temperature series were best described by two distinct slopes. Figure 6 shows that for high extreme maximum temperature the breaks were concentrated in two time periods, with the majority occurring between 1940 and 1949. A second grouping of lesser magnitude occurred in the 1965–79 interval. Most of the high extreme minimum temperature series changepoints occurred between 1960 and 1975, with a secondary maximum in the 1940s (Fig. 6).

In addition to this time dependence, the breaks were also concentrated spatially, as approximately 60% of all stations within the $119^{\circ}-110^{\circ}W$ and $89^{\circ}-80^{\circ}W$ longitude bands exhibited significant changes in the slope of high extreme minimum temperature series. Based on resampling, such a spatial grouping occurred in <1% of the cases. Figure 7a shows the composite minimum temperature exceedence series for the 40 stations (re-



FIG. 4. Stations with positive (solid) and negative (open) trends in extreme warm min temperature exceedences (i.e., \geq 95th percentile) during (a) 1930–96 and (b) 1960–96. Trends that are significant ($\alpha = 0.05$) based on resampling of the first difference series are indicated by large symbols. The symbols also classify the stations as urban (triangle); suburban (square); or rural (circle).

gardless of the presence of a changepoint) in the 119° – 110° W band. These stations predominantly show a change in the slope of the exceedence series in the 1940s. More than 50% of the significant changepoints at stations in this longitude band occurred in the 1940s, as opposed to <20% in the later 1960–75 period. When the series from stations in the more easterly longitude band are composited (Fig. 7b), the prominent changepoint occurs in the early 1970s. Over 86% of the significant changepoints occur in the 1960–75 interval for stations in the 89°–80°W longitude band.

A relationship between the occurrence and timing of trend changepoints and station latitude was not apparent. Also, the existence of trend changepoints does not appear to depend upon the sign or significance of the slope of the overall (1930–96) series.

Figure 8 illustrates the magnitude of the high exceedence trends. Given the geographic variability of the results shown in Figs. 4 and 5, the composite trends are shown for three regions, delineated by 95° and 110°W longitude, as well as for the contiguous United States.



FIG. 5. As in Fig. 4 but for extreme warm max temperature exceedences (i.e., \geq 95th percentile).

As expected from Table 2 the high minimum temperature extreme trends exhibit the greatest regional and temporal differences. The largest time-dependent changes occur in the eastern region, where over the last 37 yr (1960–96), the linear trend has resulted in an average of 10.7 additional high minimum temperature occurrences. The increase is more than half this amount in the western region. In the central region, the relatively flat trend resulted in an additional two occurrences over the 37 yr. In the western and eastern regions, the present (1996) number of high minimum temperatures is similar to that which was common in the 1930s. In the central band, the 1930s' peak exceeds the current number of extreme occurrences, producing the most negative longterm (1930–96) high minimum temperature occurrence trend.

In addition to these differences in trends, the three regions also contain different percentages of urban, rural, and suburban station types. In the east, 48% of the stations that comprise the 1960–96 composite are urban, as compared to 23% and 31% in the central and western regions, respectively. Rural stations represent 20% of the eastern composite sites and approximately 35% of the central and western stations. A similar percentage of urban stations form the 1930–96 composite time se-



FIG. 6. Percentage of significant regression changepoints occurring within 5-yr intervals, based on the 1930–96 extreme warm max (dark shading) and min (light shading) temperature extreme exceedence series.

ries. However, only 12% of the eastern stations are classified as rural. In the central and western regions, about 30% of the stations that form the composite are classified as rural.

b. Cold extremes

Table 3 summarizes the results for cold maximum and minimum temperature extremes. Using the 5th percentile of the daily distribution as the threshold for extreme, the number of decreasing trends generally ex-



FIG. 7. Composite extreme warm min temperature exceedence series for stations in the regions bounded by (a) $119^{\circ}-110^{\circ}W$ and (b) $89^{\circ}-80^{\circ}W$.



FIG. 8. Composite extreme max and min temperature exceedence series for the (top row) contiguous United States, and (second row) eastern, (third row) central, and (bottom row) western lon bands. East refers to stations east of $95^{\circ}W$ and west to stations west of $110^{\circ}W$. Linear trend lines are given for the 1930–96 and 1960–96 periods. The regression slopes (exceedences yr⁻²) are also given numerically in each panel, with the first value corresponding to the 1930–96 period.

ceeds that of the increasing trends. This agrees favorably with the results of the warm extremes, as each shows predominate warming through the study periods. Unlike the warm extremes, however, a high number of increasing (i.e., cooling) trends is not associated with a 1930 starting date. Field significance is achieved for the number of significant cold extreme trends only in the 1910– 96 period and the more recent 1970–96 period. This is

TABLE 3. Percentage of increasing (Inc) and decreasing (Dec) extreme cold max and min temperature occurrence trends and associated field significance based on different starting decades. Each series ends in 1996. Field significance based on resampling is indicated by $^{a}(\alpha = 0.10)$, and $^{b}(\alpha = 0.05)$.

| | Μ | lax ten | nperatu | ire | Ν | | | | |
|--------|-------|-----------------|---------|-----------------|-----|-------|-----------------|-----------------|----------------|
| Begin- | All o | cases | Signi | ficant | All | cases | Signi | ficant | Avail- able |
| decade | Inc | Dec | Inc | Dec | Inc | Dec | Inc | Dec | stations |
| 1900 | 21 | 79 | 4 | 14 | 33 | 67 | 10 ^a | 20 ^b | 28 |
| 1910 | 8 | 92ь | 3 | 27ь | 16 | 84 | 4 | 29ь | 75 |
| 1920 | 37 | 63 | 3 | 8 | 34 | 66 | 4 | 10 ^a | 115 |
| 1930 | 39 | 61 | 3 | 5 | 40 | 60 | 5 | 7ª | 162 |
| 1940 | 45 | 55 | 4 | 3 | 49 | 51 | 5 | 7 | 217 |
| 1950 | 60 | 40 | 6 | 3 | 52 | 48 | 6 | 5 | 357 |
| 1960 | 22 | 78 | 1 | 11 | 23 | 77 | 3 | 13 ^b | 358 |
| 1970 | 13 | 87 ^a | 1 | 15 ^b | 15 | 85ª | 2 | 12ь | 359 |

quite different from the warm extremes where the number of significant increasing and decreasing trends was field significant in the majority of time intervals. For both low maximum and minimum temperature extremes, the number of increasing trends (i.e., toward cooler extremes) decreases rapidly after the 1950–96 period (Table 3). Similar results were also obtained based on the Kendall–Stuart test.

Given this difference in trend characteristics between the pre- and post-1950 periods and for comparability with the warm extremes, the subsequent discussion of results will also focus on the 1930–96 and 1960–96 periods. Figures 9a and 10a show that from 1930–96 increasing low maximum and minimum temperature extreme trends were confined primarily to the northeastern and midwestern portions of the United States. Significant decreasing cold extreme trends were clustered in the Southwest and in western Montana (Figs. 9a, 10a). In the more recent period, increasing trends were limited to the extreme northeast, with most of the significant increasing trends occurring in Maine (Figs. 9b, 10b). A relatively high number of increasing trends also occurred to the west of the Rocky Mountains.

The most notable feature of the 1960–96 period is the grouping of significant decreasing cold extreme





FIG. 9. As in Fig. 4 but for cold min temperature exceedences (i.e., \leq 5th percentile).

trends across the southern United States (Fig. 9b, 10b). For maximum temperatures, significant decreasing cold exceedence trends occur predominantly in California and the southeastern United States. A dense clustering of decreasing low minimum temperature extreme trends is evident in the southeastern United States, particularly in the Carolinas and Virginia.

Despite the increase in the number of decreasing cold extreme exceedence trends between the 1930-96 and 1960-96 periods, a significant number of trend changepoints is evident only in the minimum temperature series. Of the 162 series, 33 are best described by a twophase regression model. Based on resampling, this number of series is field significant at the $\alpha = 0.05$ level. These two-slope series are predominantly located in the area bounded by 30° and 40°N latitude and 89°-80°W longitude. Based on stations within this quadrangle, a composite exceedence series is shown in Fig. 11. A change of slope is evident in the late 1970s, in agreement with the changepoint test results, which indicate that 45% of the breaks occur between 1975 and 1979. The timing of these extreme low minimum temperature series breaks and the location of the associated stations, is similar to that of the warm minimum temperature extreme series (Fig. 7b).





FIG. 10. As in Fig. 4, but for cold max temperature exceedences (i.e., \leq 5th percentile).

The magnitude of the cold minimum temperature trends is shown in Fig. 8. Again it is the low minimum temperature extreme exceedence trends that display the greatest temporal and spatial variability. In all regions, extreme cold minimum temperature occurrences decrease from 1960–96. The decrease is greatest in the



FIG. 11. Composite extreme cold min temperature exceedence series for stations in the region bounded by 30°–40°N, 89°–80°W.

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TABLE 4. Percentage of increasing (Inc) and decreasing (Dec) extreme max (TMax) and min (TMin) temperature occurrence trends and associated field significance based on different extreme thresholds. Field significance based on resampling is indicated by $^{a}(\alpha = 0.10)$, $^{b}(\alpha = 0.05)$ or $^{c}(\alpha = 0.01)$.

| | | 1930–96 | | | 1960–96 | | | | |
|---------|----------|-----------|-----|-----------------|----------------|-----------------|-----|-------------|-----------------|
| Percen- | | All cases | | Significant | | All cases | | Significant | |
| tile | Variable | Inc | Dec | Inc | Dec | Inc | Dec | Inc | Dec |
| 90th | TMax | 30 | 70 | 12ь | 38° | 75ª | 25 | 20° | 3 |
| 99th | TMax | 28 | 72 | 13 ^b | 42° | 80 ^b | 20 | 20° | 1 |
| 90th | TMin | 42 | 58 | 16 ^b | 31° | 75ª | 25 | 36° | 5 |
| 99th | TMin | 37 | 63 | 11 ^b | 35° | 73ª | 27 | 27° | 3 |
| 10th | TMax | 35 | 65 | 5 | 7 | 19 | 81ª | 1 | 18 ^b |
| 1st | TMax | 32 | 68 | 1 | 5 | 32 | 68 | < 1 | 4 |
| 10th | TMin | 49 | 51 | 11 ^a | 6 | 21 | 79ª | 5 | 15ь |
| 1st | TMin | 28 | 72 | 0 | 8 ^a | 31 | 69 | <1 | 4 |

central and eastern regions, where the linear trends result in about four less extreme exceedences in 1996 as opposed to 1960. The 1930–96 trends, however, range from little change in the central region, to a modest increase in extreme occurrence (about 5 days over the 67 yr) in the east, to a relatively large decrease in the west. Cold maximum temperature occurrences generally follow the sign of the corresponding cold minimum temperature trend, but the magnitudes of the trends are damped.

c. Alternate extreme thresholds

Similar spatial and temporal patterns of exceedence series trends occur when the extreme threshold is reduced (e.g., 90th or 10th-percentile) or increased (e.g., 99th or 1st percentile). As was the case with the 95thand 5th-percentile thresholds, a marked difference in trend behavior is apparent between the 1930-96 and 1960-96 periods (Table 4). For the 1960-96 period, significant increasing trends in both warm maximum and minimum temperature exceedences display spatial patterns similar to those based on the 95th percentiles (Figs. 4 and 5) when the 90th and 99th percentiles are used. One notable exception (not shown) is the presence of fewer significant trends over Minnesota and Wisconsin. The spatial patterns of the decreasing cold extreme exceedence trends are less similar (not shown). In these cases, most of the decreasing trends over the southeastern United States fail to attain statistical significance ($\alpha = 0.05$) when based on the 1st percentile threshold.

Since these differences are mainly in the degree of statistical significance, rather than the sign of the trend, subsequent discussions will be limited to the 95th- and 5th-percentile thresholds. This consistency in results based on different thresholds indirectly addresses the concern of Sen et al. (1998) that occurrence trends may behave differently than trends based on degree-days above (or below) some extreme threshold. Although a direct analysis of this alternative variable is possible, it

TABLE 5. Differences between the percentage rural, suburban (sub), and urban stations with specific extreme temperature occurrence trends based on the 95th-percentile extreme threshold and the 1960–96 study period. Significantly different pairs are indicated by bold type. Field significance is indicated by ${}^{\circ}(\alpha = 0.10)$, ${}^{\circ}(\alpha = 0.05)$, or ${}^{\circ}(\alpha = 0.01)$. "All +" refers to all positive trends regardless of significance. Values for negative trends ("all –") are omitted since these differences have the same magnitude, but opposite sign of the "all +" values.

| Extreme | Trend type | Rural – urban | Rural – sub | Sub – urban |
|----------|---------------|------------------|-------------------------|-------------------------|
| Warm max | Significant + | -2 | 3 | - 5 ^a |
| Warm max | Significant - | <1 | <1 | <1 |
| Warm max | All + | -4 | 2 | -6 |
| Warm min | Significant + | - 30 ° | - 9 ^b | -21° |
| Warm min | Significant - | -1 | -1 | 0 |
| Warm min | All + | -10 | -7 | -3 |
| Cold max | Significant + | 0 | -1 | 0 |
| Cold max | Significant - | -7^{a} | -1 | - 6 ^b |
| Cold max | All + | 10 | 8 | 2 |
| Cold min | Significant + | 2 | -1 | 3 |
| Cold min | Significant - | -15 ^b | -3 | -12 ^b |
| Cold min | Alı́ + | 15 | 6 | 9 |

would require the development of a different set of observation time adjustment equations. This task is beyond the intended scope of this paper.

d. Urbanization

To determine whether urbanization influenced the 1960-96 extreme exceedence trends, a resampling analysis similar to that used to obtain field significance probabilities was used. This allowed distributions of the difference between the percentage of specific trends (e.g., increasing, significantly decreasing, etc.) at rural, suburban, and urban stations to be developed based on cases where the trends were independent of urbanization category. Table 5 summarizes these results. For illustration, the rural-urban difference of -30 in the fourth row of the table, was obtained since 19% of the rural stations exhibited significant positive (increasing) high minimum temperature extreme trends, while 49% of the urban stations displayed this type of trend. Based on resampling, a rural-urban difference of 30 is significant at the $\alpha = 0.01$ level.

Considering only the slope of the trends (i.e., either increasing or decreasing regardless of significance), none of the trends exhibit a dependence on urbanization $(\alpha = 0.10)$. This is also true for the 1930–96 period (not shown). With regard to the significant trends, however, the percentage of increasing warm minimum temperature trends is significantly higher at urban stations than at rural or suburban sites ($\alpha = 0.01$). Similarly the percentage of increasing trends at suburban stations exceeds that of the rural sites ($\alpha = 0.05$). Analogous results are obtained for both cold extremes, where decreasing trends are more prevalent at urban stations (Table 5). The results for warm maximum temperatures are inconsistent, with suburban stations showing a signifi-



FIG. 12. Composite extreme max and min temperature exceedence series. Rows show rural, suburban, and urban stations from top to bottom. The linear trend line and numeric regression slope (exceedences yr^{-2}) are shown in each panel.

cantly higher percentage of both increasing trends than the urban sites.

A set of composite temperature extreme exceedence series is shown in Figure 12. Here, each series is based on stations from a specific urbanization category, regardless of the sign or significance of the trend. The behavior of the linear trends is comparable to the trend counts given in Table 5. The steepest slope (0.26 exceedences yr^{-2}) corresponds to warm minimum temperatures at urban sites. This slope is nearly 3 times greater than that for the rural stations and slightly less than double the composite suburban trend (Fig. 12). Although the urban trend is consistently the steepest for the other extremes, a similar marked decrease in slope at the suburban and rural sites is not evident.

Collectively, each of the trends is representative of warming. The warming tends to be greater for minimum temperature extremes as opposed to those based on the daily maximums, particularly for the warm thresholds. At urban stations the trend in high minimum temperature extremes is almost 1.5 times that of the corresponding maximum temperature trend. This agrees well with the behavior of trends based on temperature averages (e.g., Karl et al. 1988).

e. Consecutive-day extreme occurrences

The impact of temperature extremes is exacerbated by the persistence of the heat wave or cold spell. To ascertain whether the trends in daily extreme occurrences also manifest themselves as trends in multipleday events, series representing occurrences of ≥ 2 and ≥ 3 consecutive extreme exceedences were formulated and analyzed. Table 6 summarizes these results for both the 1930–96 and 1960–96 periods. A comparison of Tables 6, 2, and 3 shows that the characteristics of the consecutive-day exceedence trends closely match those of the total exceedences. This is true not only based on the number of specific trend types, but also for the spatial distribution (Fig. 13).

Figure 14 illustrates the magnitude of the \geq 3 consecutive-day exceedence trends, hereafter heat waves or cold spells, based on the regionalization used in Fig. 7. Heat waves exhibit the greatest regional and temporal differences. The time-dependent change averaged over the eastern region, is 2 to 3 times that of the other regions. There is relatively little change in heat wave occurrence based on minimum temperature in the central region. The present (1996) number of heat waves is below that which was common in the 1930s, except in the western region.

The magnitudes of the cold spell trends during the 1960–96 period are comparatively small. As opposed to heat waves there is general agreement between the 1930–96 and 1960–96 trends. The eastern region shows the largest increase in cold spell occurrence, while in the west a trend of similar magnitude, but opposite sign

| Beginning | | Maximum temperature | | | | Minimum temperature | | | |
|---------------|-----------|---------------------|-------------|-----------------|-----------|---------------------|-------------|-----|-----|
| | All cases | | Significant | | All cases | | Significant | | |
| Event type | e decade | Inc | Dec | Inc | Dec | Inc | Dec | Inc | Dec |
| ≥2 warm | 1930 | 31 | 69 | 18 ^b | 36° | 38 | 62 | 12ь | 26° |
| ≥3 warm | 1930 | 34 | 66 | 13 ^b | 34° | 40 | 60 | 12ь | 24° |
| ≥ 2 cold | 1930 | 52 | 48 | 4 | 1 | 57 | 43 | 6 | 5 |
| \geq 3 cold | 1930 | 47 | 53 | 3 | 2 | 53 | 47 | 5 | 5 |
| ≥2 warm | 1960 | 71 | 29 | 18° | 2 | 73ь | 27 | 27° | 3 |
| ≥3 warm | 1960 | 78 ^b | 22 | 20° | 1 | 73ь | 27 | 28° | 3 |
| ≥ 2 cold | 1960 | 24 | 76ª | 1 | 11ь | 23 | 77ª | 2 | 12ь |
| \geq 3 cold | 1960 | 29 | 71 | 2 | 7 | 26 | 74ª | 2 | 9ª |

TABLE 6. Percentage of increasing (Inc) and decreasing (Dec) extreme max and min temperature trends based on ≥ 2 and ≥ 3 consecutive day dexceedence events. Field significance based on resampling is indicated by ${}^{a}(\alpha = 0.10)$, ${}^{b}(\alpha = 0.05)$ or ${}^{c}(\alpha = 0.01)$.

is present in the 1930–96 minimum temperature cold spell series.

5. Discussion

a. Urban effects

Urbanization exerts a strong influence on recent (1960–96) warm temperature extreme trends. For each extreme temperature measure (i.e., maximum or minimum temperature and warm or cold extremes), the greatest warming occurs at urban stations. For warm minimum temperatures, the composite slope is nearly 3 times greater at urban than rural stations (Fig. 12). For

cold minimum and warm maximum temperature extremes, the urban trends' slopes are over 1.5 times higher than those of the rural composites. Only minimal differences in slope are evident for cold maximum temperature extremes.

This urban influence on the slope of the temperature extreme trends agrees with the results of Gallo et al. (1999). Based on monthly average temperature for the entire U.S. HCN, they found that the steepest trends were also associated with minimum as opposed to maximum temperature. At urban stations, the increase in mean minimum temperature was over twice that of the rural sites during the 1950–96 interval. Although the



FIG. 13. As in Fig. 4, but for (a) ≥ 3 day 95th-percentile max temperature exceedences (1930–96), (b) ≥ 3 day 95th-percentile min temperature exceedences (1960–96), (c) ≥ 3 day 5th-percentile max temperature exceedences (1960–96), and (d) ≥ 3 day 5th-percentile min temperature exceedences (1960–96).



FIG. 14. Composite \geq 3 day extreme max and min temperature exceedence event series for (top row) the contiguous United States, and (second row) eastern, (third row) central, and (bottom row) western lon bands as defined in Fig. 8. Linear trend lines and slopes are also given as in Fig. 8.

mean maximum temperature trends were not statistically significant, the urban trends were over 3 times as steep as their rural counterparts.

Karl et al. (1988) also show a disparity between the influence of urbanization on average maximum and minimum temperatures that agrees with the difference in slope between the rural and urban temperature extreme series analyzed in this study. They calculated the average heat island impact during the 1901-84 period to be 0.13°C for daily minimum temperatures and only 0.01°C for maxima. These biases reflect temperature differences between urban-rural stations pairs, with urbanization inferred from population. Thus, the magnitude of the urban-rural difference is not comparable to the difference in slopes presented in this study. Nonetheless, both studies indicate that the influence of urbanization is greatest for minimum temperatures and also that summer temperatures are affected to a greater degree than winter values. This seasonal influence is also supported by Kukla et al. (1986) and Changnon (1992) using mean temperature.

b. Inclusion of the 1930s

Century-long trends in warm temperature extreme occurrence across the United States are strongly influenced by peaks in warm maximum and minimum temperature extremes in the 1930s and to some extent the 1950s. These peaks coincide temporally and spatially with widespread drought episodes (Diaz 1983; Namias 1983). This correspondence suggests a possible association between the highest annual warm temperature extreme exceedence counts and drought. The spatial grouping of warm extreme trend change points is also suggestive of such a relationship. In the western 119°–110°W longitude band, changes in slope predominantly occur in the 1940s, while in the eastern 89°–80°W cluster of changepoints, the majority of stations experience slope reversals in the 1960s and early 1970s.

These differences reflect disparities in the atmospheric circulation patterns associated with the two major drought episodes of the 1900s. Namias (1983) shows that during the 1934–38 period, the maximum heights of the 315-K isentropic surface are aligned between 110° and 105°W longitude, with dry anticyclonic flow extending eastward to between 90° and 85°W longitude. Karl and Quayle (1981) characterize most of the area between 110° and 90°W longitude as experiencing extreme drought during the summer of 1934. Within this area, Diaz (1983) shows two distinct maxima in July 1934 drought severity based on the Palmer index, one centered near 110°W and the second near 93°W. In terms of drought duration, however, moderate to extreme drought was far more persistent in the western band.

The prominent circulation anomaly associated with the 1950s drought tended to be displaced further east. Namias (1983) shows the maximum 700-hPa summer height anomaly (1952–54) centered near 90°W longitude, but extending westward to almost 110° W. Again this corresponds with the area of extreme drought during August 1954 (Karl and Quayle 1981). However, Diaz (1983) shows only a single drought severity maximum over southwestern Iowa (95°W). He also shows that the duration of the 1950s drought was greater to the east (i.e., Kansas, Oklahoma, Texas, Missouri). An east–west dichotomy in drought severity between the 1930s and 1950s is not quite complete as the 1950s drought also tended to be more severe in southwestern states like New Mexico.

These spatial differences in drought severity and duration are reflected in the composite warm minimum temperature series shown in Fig. 7. Both the western and central time series are characterized by peaks in extreme exceedence during the early and middle 1930s. However, the 1950s' peak is pronounced only in the 89°–80°W longitude band (Fig. 7b). In fact, the early 1950s correspond to a minimum of extreme exceedences in the western band (Fig. 7a).

Peaks in extreme temperature occurrence around 1980 and in the late 1980s (Figs. 7b, 8, and 14) also correspond to major drought periods (Kunkel et al. 1999). Likewise, the peak in extreme occurrences in 1984 (Fig. 7a) corresponds to summer drought conditions, particularly in western Montana, where the density of daily HCN stations is relatively high.

A correspondence between warm extreme occurrence and drought is supported by Durre et al. (2000). They show an inverse relationship between soil moisture anomalies and daily maximum temperature in the central and eastern United States during summer. For days on which the soil moisture anomaly is in the lower quartile of the historical distribution, the frequency distribution of maximum temperature is shifted toward higher values. The shift is greatest for the extreme right tail of the temperature distribution, indicating that as the soil dries, the increase in the temperature on the hottest days is greater than that which occurs on relatively cool days. This temperature-soil moisture relationship tends to be most persistent (i.e., lasts several weeks after the soil moisture anomaly is observed) in the southeastern United States.

Given that a decrease in evaporation plays a role in urban biases (Oke 1990), the increase in temperature extreme occurrence observed at urban locations may be analogous to the increase in extremes noted during drought periods. Here, anthropogenically created soil moisture anomalies may produce a shift in the temperature frequency distributions resulting in a two to threefold increase in extreme occurrence at urban locations. Durre et al. (2000) found this effect to be greatest for the hottest temperatures, giving some insight as to why the urban influence on maximum temperature extremes appears relatively high compared to that found for means (i.e., Karl et al. 1988). We are currently investigating this influence more fully.

c. Comparison with previous studies

Clearly, the effects of circulation anomalies and urbanization complicate the task of collectively quantifying the temporal change in temperature extremes across the United States. Although the cold maximum temperature extreme series display minimal drought and urbanization effects, the series also provide no evidence for any time-dependent change through the twentieth century. Extreme minimum temperature occurrences, on the other hand are affected to a moderate degree by urbanization. Although significant decreases in cold minimum temperature extremes were detected at 10% of the rural stations, this number of trends (for the subset of rural stations) fails to achieve field significance at the $\alpha = 0.10$ level. This is surprising considering that over many regions of the country, the coldest minimum temperatures can be expected to occur due to radiational heat loss (e.g., Newman 1991). Nonetheless, without regard to urbanization category or trend significance, decreases in cold minimum temperature exceedences have occurred at over 80% of the stations since 1960.

Karl et al. (1989) describe a pattern of seasonal average maximum and minimum temperature fluctuations that corresponds to the pattern of extreme exceedences (both warm and cold) identified in this analysis. Unfortunately, it is not possible to directly compare the spatial pattern of the extreme trends with published average temperature trends, given differences in the periods of record and regional groupings. However, given that the extreme counts were derived from USHCN stations, it was possible to compute seasonal average temperature trends based on the homogenized monthly HCN data (Karl et al. 1990). Urbanization adjustments were not applied to the seasonal averages for compatibility with the extremes.

Figure 15a shows a strong relationship ($R^2 = 91.9\%$) between the least squares slope of the average summer maximum and minimum temperature series and the corresponding trends based on 95th-percentile maximum and minimum temperature exceedences. The 16 points in Fig. 15a represent maximum and minimum temperature for the three (east, central, west) regions and the combined United States for both the 1930-96 and 1960-96 periods. Based on the regression, if the mean summer temperature (maximum or minimum) is increased by 0.5°C over 50 yr, the corresponding 95th-percentile exceedence count would increase by about 6 events yr^{-1} . Although these values are not independent, the correlation between the trends in mean and extreme temperature is intriguing. If such a relationship proves to be robust, it could facilitate the analysis of global extreme trends based on seasonal means. A similar, although somewhat weaker ($R^2 = 84.9\%$) relationship exists between winter average maximum and minimum temper-



FIG. 15. Plot of the slope of the average temperature series versus that of the exceedence count series for (a) warm max and min temperature exceedences, (b) cold max and min temperature exceedences, (c) \geq 3 day warm max and min temperature extreme events and (d) \geq 3 day cold max and min temperature extreme events.

ature and extreme cold exceedences (Fig. 15b). In this case a 1°C increase in average temperature over 100 years translates to about one fewer exceedence per year. Changes in heat wave occurrence (\geq 3 consecutive exceedences) are also related to changes in seasonal mean temperature (Fig. 15c). In this case, a 1°C rise in average summer maximum or minimum temperature over 100 yr results in less than one additional heat wave per year. A similar relationship does not exist for cold spells (Fig. 15d).

Given this relationship, it is not surprising that the spatial pattern of highly significant increasing trends in extremely warm temperature occurrence in the Northeast and West matches the general pattern of mean temperature change across the United States (e.g., Karl et al. 1996). The most notable exception is that the pattern of general cooling in the southeastern United States for average temperatures does not manifest itself in the ex-

tremes. Significant increases in warm minimum (and to a lesser degree maximum) temperature extremes are widespread in the Southeast. For cold extremes, significant decreases in both maximum and minimum temperatures are concentrated in the Southeast, indicating a warming of winter extremes over the last 40 yr in this region.

Overall, there is good agreement between the results of this U.S. study and a similar analysis for Canada (Bonsal et al. 2001). For winter cold extremes, the Canadian results generally show trends toward fewer cold extreme exceedences, however, few of these trends are statistically significant. A notable exception occurs over eastern Canada, where significant increases in the number of winter cold exceedences predominate. The U.S. results show a similar pattern of generally nonsignificant decreases in cold extremes, except over extreme northern New England where stations are characterized by significant increases in cold extremes (Figs. 9 and 10). The Canadian results also show a cluster of increasing cold extreme exceedences along the central U.S.–Canadian border. This pattern does not continue south into the United States.

Although summer extreme minimum temperature trends are in agreement across the U.S.-Canadian border, the trends for maximum temperature extremes do not agree as closely. Significant increases in extremely warm summer minimum temperature are widespread across Canada, as they are across the United States. Extremely warm maximum temperatures, however, display no consistent trends at the Canadian stations, despite fairly widespread significant increases across the United States. This presumably results from differences in the period of records. Using 1950-96 exceedence series, the U.S. results show a similar number of increasing and decreasing warm maximum temperature trends (Table 2). A cluster of significant decreasing extreme maximum temperature trends over southern Ontario, is not supported by the (1960-96) U.S. analysis, which shows predominantly nonsignificant increasing trends adjacent to this region.

6. Summary

Trends in the occurrence of maximum and minimum temperatures greater than the 90th, 95th, and 99th percentile across the United States are strongly influenced by urbanization. The drought periods of the 1930s and 1950s also tend to be characterized by the highest number of annual extreme occurrences regardless of the degree of station urbanization. This results in predominantly decreasing warm exceedence trends across the country during the 1930-96 period. For longer periods (i.e., 1910-96) and the 1940-96 and 1950-96 periods, decreasing and increasing (and significantly increasing and decreasing) extreme maximum temperature trends generally occur at a similar number of stations. In terms of extremely warm minimum temperatures during these periods, almost twice as many stations experience increasing trends as opposed to decreases. Such a partitioning, however, could be expected by chance more than 10% of the time.

This dependence on period of record, along with a strong influence of urbanization, explains much of the disparity in the results of previous high temperature extreme occurrence studies. Overall, the results presented here generally reflect those which have found little trend in the occurrence of temperature extremes for series beginning prior to 1930 (e.g., Easterling et al. 2000). Likewise, the present results support the finding of significant increases in high temperature (both maximum and minimum) extremes over the 1950–96 period in studies such as Gaffen and Ross (1998), particularly at urban sites. As in almost all the previous works, the results of the current study show a greater temporal trend

in high extreme minimum temperatures than maximum temperatures.

During the 1960–96 period there is a distinct shift toward a widespread increase in the number of both warm maximum and warm minimum temperature exceedences. For this period, the following results are noteworthy:

- Based on a composite of urban stations, warm minimum temperature exceedences have increased at a rate of 0.26 exceedences yr⁻². This slope is nearly 3 times greater than that for the rural composite series and about double the composite suburban trend.
- 2) Half of the stations classified as urban experience significant warm minimum temperature trends.
- Collectively increasing extreme warm maximum and minimum temperature trends occur at three-quarters of the stations.
- Significant increasing warm minimum temperature exceedence trends are found at one-third of the stations (regardless of urbanization category). About 20% of the stations experience significant increases in warm maximum temperature occurrence.
- 5) Similar increases in the number of ≥ 2 and ≥ 3 day runs of extreme temperatures occur across the country.
- 6) The rate of extreme temperature warming is greatest in the eastern United States and least in the central region. This geographic pattern is a reflection of the spatial distribution of urban stations. These sites comprise 49% of the eastern, 35% of the western and only 24% of the central stations.

Trends in cold extreme occurrence are not as strongly affected by period of record. However, the period 1910-96 tends to be uncharacteristic of the other periods with pre-1960 starting dates since during this interval approximately 90% of the stations exhibit decreasing cold extreme trends. In the intervening periods there is not a strong tendency for increasing or decreasing trends to dominate. However, as with the warm temperature extremes, the 1960-96 period is characterized by a sharp increase in the number of decreasing cold extreme occurrence trends. Collectively these results also match those reported by earlier studies (e.g., Kunkel et al. 1999), but highlight the influence of the choice of period of record and the degree of urbanization of the stations analyzed. The 1960-96 period is characterized by a number of interesting features:

- 1) Cold minimum temperature decreases preferentially occur at urban station as opposed to suburban or rural sites.
- 2) Decreasing cold maximum and minimum temperature occurrence trends are present at nearly 80% of the stations.
- Significant decreases in cold extreme temperatures occur at about 15% of the stations. These stations tend to be predominantly located in the southeastern United States.

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- Similar decreases in the number of ≥2 and ≥3 day runs of extreme cold temperatures occur across the country.
- 5) There is little geographic variation in the rate of change of cold extreme temperature occurrence.

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