The 1995 Chicago Heat Wave: How Likely Is a Recurrence?

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ABSTRACT

The deadly heat wave of July 1995 that affected much of the U.S. midwest, most notably Chicago, Illinois, has been put into historical perspective. The heat wave has been found to be remarkably unusual, but only partially because of the extreme high apparent temperatures (an index of the combined effect of temperature and humidity on humans), where the authors calculate a return period of the peak apparent temperature of ≤ 23 yr. Of greater significance were the very high temperatures that persisted day and night over an extended 48-h period. Analysis presented here indicates that for Chicago such an extended period of continuously high day and night apparent temperature is unprecedented in modern times. The 2-day period where the minimum apparent temperature failed to go below 31.5°C (89°F) is calculated to be an extremely rare event (probability of occurrence < 0.1%) based on a 10 000-yr-long simulation of a four-parameter (temperatures related to the mean, the intraseasonal daily variance, the interannual variance, and the day-to-day persistence of temperature) probabilistic model.

Such unusual heat waves evoke questions related to the future course of the climate and whether this recent event was merely an extreme anomaly or part of an ongoing trend toward more extreme heat waves. A Monte Carlo analysis of trends (1948–95) for various quantiles of the hourly apparent temperatures during the most severe heat waves each year from 26 midwestern stations reveals a modest, statistically insignificant increase of apparent temperatures for a wide range of quantiles without the inclusion of 1995 data. There is a statistically significant increase in apparent temperature with its inclusion, reflected most strongly for upper quantiles or daytime temperatures. It is argued, however, that because of the impact of changes in instrumentation at primary National Weather Service stations, the potential affects of urbanization, and little trend of summer mean temperatures, it is unlikely that the macroscale climate of heat waves in the Midwest or in Chicago is changing in any significant manner.

Trends notwithstanding, the authors demonstrate the difficulty associated with projecting changes in the frequency and severity of similar types of events, even if the mean apparent temperature could be accurately predicted for the next century, for example, global warming projections. This is demonstrated using Chicago temperatures. The authors show that accurate projections of the frequency, severity, and duration of heat waves in the Midwest require accurate projections not only of the mean, the interannual variance, the intraseasonal variance, and day-to-day persistence, but also the interrelationships among these quantities within different synoptic-climatic regimes.

1. Introduction

The 1995 heat wave in the midwest of the United States received considerable press attention, primarily due to the large number of deaths in Chicago, which was well over 500. Changnon et al. (1996) have analyzed the impacts and responses to the 1995 heat wave, and Kunkel et al. (1996) have reviewed the synoptic weather associated with the heat wave. Kunkel et al. (1996) have also compared the Chicago heat wave with previous great heat waves of this century. Their analysis, like this one, considered the apparent temperature T_{ap}, which attempts to quantify the effects of temperature and moisture on the human body (Steadman 1984). Kunkel et al. (1996) showed that during the 1995 heat wave high dewpoints, due to limited vertical mixing from a subsidence inversion, played a key role in the high values of T_{ap}. They also concluded that the peak intensity of the 3- to 4-day

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heat wave was exceeded by only a few other heat waves during the 1930s, but this was based on the mean T_{ap}. Their historical analysis was based on twentieth-century data from Chicago and nearly 50 years of data from 18 other Midwest stations.

In this analysis we take a closer look at the full distribution of T_{ap} during the heat wave, both during day and night. The minimum temperature may be especially important. In other heat waves, such as the 1966 heat wave in St. Louis, fatalities attributed to the heat have been linked to extremely high elevated nighttime (or minimum) temperatures (McMichael et al. 1996; Henschel et al. 1969). We also note that deaths due to heat are greatest during the first few days of a heat wave (Kalkstein and Davis 1989) and that acclimatization factors (possibly both behavioral and physiological) also seem to be important (IPCC 1996a), so we focus on the full distribution of hourly temperatures during the first few days, 24-, 48-, and 72-h periods, of the most extreme heat wave each year for 26 midwestern stations in and around the core area of the 1995 heat wave.

An analysis of the trends of various quantiles of the T_{ap} during the most severe heat waves each summer is also described both with and without consideration of the growth of urban heat islands. Given the impact of the 1995 heat wave and the projections of further increases in temperature due to an enhanced manmade greenhouse effect, an analysis was also undertaken related to the probability of heat waves of similar or greater intensity using a variety of future climate scenarios. These scenarios ranged from no climate change to various combinations of temperature increase and concomitant changes of temperature variability. Specifically, the analysis focuses on the severity and duration of extreme heat waves relative to changes of mean temperature, variance, day-to-day persistence (correlation) of temperature, and the cross correlations of these quantities.

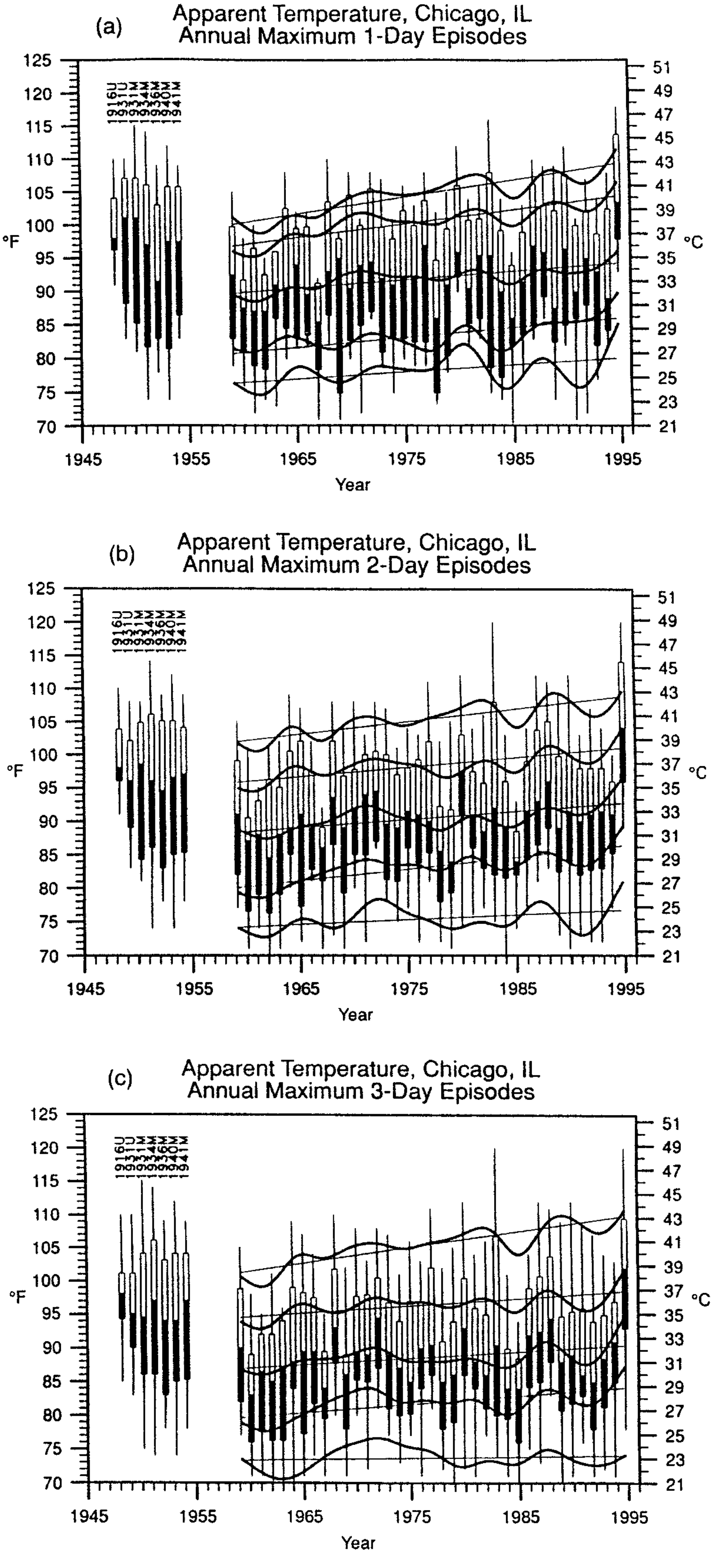
2. Assessing the 1995 heat wave

A convenient and useful approach to evaluating the historical significance of heat waves is to use the T_{ap} (Steadman 1984), sometimes referred to simply as the "heat index." The T_{ap} used in this analysis is based on the algorithm developed by Steadman (1984). It was developed to quantify heat stress on the human body. Steadman (1984) uses temperature, humidity, wind speed, and solar radiation to determine heat stress. In this analysis the effects of wind speed and solar radiation are ignored for several reasons, including the difficulty of developing homogeneous time series of solar radiation measurements. Therefore, our values of T_{ap} apply to shaded daytime conditions and night. Since this study's primary focus is comparative in nature, this is probably not a significant omission. Cloud cover varies little from heat wave to heat wave in the Midwest because cloud amount is almost always at a minimum. For comparative analyses, such as this one, the effect of wind speed on the apparent temperature is also problematic and likely to be insignificant compared with the effects of relative humidity. Steadman (1984) showed that the effect of wind speed on T_{ap} is to increase its value when ambient temperatures are above the body temperature, but this was for a fully clothed person. More recently, R. G. Steadman (1996, personal communication) has developed an apparent temperature for partially clothed bodies (varying between 35% and 80%). In this scenario the effects of wind speed are to cool the body at temperatures up to 44°C. So it is clear that the effects of wind speed on apparent temperature are highly dependent upon the amount of exposed skin, which varies from individual to individual. Furthermore, we find that winds during the heat waves in Chicago are light, averaging about 5 m s^{-1} in the afternoon and 2 m s^{-1} during the night. Additionally, we find that the correlation between wind speed and temperature is negligible, –0.07, when the data are stratified by the time of day. For all these reasons we ignore the effects of wind speed on T_{ap}.

The 25th, 50th, and 75th percentiles (25P, 50P, and 75P) of the hourly T_{ap} as well as the maximum and minimum T_{ap} based on data for all 1-day (24 h), 2-day (48 h), and 3-day (72 h) periods from 15 June to 15 August were calculated at each of 26 stations in and around Chicago, Illinois. Quantiles were calculated based on the method of Chambers et al. (1983), but estimates for the maximum (MAX) and minimum (MIN) were required for 7 years during the 1970s with 3-h data. The estimates were based on the interquartile range times 1.5 plus (or minus) the value of the 75th (or 25th) percentile T_{ap} as described in Chambers et al. (1983) to identify outliers. For a normal distribution, this is about 2.6 standard deviations from the mean. During each summer the most extreme 1-, 2-, and 3-day events were identified based on the median T_{ap} during these periods.

Data from other severe heat waves were also put into electronic format for selected events prior to the period of record for O'Hare Airport, which is complete since 1959. These events were selected based on the analysis of Kunkel et al. (1996). Because these data were taken from sites with a different local microclimate as well as differing mesoscale climate characteristics, they were not used in any quantitative evaluation of the 1995 heat wave but are included for qualitative comparison. Figure 1 indicates that the 24- and 48-h T_{ap} for the 1- and 2-day events were higher for the MIN, 25P, 50P, 75P, and MAX than any other previous heat waves. Clearly, there was little relief from the heat during any time of the 2-day period, even during nighttime hours.

To help delineate the areal extent of the heat wave, the highest median T_{ap} was calculated for *any* 2-day period during the 1995 heat wave. Figure 2 shows that the heat wave was centered in the northern half of Illinois and the southern half of Wisconsin. The highest values of T_{ap} were north of Chicago relative to the maximum hourly T_{ap}. The maximum hourly T_{ap} is a good proxy for the highest temperature[1] during the period of interest and similar characteristics hold for the minimum hourly temperature. Notice, however (Fig. 2), the highest values of the minimum T_{ap} were located in and around Chicago. Clearly the impact of the 1995 heat wave in Chicago was in no small measure due to the extremely high nighttime values of the T_{ap}.


(a) Apparent Temperature, Chicago, IL Annual Maximum 1-Day Episodes

(b) Apparent Temperature, Chicago, IL Annual Maximum 2-Day Episodes

(c) Apparent Temperature, Chicago, IL Annual Maximum 3-Day Episodes

FIG. 1. Time series of various quantiles [the minimum (MIN) 25th, 50th, 75th percentiles, and the maximum (MAX)] for the warmest annual 1-day, 2-day, and 3-day events based on T_{ap} (°C) for Chicago, Illinois. Data are for O'Hare Airport back to 1959. Prior to 1959, other notable heat waves are plotted using data from Midway Airport (M) and the University of Chicago (U) with related dates displayed above the box plot.

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[1] Higher temperatures may have occurred between the hourly readings.

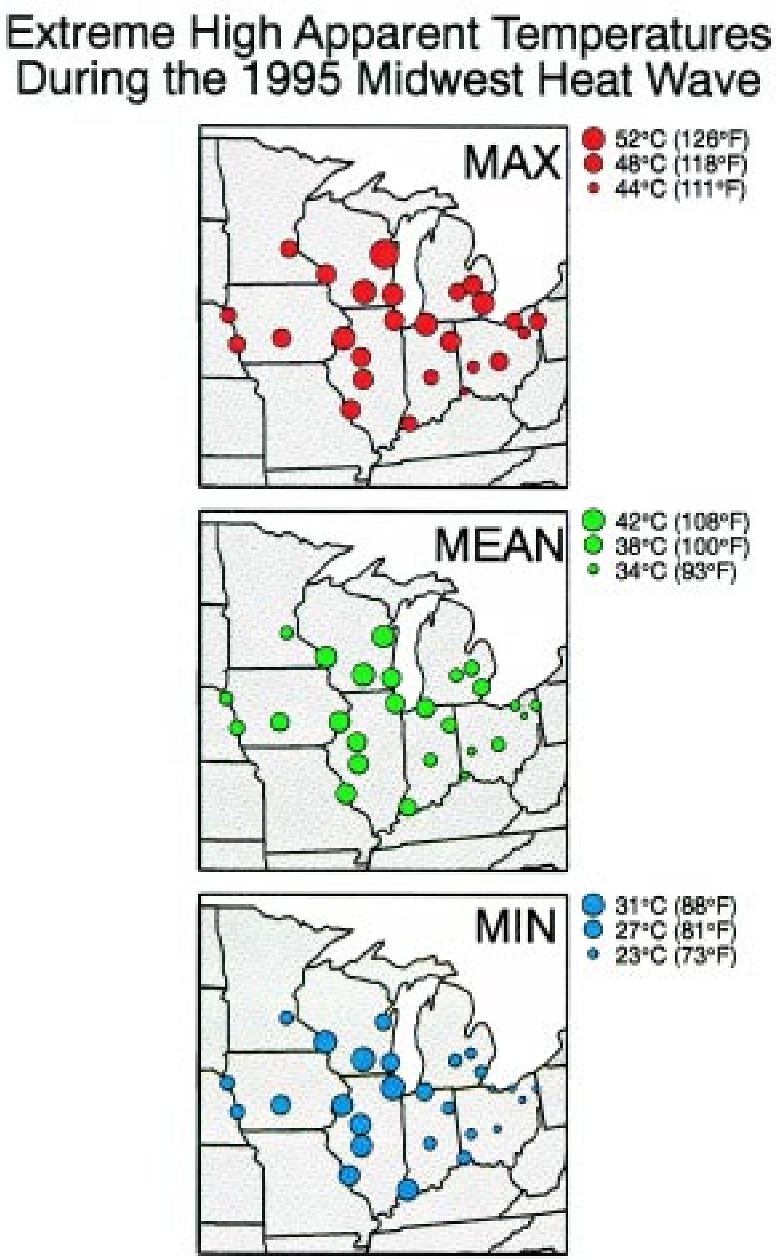


FIG. 2. The maximum, minimum, and mean T_{ap} during the 1995 heat wave for the 2-day period with the highest median T_{ap}. Temperatures are represented by the area of the circle.

Obviously, the disadvantage of the annual series method is that in some years the second or third highest heat waves may be less intense than the most severe heat wave in another year. The decision to use the annual series, however, was based on the information about human acclimatization to heat waves after several days of very high apparent temperatures. These statistics were used in a trend analysis to gauge whether the climate in the Midwest, and in Chicago in particular, reflected characteristics of a stationary or nonstationary climate as related to extreme heat waves.

The full distribution of all daily values of T_{ap} was also used in our study. Specifically, it was used to develop a statistical model from which simulated daily values of T_{ap} could be derived. These simulated values were then used to calculate probability and duration statistics for various threshold values of T_{ap} relative to the 1995 heat wave. In developing our model, it is important to know if the samples used to calculate the model parameters are from a stationary or nonstationary climate. Updates from our previous work (Plantico et al. 1990) show that mean temperatures during summer in the Midwest (Minnesota, Wisconsin, Iowa, Michigan, Illinois, and Indiana) are consistent with the notion of a stationary climate. Our motivation for examining the trends of the extremes was to ensure that this characteristic, at least over the last 40 yr or so, was not seriously violated by the episodic events. We endeavor to estimate probabilities of occurrence, both for today's climate and future scenarios of climate change.

3. Methods

Our method of selecting and analyzing the most extreme 1-, 2-, and 3-day events during each summer (mid-June to mid-August) is often referred to as an "annual series" in extreme value analysis (Kite 1977). Another approach, the "partial duration series" is to analyze all heat waves above a certain threshold, so that in some years there may be several heat waves.

a. Trends of apparent temperature

The analysis of the trends related to the hourly T_{ap} during 1-, 2-, and 3-day intervals during the period of most intense summertime heat in the Midwest (15 June through 15 August) focused on the MIN, 25P, 50P, 75P, and MAX T_{ap}. The analysis was performed for both observed T_{ap} and those adjusted for the effects of the growth of the urban heat island. Heat island adjustments were applied based on the algorithm developed by Karl et al. (1988). This algorithm uses population to estimate of the effect of urbanization on mean monthly maximum and minimum temperature, with different adjustments for the maximum and minimum. Since our interest is in events, not monthly means, we could not directly apply these adjustments. Instead, we used the algorithm to help develop an interval that would bound the effects of urbanization on temperature trends. With this in mind we applied the algorithm by assuming that the hourly temperatures at 1500 LT were associated with the maximum and 0600 LT with the minimum temperature. The hours between were interpolated. This assumption is quite close to reality during major heat waves. To provide an upper bound for the effect of urbanization on the trends of temperature, we used a population of zero for each urban area starting with the beginning of available electronic data (this varied from 1948 to 1959, the latter for Chicago) with the final population estimate equal to the 1990 metropolitan or city census. This is surely a gross overestimate of the effect of urban growth for monthly averages, but since we are focusing on events during periods of mostly clear skies and light winds, when the heat island effect is stronger than average, it is not as large an overestimate as one might presume.

Trend analysis was conducted based on Monte Carlo simulations of detrended autoregressive moving-average (ARMA) models of the T_{ap}. The procedure is virtually identical to that used by Karl et al. (1996) to identify trends in climate indicators and indices using ARMA models with a maximum order of 4, for example, ARMA (2,2). Briefly, an ARMA model is fit to the residuals from the trend and the Bayesian Information Criterion (Katz 1982) is used to select the most appropriate and second most appropriate models. These models are then run 1000 times to calculate the percent of time that trends from the ARMA models exceeded the observed trend. This is used as a direct estimate of the statistical significance of the trend. The best two models are selected to test the sensitivity of the significance levels to the model used.

Trend analysis is sensitive to unusually large anomalies at the beginning and end of the time series. Since the 1995 heat wave was such a dramatic anomaly, the trend analysis was performed both with and without the data for 1995. This provides a means to disregard the effect on the 1995 heat wave on the trend analysis.

b. Probability of recurrence

A statistical model was used to simulate the day-to-day maximum and minimum hourly values of T_{ap}. The model captures those aspects of the climate and weather that affect the interannual variability of T_{ap} (s_a^2; e.g., the variance of the monthly mean T_{ap} calculated across years), the intramonthly variability of T_{ap} (s_m^2; e.g., the variance of T_{ap} calculated for a given month, e.g., July, using daily values), the persistence or the lag 1 correlation coefficient of the daily T_{ap} (r), and the mean $T_{ap}(\overline{T}_{ap})$ over the years of interest. In the model, the (total) variance of daily temperature is decomposed into a sum of two component variances, that is, $s_m^2 + s_a^2$. Each of the model quantities is considered relative to either the daily maximum or minimum T_{ap}. The importance of considering the effect of intraseasonal variance on temperature extremes has been well demonstrated in previous work by Katz and Brown (1992). We applied the model to various threshold temperatures related to the 1995 heat wave as well as a number of climate change scenarios by varying each of the four model parameters. The basis of the model is an AR(1) and can be written in the form

$$Y_{ap,t} = rY_{ap,t} + a_t, \tag{1}$$

where $Y_{ap,t}$ is the value that will be used to generate the T_{ap} for time t, r is the first-order autoregressive coefficient, and a_t is random noise represented by a standard normal deviate. For convenience of calculation, the values of $Y_{ap,t}$ are standardized such that they have unit variance (they already have zero mean), for example, $Y_{s,ap,t} = (Y_{ap,t} - \overline{Y}_{ap})/s_{Y_{ap}}$. The value of $T_{ap,t,i}$ for year, i, is calculated by

$$T_{ap,t,i} = s_m Y_{s,ap,t} + \overline{T}_{ap} + T_{ap,anom,i}, \tag{2}$$

where the quantity $T_{ap,anom,i}$ is the anomaly of the apparent temperature for any given year, i, for a specific month of the year, July in our application. The value of $T_{ap,anom,i}$ is calculated from

$$T_{ap,anom,i} = s_a(a_t). \tag{3}$$

Ten-thousand sequences of monthly July daily maxima or minima values of T_{ap} were simulated using various values of the four-parameter model ($\overline{T}_{ap}$, s_a, s_m, r) based on data from O'Hare Airport. Using the simulated July values of daily maximum and minimum T_{ap}, the probability of exceeding

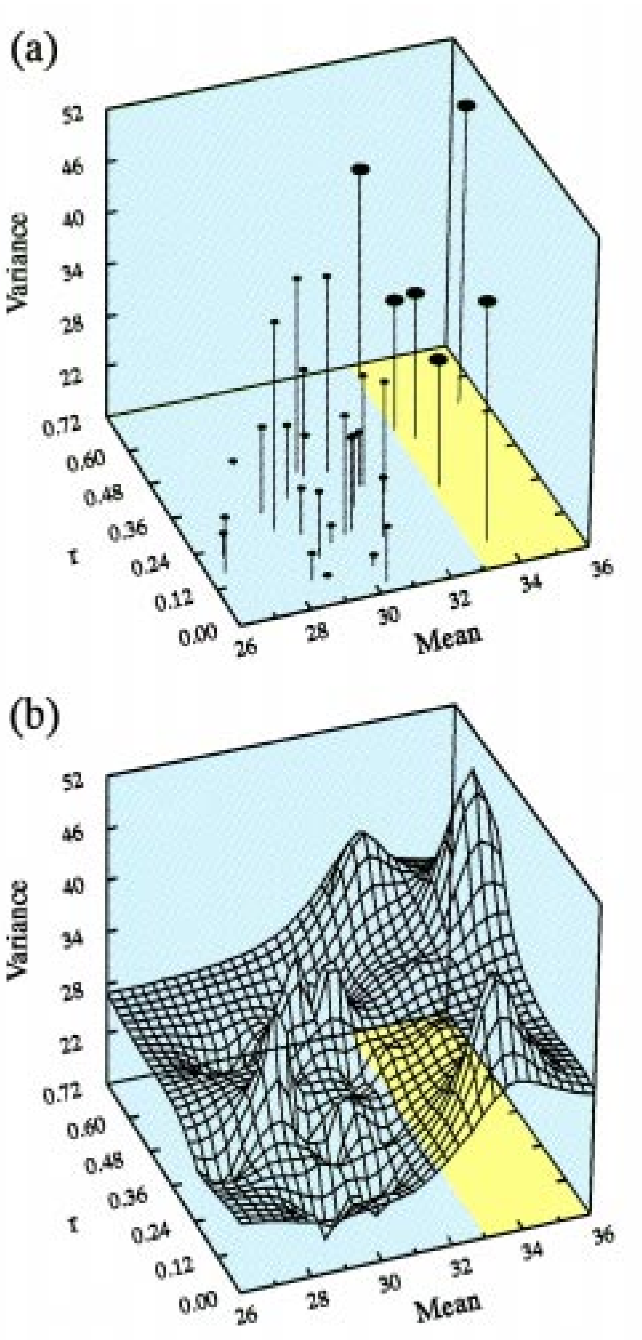


FIG. 3. The three-dimensional space defined by 30 years of Chicago's mean maximum July T_{ap} in degrees C (mean), the variance of July's daily maximum T_{ap} in degrees C (variance), and the lag 1 correlation (r) of these values. (a) The spikes represent calculated values for each year and the spikes with large heads represent a statistically significant cluster, based on tests of r and variance for T_{ap} means below and above 33°C. (b) The three-dimensional surface represented by the observations, where the shaded region represents values with the mean above 33°C.

specific thresholds of temperature can be easily calculated relative to what actually occurred during 1995.

To calculate the probability of exceeding the observed extremes of T_{ap} using the estimates of $\overline{T}_{ap}$, s_a, s_m, and r, a simplifying step could be to assume, for practical purposes, that s_a, s_m, and r are independent of $\overline{T}_{ap}$ over the historical record. Figure 3 strongly suggests this is not a good assumption, at least for July values of maximum T_{ap} in Chicago (similar results are obtained for the minimum). For the daily maximum hourly apparent temperatures, as $\overline{T}_{ap}$ crosses a threshold of about 33°C, both s^2_m and r tend to be higher than would be expected if the quantities were unrelated. The values of s^2_a may also be dependent on $\overline{T}_{ap}$, but the nature of the data does not allow us to adequately test this potential dependency. Clearly, if the average value of r or s^2_m were used to simulate July temperatures, it would quite likely introduce bias into the simulated data.

There are a number of ways to overcome this dependence. One would be to make Eqs. (1) and (2) conditional on $T_{ap,i}$. For example, it is possible to regress the $T_{ap,i}$ with s^2_m and r, and use this relationship to account for any dependence of s^2_m and r with T_{ap}. It is not evident, however, that the relationship is linear or continuous. Instead, we developed a Monte Carlo approach to identify group clusters. We estimate the probability of unique clusters of simultaneous values of $s^2_{m,i}$ and r_i as related to $T_{ap,i}$. We note that sampling errors associated with the calculation of these quantities can lead to cross correlations, but for practical purposes with large enough samples these cross correlations should approach zero. The null hypothesis, therefore, is the variates are not segregated into specific clusters. This is tested by first calculating the standardized departures of the three quantities $s^2_{m,i}$, r_i, and $T_{ap,i}$ for a 30-yr sample of 24-h maximum apparent temperatures (1959–95; the 7 yr that had 3-h data were omitted from this analysis). The standardized departures of the three quantities were summed for each year i and sorted from highest to lowest. This sum is compared to a similar sum obtained by separately randomizing the years i relative to each value of T_{ap}, r, and s^2_m. These sums are also ranked and compared with the observed ranked sums. This is repeated 10 000 times, and the probability is calculated that the sum of the three standardized departures is as large or larger than that observed. These calculations indicate that it is highly unlikely that the variates are independent and the most improbable random cluster (probability less than 0.0001) breaks at $T_{ap} = 33$°C (Fig. 3), which splits the sample of 30 years into a group of 6 and 24 years. Based on this split, separate statistics are calculated for s^2_m and r, and they are used in Eq. (2) based on values of $T_{ap,anom,i}$ falling on either side of the two clusters (Fig. 3). This method is used for both the maximum and minimum daily values of T_{ap} since a separate analysis for the minimum temperature yielded similar results but with a different break point.

4. Results and discussion

a. The stationarity of extreme summer apparent temperatures

In Chicago, the trends of T_{ap} without the 1995 event range from near zero at the lower quantiles (including minimum temperature) for heat island adjusted data to strongly positive (over 1°C decade^{-1}) and highly significant at the higher quantiles, for example, near the maximum temperature (Table 1). The inclusion of the 1995 heat wave in the trend analysis considerably strengthens the trend and makes virtually all of the trends statistically significant except for the lower quantiles (late night and early morning temperatures), which remain small and statistically insignificant. Unlike average trends of the mean temperature across the United States, where the daily mean minimum and the extreme minimum are increasing at a faster rate than the maximum (Karl et al. 1993; Karl et al. 1991), the values of T_{ap} near the daily minimum (lower quantiles) are increasing at a slower rate than those near the maximum upper quantiles. Moreover, the rates of change of the T_{ap} are more or less similar for the 1-day through 3-day events. It is quite likely that this apparent inconsistency is at least partially attributable to the change in instrumentation introduced at all primary National Weather Service stations when the hygrothermometer-83 (HO-83) series replaced the HO-63 series of instruments. Karl et al. (1995) show that, on average, the HO-83 increased the maximum temperature by about 0.5°C relative to the HO-63 instrument and also increased the minimum but only by 0.1°C. Much larger effects have been noted in Tucson, for example (Gall et al. 1992), and Jones and Young (1995) also find a consistent positive bias at several stations they examined in the southern and central plains. This suggests that the trends of maximum T_{ap} in Chicago are biased warm not only due to increased urbanization but by the introduction of the HO-83 instrument in 1986. This will tend to exaggerate the extreme high temperature during the 1995 heat wave, but the HO-83 effect on the minimum temperature may in fact be insignificant.

By comparison, the overall trends of T_{ap} in the Midwest are more moderate than the Chicago result (Table 1). Virtually all of the statistically significant positive trends are associated with non–heat island adjusted data extending through 1995, although there are some significant trends at the higher quantiles. If the HO-83 maximum temperature bias is taken into account, the trends are essentially close to zero, and the trends of the T_{ap} for both the maximum and minimum would be negligible. When allowances are made for an average warm bias of the maximum temperature of 0.5°C, which could be higher at an individual station such as O’Hare Airport, as well as the potential affects of increased urbanization, it would appear that it is difficult to make a compelling case for a nonstationary climate in the Midwest, including Chicago, as related to increases in extreme T_{ap}. Moreover, it is likely that the maximum temperature in Chicago’s 1995 heat wave was exaggerated to some extent, relative to pre-1986 data, and the minimum T_{ap} (lower quantiles in Table 1) shows little trend. The assumption of a stationary climate is difficult to convincingly refute in relation to summer temperatures and heat waves in the Midwest.

b. Sensitivity analysis of the probabilistic model

Prior to exploring the return periods related to the 1995 heat wave relative to current climate statistics or scenarios of future climate change, it is important to understand the sensitivity of various thresholds not only to changes in changes in $\overline{T}_{ap}$ but also to change in s^2_m, s^2_a, and r. This is graphically depicted in Fig. 4. It is apparent that the effect of changing the mean temperature is certainly of major importance, but changes in the daily variability of temperature can be nearly as important with respect to the frequency of the T_{ap} exceeding various thresholds for different durations. For scenarios of change, not unlike those that have already occurred on decadal timescales, changes in the interannual variance have less of an impact on daily extremes compared with comparable changes in daily variance. In reality, the two should be positively correlated, but by no means does the daily variance (synoptic-scale weather variability) completely determine the magnitude of the interannual variability. Although changes in persistence have little impact on short duration 1-day events, they can have a significant impact on the longer duration infrequent events. For example, a 50% increase in persistence (just a

TABLE 1. Trends (°C decade^{-1}) of the minimum (MIN); 25th, 50th, 75th percentiles; and the maximum (MAX) for 1-, 2-, and 3-day hourly values of T_{ap} during the most intense heat wave each summer. The statistical significance of the trends is based on Monte Carlo simulations using the best and second best ARMA model up to order 4. The asterisk (*) denotes the statistical significance of the best model and the pound (#) the second best model. The 0.01 significance level is represented by double symbols and the 0.10 level by a single symbol. The length of the trends is also listed.

	Observed			Heat island adjusted		
Percentiles	**1-day**	**2-day**	**3-day**	**1-day**	**2-day**	**3-day**
Chicago (1959–95)						
Min	0.6**	0.4*	0.1	–0.1	0.0	0.0
25.0	0.8**$^{\#\#}$	1.0**$^{\#\#}$	0.7**$^{\#\#}$	0.2	0.1	0.0
50.0	0.7**$^{\#\#}$	0.7**$^{\#\#}$	0.5*$^{\#}$	0.3*$^{\#}$	0.0	0.1
75.0	1.1**$^{\#\#}$	0.8**$^{\#\#}$	0.6**$^{\#\#}$	1.0**$^{\#\#}$	0.7**$^{\#}$	0.4**$^{\#\#}$
Max	1.4**$^{\#\#}$	1.1**$^{\#\#}$	1.3**$^{\#\#}$	1.4**$^{\#\#}$	1.0**$^{\#\#}$	1.4**$^{\#\#}$
Chicago (1959–94)						
Min	0.2*	0.1	0.0	–0.2	–0.1	0.0
25.0	0.5*$^{\#}$	0.7**$^{\#\#}$	0.5*$^{\#}$	0.1	0.0	0.0
50.0	0.4*$^{\#}$	0.4*$^{\#}$	0.2	0.1	0.1	0.0
75.0	0.9**$^{\#\#}$	0.5$^{\#\#}$	0.3*$^{\#}$	0.9**$^{\#\#}$	0.4**$^{\#\#}$	0.2$^{\#}$
Max	1.2**$^{\#\#}$	0.8**$^{\#\#}$	1.1*$^{\#}$	1.1**$^{\#\#}$	0.8**$^{\#\#}$	1.1**$^{\#\#}$
Midwest (1948–95)						
Min	0.2*$^{\#}$	0.2*$^{\#}$	0.1*$^{\#}$	0.1	0.0	0.0
25.0	0.2*$^{\#}$	0.2*$^{\#}$	0.2*$^{\#}$	0.0	0.1	0.0
50.0	0.2	0.2*$^{\#}$	0.2*$^{\#}$	0.0	0.1	0.0
75.0	0.4*$^{\#}$	0.2*$^{\#}$	0.3*$^{\#}$	0.3*$^{\#}$	0.3	0.2
Max	0.4*$^{\#}$	0.4*$^{\#}$	0.4*$^{\#}$	0.5*$^{\#}$	0.4*	0.4*$^{\#}$
Midwest (1948–94)						
Min	0.2**$^{\#}$	0.1	0.1*	0.0	0.0	0.0
25.0	0.1	0.2	0.1	0.0	0.0	–0.1
50.0	0.0	0.1	0.1	–0.1	0.0	–0.1
75.0	0.2	0.1	0.1	0.2	0.1	0.1
Max	0.3	0.2	0.2	0.3*$^{\#}$	0.2	0.2

small change in r from $r = .27$ to $r = .33$ increases r^2 from .07 to 0.11) substantially reduces the average return period from 1 in 66 yr to 1 in 35 yr as related to the occurrence of 4 consecutive days with the hourly maximum T_{ap} exceeding 40°C (Fig. 4a). For a higher (Fig. 4b) threshold (49°C), a 100% increase in persistence ($r = 0.23$ vs $r = 0.33$) reduces the return period for 2 consecutive days ≥ 49°C from about 1 in 450 yr to about 1 in 150 yr, a substantial reduction for a modest change in persistence.

From these sensitivity experiments it is important to realize that changes in the mean T_{ap} are certainly important with respect to estimating the probability of future heat waves like the 1995 heat wave, but other parameters are also critical, such as the persistence and variance. Our uncertainty about changes in these latter quantities can have just as big an effect as the uncertainty about the impact of doubled atmospheric CO_2 concentrations on global mean temperatures, for example, 1.5°–4.5°C (IPCC 1996b).

c. *Recurrence for the 1995 heat wave in the present climate*

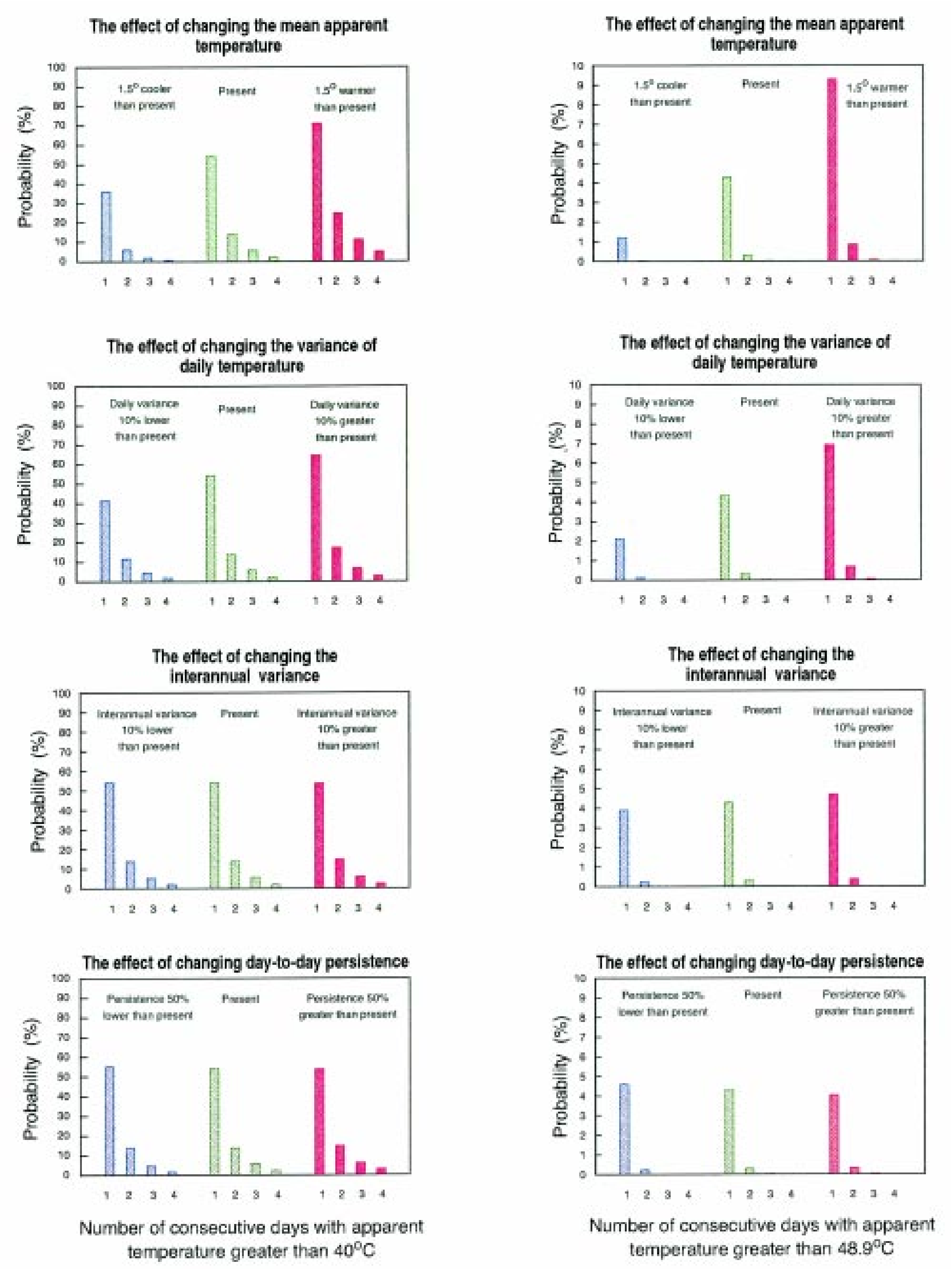
During the 2-days of most intense heat and humidity the hourly apparent temperature reached about 49°C (120°F) on 13 July and almost 48°C (118°F) on 14 July at O'Hare Airport, while the minimum apparent temperature never fell below about 31.5°C (89°F) on 13 July and 34°C (93°F) on 14 July. As suggested by Figs. 1 and 2, the most unusual aspect of the 1995 Chicago heat wave seems to be the combination of extremely high values of the minimum T_{ap} along with unusually high values of the maximum T_{ap}. This subjective judgement is borne out through a probability analysis of the event. As calculated from the probabilities depicted in Fig. 5a, the probability of the T_{ap} exceeding 48.9°C for any given day is above 4% (4.3%), which translates to a return period of about 1 in 23 yr, but for 2 consecutive days exceeding 47.8°C the probability is less than 1%, which equates to a return period of about 1 in 150 yr. Given the likely overestimate of the maximum temperature due to the HO-83 instrument, these probabilities and return periods are likely to be exaggerated, so it would seem that, although the extremely high daytime values of T_{ap} in Chicago were not typical summer extremes, they cannot be considered unusual (probabilities < 1%) and by no means rare events (probabilities < 0.1%). This suggests that the weather-related cause of the large number of fatalities during the heat wave could hardly be primarily due to the high daytime values of the T_{ap} during the 1995 heat wave.

A significantly different scenario unfolds for Chicago related to the lowest temperatures observed during the heat wave on the nights of 13 and 14 July. The probability of having 2 consecutive days with values of the T_{ap} remaining above 31.6°C reflects a very rare event in our simulations (< 0.1%). The possibility of a 1-day event with the minimum T_{ap} remaining at or above 33.9°C is also rare (< 0.1%). Although, there may be many other possibilities why the number of heat-related deaths were so high in Chicago during 1995 compared to previous heat waves, our analysis suggests that the extremely high nighttime values of the T_{ap} that persisted for at least 48 h were unprecedented and quite rare.

Since the minimum temperature is likely to be only marginally affected by the HO-83 warm bias, the only other factor that could have significantly affected the low probabilities would be increases in urbanization over the past 30–40 yr in and around O'Hare Airport. Some idea of the potential effect this might have had on the heat wave can be elucidated through an analysis of the likelihood of such an event in a warmer climate as described in the next section.

d. *Recurrence for the 1995 heat wave in a changed climate*

Projected increases of temperature in the Midwest due to increases in greenhouse gases (IPCC 1996b) suggest an increase of summertime temperature of about 3°C by the end of the next century. Less certain are exactly how the interannual and intramonthly variability may change, as well as the day-to-day persistence of temperature, but there is a suggestion of reduced intramonthly temperature variability. Uncertainties in changes in these quantities produce an expanded uncertainty range of the likelihood of such an event in a warmer climate. Using changes of s_m^2, s_a^2, and r that are bounded by the type of decadal variations seen during the recent century, we can provide some measure of this uncertainty. Figure 5a indicates that with a 3°C increase of temperature, the return period of an extreme 1-day T_{ap} 47.8°C would change from the current 1 in 23 to 1 in every 6 yr, and for the 2-day event from 1 in 150 down to about 1 in 25 yr. The atypical nature of the extremely high values of T_{ap} would not become commonplace but certainly would become frequent enough to remember. Perhaps of greater interest, however, because of the more extreme nature of the record high minimum T_{ap}, the 1-day (2 day) event with the minimum T_{ap} remaining above 33.9°C (31.6°C) continues to be an unusual event with probabilities of occurrence less than 1%. So clearly, even if the temperatures of O'Hare Airport were increased by 3°C, either by urbanization or greenhouse gases, the 1995 heat wave would still not


The effect of changing the mean apparent temperature
1.5° cooler than present
Present
1.5° warmer than present
The effect of changing the variance of daily temperature
Daily variance 10% lower than present
Present
Daily variance 10% greater than present
The effect of changing the interannual variance
Interannual variance 10% lower than present
Present
Interannual variance 10% greater than present
The effect of changing day-to-day persistence
Persistence 50% lower than present
Present
Persistence 50% greater than present
Probability (%)
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
Number of consecutive days with apparent temperature greater than 40°C
Number of consecutive days with apparent temperature greater than 48.9°C

be an event that many would have anticipated.

Since the changes of interannual and intramonthly variability as well as the day-to-day persistence are even less certain than changes in the mean, the range of uncertainty about the frequency of future heat waves under a global warming scenario are substantial. For example, if we knew the mean would increase by 3°C, with a 20% increase in interannual and intramonthly variability, along with a 50% decrease in persistence, the annual probability of the 1995 extreme 1-h T_{ap} of 48.9°C increases sevenfold from just over 4% to 28%, but with opposite changes in variance and persistence, the frequency only doubles to 9%. This latter value is approximately the same as that associated with only a 1.5°C increase in mean temperature, so it is clear that uncertainties about changes in variance and persistence preclude accurate projections of the probabilities of extreme temperatures, even if the change in the mean is accurately projected. A similar characteristic holds for the other thresholds. For 2 consecutive days with the T_{ap} exceeding 47.8°C with a 3°C temperature increase, the frequency of occurrence increases from 0.7% to over 5% with increased variances and reduced persistence but only increases to just over

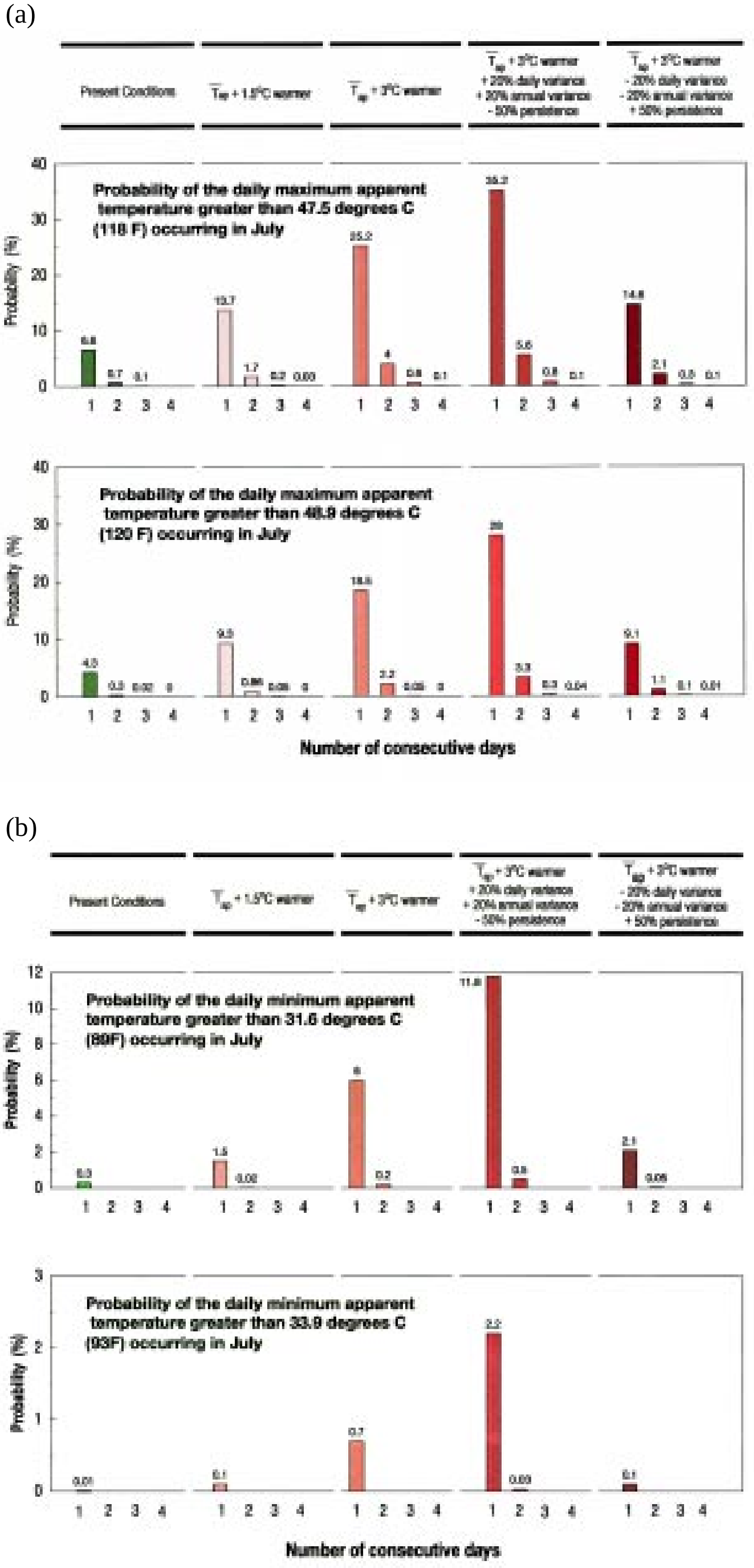


FIG. 4 (opposing page). The sensitivity of univariate changes of $\overline{T}_{ap}$, s^2_m, s^2_a, and r on the probability that any given July would have at least 1 h with T_{ap} exceeding 40°C or 48.9°C for 1, 2, 3, or 4 consecutive days for Chicago (O'Hare).

FIG. 5. For Chicago (O'Hare) the sensitivity of multivariate and univariate changes of the $\overline{T}_{ap}$, s^2_m, s^2_a, and r on the probability that any given July would have at least 1 hour with the T_{ap} exceeding various thresholds for 1, 2, 3, or 4 consecutive days. Thresholds are (a) 48.9°C or 47.8°C for the daily maximum, and (b) 31.6°C or 33.9°C for the daily minimum.

2% for opposite changes of variance and persistence (Fig. 5a).

The effect of increased variance and reduced persistence with a 3°C increase in the $\overline{T}_{ap}$, as related to the frequency of the elevated minimum temperature of the 1995 1-day event (Fig. 5b), is to dramatically increase its frequency of occurrence from $< 0.1\%$ to about 2%. For the 2-day event the frequency increases from $< 0.1\%$ to $< 1\%$. For decreased variance and increased persistence the probabilities remain smaller than those associated with simply a 3°C increase in the mean, but with no change in variance and persistence (Fig. 5b). In fact, the probabilities related to the minimum are also similar to the probabilities associated with a 1.5°C increase in T_{ap} with no change of variance or persistence. The uncertainty introduced simply due to unknown changes in variances and persistence produces a rather large band of potential changes in heat wave frequency, in addition to any uncertainty related to the changes in the mean.

5. Summary and conclusions

Chicago's deadly 1995 heat wave was an unusual event, not so much because of the very high values of T_{ap}, but because of the elevated nighttime apparent temperatures that persisted for 2 consecutive days. No heat wave during the twentieth century was comparable in this respect. The data would suggest that trends of T_{ap} in Chicago are increasing at an appreciably faster rate near the time of the daily maximum temperature compared with times near the minimum, but this is likely to be at least partially, if not fully, due to a change from the HO-63 to the HO-83 instrument that the National Weather Service introduced at all of its primary stations in throughout much of the 1980s. In fact, when consideration is allowed for urbanization affects, changes in instrumentation, the trends of nearby Midwestern cities, the absence of trends in the mean summer temperature, and the exclusion of the 1995 event at the end of the times series, it is difficult to argue that the climate related to extreme heat waves in and around the Chicago area is not stationary. Even in light of these issues, statistical simulations indicate that the severity of the heat wave during 1995 was quite rare, due to the elevated 48-h nighttime temperatures. In fact, it could be argued that although urbanization effects tend to increase the temperature, they also tend to reduce the moisture supply (Landsberg 1981), thereby possibly reducing the T_{ap}.

The duration and intensity of heat waves have been shown to be affected in a significant manner not only by changes in $\overline{T}_{ap}$, but by changes in s^2_m, s^2_a, and r. Depending on the exact combination of increases or decreases in variance and persistence, the return period of the Chicago 1-day extreme high T_{ap} of 48.9°C with a 3°C increase in the mean, ranges from 1 in 3 yr to 1 in 11 yr and for the 2-day event with an T_{ap} of exceeding 47.8°C on each day from 1 in 19 yr to 1 in 45 yr, a significant spread. This compares with the estimated frequency of occurrence for the 1995 extreme high T_{ap}, based on climate statistics since 1959, of just over 4% for the 1-day event and just under 1% for the 2-day event. In contrast, the probabilities of occurrence for minimum values of T_{ap} as high as observed during the 1995 heat wave are significantly smaller. The 24-h record high minimum could not have been anticipated as the percent frequency of occurrence is $< 0.1\%$, and even with a 3°C increase in the minimum temperature it is still $< 1\%$. Moderate increases in the variance and decreases of persistence, along with a 3°C increase of temperature (the latter projected to occur with doubled CO_2 concentrations), increases the probability to nearly 12%. For the observed 2-day minimum temperature event in Chicago, where the minimum T_{ap} remained at or above 31.6°C, we obtained very low probabilities, $< 0.1\%$. Even with increases in the mean temperature of 3°C, and with a plausible increase in variance and reduced persistence, the event is still unusual ($< 1\%$).

In the absence of significant summertime warming, when consideration is given to both the extreme high maximum and extreme high minimum values of T_{ap} during the 1995 event, the Chicago heat wave is not likely to be repeated any time soon. If the projected greenhouse warming (IPCC 1996b) manifests itself in this region, or comparable increases in temperature occur due to urbanization, but with modest decreases in variance (IPCC 1996b), then the frequency of such an event related to the elevated 48-h minimum temperature would still be rare (probability $< 0.1\%$). If, on the other hand, the warming is associated with an increase in variance, then the frequency of such an event related to the maximum T_{ap} would *not* be unusual but still rather uncommon (around 1% likelihood in any summer) as related to the extreme high minimum values of the T_{ap} during the 1995 Chicago heat wave.

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