# Statistical Explanation for Trends in Extreme Summer Temperatures at Phoenix, Arizona

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## ABSTRACT

A reanalysis of the same Phoenix daily minimum and maximum temperature data examined by Balling et al. has been performed. As evidenced by substantial increasing trends in both the mean minimum and maximum temperatures, this area has experienced a marked heat island effect in recent decades. Balling et al. found that a statistical model for climate change in which simply a trend in the mean is permitted is inadequate to explain the observed trend in occurrence of extreme maximum temperatures. The present reanalysis establishes that by allowing for the observed decrease in the standard deviation, the tendency to overestimate the frequency of extreme high-temperature events is reduced. Thus, the urban heat island provides a real-world application in which trends in variability need to be taken into account to anticipate changes in the frequency of extreme events.

## 1. Introduction

The so-called urban heat island refers to a warming that occurs inadvertently as metropolitan areas develop (e.g., Landsberg 1981). Research on the heat island effect has dwelt on average temperatures, with little mention of any changes in variability or in the frequency of extreme events. One notable exception is the work by Balling et al. (1990). They examined the trend in the occurrence of extreme minimum and maximum temperatures during summer at Phoenix, Arizona, an area that has experienced a marked heat island effect in recent decades. Their results established the inadequacy of a statistical model for climate change in which simply a trend in the mean is allowed. Although changes in the mean are apparently sufficient to explain the trend in occurrence of extreme minimum temperatures, such a model overestimates the frequency of extreme maximum temperatures.

Katz (1993) raised the need for a "statistical paradigm" for climate change. As a prototype model, he proposed allowing for at least shifts in both the location and scale parameters of the distribution of a given climate variable (e.g., the mean and standard deviation in the case of a normal distribution). Katz and Brown (1992) relied on such a model for climate change in addressing the issue of the sensitivity of extreme events. By making use of relevant statistical theory, they demonstrated that the frequency of occurrence of extreme events must be relatively more sensitive to changes in variability than in average conditions. In the present context, such considerations would naturally lead one to consider the possibility of a change in the overall variability of daily maximum temperatures in conjunction with the urban heat island.

In section 2, the Phoenix summer daily minimum and maximum temperature data are discussed, with descriptive statistics for extreme low- and high-temperature events being provided. In addition to the well-documented increasing trends in mean minimum and maximum temperatures, possible trends in the corresponding standard deviations are examined. Two statistical models for climate change are formulated in section 3, one in which only a trend in the mean exists, and another in which trends in both the mean and standard deviation are present. Both of these models are applied to the observed time series of the frequency of occurrence of extreme low and high temperatures. Finally, section 4 contains some concluding remarks, stressing the implications for global climate change studies.

## 2. Data and descriptive statistics

We used the daily time series of minimum and maximum temperatures for July–August 1948–1990 (i.e., 62 observations per year) from the U. S. National Weather Service Forecast Office at the Phoenix Sky

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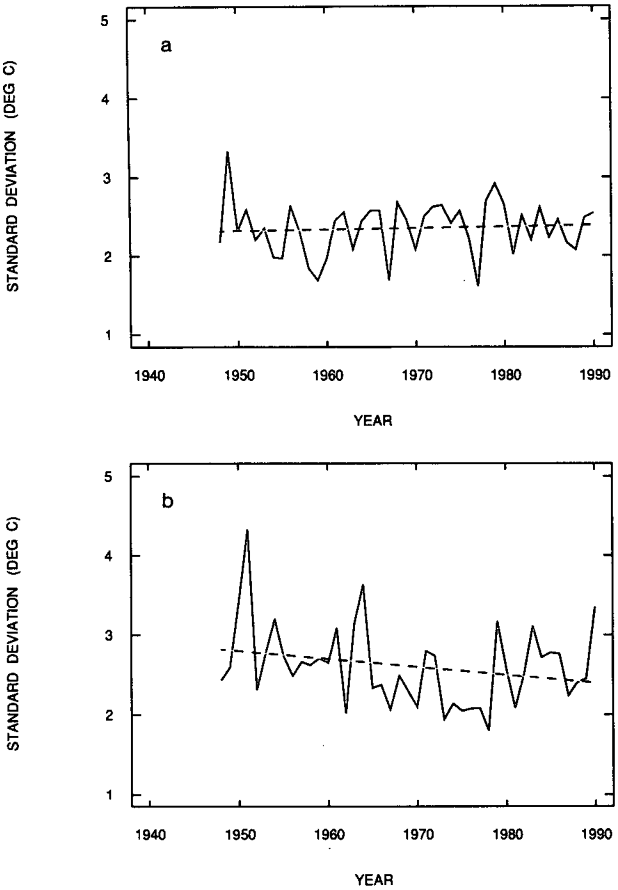

FIG. 1. Time series of standard deviation of daily temperature (solid line), along with trend (dashed line), during July–August at Phoenix, Arizona, for the time period 1948–1990: (a) minimum; and (b) maximum.

Harbor Airport. Except for the addition of the 1989 and 1990 observations, this data set is identical to the one employed by Balling et al. (1990). The station history showed only minor station changes and no missing data for the period. The census population estimates for Phoenix and vicinity exhibit fairly steady increasing trends during this time period, although population size is not a perfect surrogate even for just the mean heat island effect (Landsberg 1981).

Consistent with the findings of Balling et al. (1990), substantial trends are present in both the minimum and, to a lesser extent, maximum mean daily temperatures for July–August. When linear trends are fit to these mean minimum and maximum temperatures, slopes of about 0.0980° and 0.0427°C per year, respectively, are obtained. Such a decrease in mean diurnal temperature range is a feature typical of the urban heat island (Landsberg 1981). Figure 1 shows the corresponding time series of the standard deviation of daily minimum and maximum temperatures. In this case, linear trends of about 0.0018° and −0.0100°C per year, respectively, (also shown in Fig. 1) are obtained (statistics *not* reported by Balling et al. 1990). Although these observed trends in variability may appear to be relatively small (not statistically significant for minimum temperature, borderline significance with $p$ value of ~10% for maximum temperature), the frequency of extreme events is known to be quite sensitive to any such changes (Katz and Brown 1992). Rather than focus on the outcomes of formal tests of statistical significance, the practical significance of these apparent trends in variability will be evaluated in section 3 in terms of their effect on the frequency of extremes.

To demonstrate the extent to which the relative frequency of occurrence of extreme low- and high-temperature events has changed, we divided the data into two time periods, 1948–1968 and 1969–1990. Table 1 shows the relative frequency of the daily minimum temperature falling below and of the maximum exceeding certain fixed thresholds. In concert with the mean warming effect (and in agreement with Balling et al. 1990), the frequency of extreme low (high) temperatures has decreased (increased). Histograms (not shown) for both minimum and maximum daily temperatures are reasonably close to the normal distribution in each of these two time periods, with a small degree of negative skewness being evident for maximum temperature. The observed changes in frequency for the minimum temperature are somewhat larger than the corresponding ones for the maximum. For instance, the odds of the minimum temperature falling below 22.5°C have decreased by more than a factor of 5 (from about 1 in 5 to about 1 in 26), whereas the odds of the maximum temperature exceeding 44.2°C have roughly doubled (from about 1 in 28 to about 1

TABLE 1. Relative frequency of extreme minimum and maximum daily temperatures during July–August at Phoenix, Arizona, for the two time periods, 1948–1968 and 1969–1990.

| Extreme event threshold $c$ (°C) | Relative frequency (%) (1948–1968) | Relative frequency (%) (1969–1990) |
|---|---|---|
| *Minimum* ($<c$) | | |
| 24.7 | 43.8 | 16.1 |
| 23.6 | 28.3 | 8.0 |
| 22.5 | 16.2 | 3.7 |
| 21.4 | 6.4 | 1.1 |
| 20.3 | 4.6 | 0.2 |
| 19.2 | 1.9 | 0.0 |
| 18.1 | 1.0 | 0.0 |
| 16.9 | 0.4 | 0.0 |
| *Maximum* ($>c$) | | |
| 41.9 | 19.9 | 30.0 |
| 43.1 | 9.9 | 17.7 |
| 44.2 | 3.4 | 6.6 |
| 45.3 | 0.7 | 2.1 |
| 46.4 | 0.2 | 0.4 |
| 47.5 | 0.1 | 0.1 |

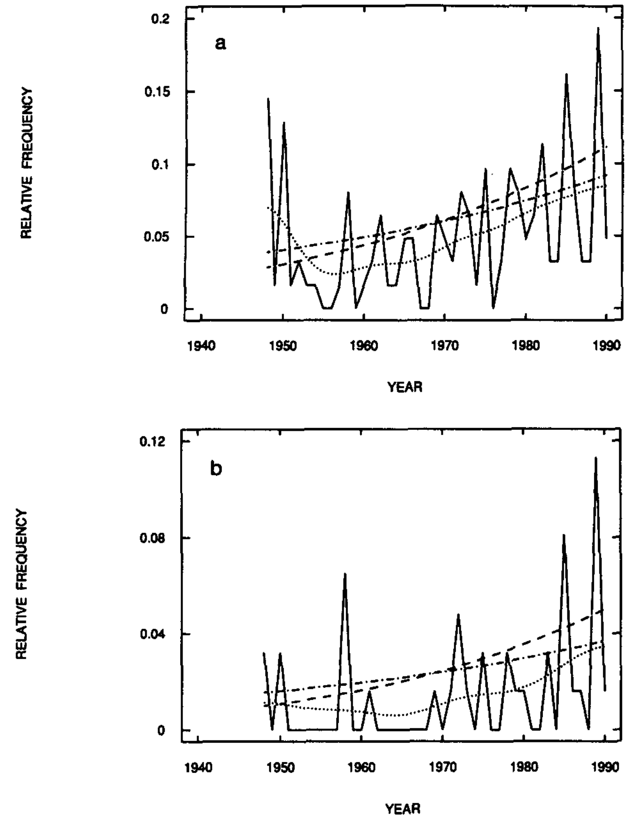

FIG. 2. Probability of extreme event, maximum temperature on a given day in July–August at Phoenix, Arizona, exceeding a threshold $c$, for time period 1948–1990. Observed relative frequency (solid line), smoothed (using repeated hanning) relative frequency (dotted line), Model 1 (changing mean, but constant standard deviation) estimate (dashed line), and Model 2 (changing mean and standard deviation) estimate (dot-dashed line): (a) $c = 44.2°C$; and (b) $c = 45.3°C$.

in 14). In the next section, we examine these trends in the frequency of extreme temperatures in greater detail, treating them on an annual timescale instead of over approximately 20-yr time periods.

## 3. Statistical models for climate change

Balling et al. (1990) have shown that the observed trend in the frequency of extreme high temperatures during summer at Phoenix is overestimated if the distribution of daily maximum temperature is simply shifted as indicated by the trend in the mean alone. Our goal is to establish whether a simple statistical model that allows for changes in variability, as well as in the mean, would more realistically represent the trend in the observed frequency of extreme high temperature events. For comparative purposes, the trend in the frequency of extreme low temperatures is treated as well.

### *a. Description of models*

To simplify matters, normal distributions are assumed for both daily minimum and maximum temperatures. Here we let $\Phi(x; \mu, \sigma)$ denote the probability distribution function for a normal distribution with mean $\mu$ and standard deviation $\sigma$. That is, the probability that the maximum temperature $X$ exceeds a fixed threshold $c$ on a given day within the summer of the $t$th year can be expressed as

$$\Pr\{X > c\} = 1 - \Phi(c; \mu_t, \sigma_t), \qquad (1)$$

where $\mu_t$ denotes the mean and $\sigma_t$ the standard deviation for the $t$th year. The probability that the daily minimum temperature falls below a threshold is determined in a completely analogous manner.

In the following two models, specific assumptions are made about whether and how these means and standard deviations actually depend on the year $t$. For simplicity, any effect of the annual cycle on the mean and standard deviation within the July–August time period of a given year is ignored. Although the normal distribution is known to provide a reasonable overall approximation for daily minimum and maximum temperatures, some evidence of departures from normality in the extreme tails exists as was noted in section 2 (also see Brown and Katz 1995).

*Model 1 (changing mean, constant standard deviation):* A linear trend for the mean is assumed; that is,

$$\mu_t = a + b(t - 1948),$$

$$t = 1948, 1949, \cdots, 1990. \qquad (2)$$

The least-squares estimates of this trend line (2) are $a = 24.17°C$ and $b = 0.0980°C$ for the minimum temperature; $a = 39.19°C$ and $b = 0.0427°C$ per year for the maximum. On the other hand, the standard deviation is held constant over the entire time period of

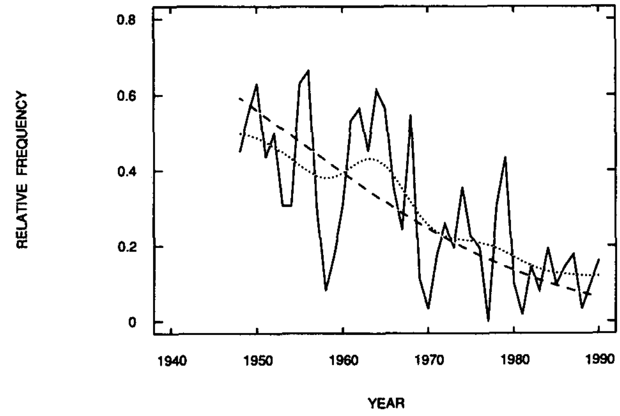

FIG. 3. Same as Fig. 2 except for extreme event, daily minimum temperature falling below $c = 24.7°C$, and curve for Model 2 not included.

1948–1990 ($\sigma_t = \sigma$ say). To adjust for the trend in the mean over this period, this constant standard deviation is estimated by averaging the individual standard deviations for the 43 years (the estimate of $\sigma$ is 2.34°C for the minimum and 2.61°C for the maximum).

*Model 2 (changing mean and standard deviation):* The same linear trend for the mean is employed as in Model 1. But now the standard deviation is also permitted to change linearly over time; that is,

$$\sigma_t = a^* + b^*(t - 1948), \quad t = 1948, 1949, \cdots, 1990. \quad (3)$$

The least-squares estimates of this trend line (3) are $a^* = 2.31$°C and $b^* = 0.0018$°C per year for the minimum temperature, $a^* = 2.82$°C and $b^* = -0.0100$°C per year for the maximum.

### *b. Application of models*

The probabilities of the extreme high temperature events listed in Table 1 were estimated under Models 1 and 2 by making use of the normal distribution (1). Figure 2 shows the results for two particular threshold values $c = 44.2$ (Fig. 2a) and 45.3°C (Fig. 2b). Even though the changes imposed on the means and standard deviations are linear, the fact that the relationship between the probability of extremes and the mean or standard deviation is highly nonlinear (Mearns et al. 1984) helps to explain the shapes of these two curves. Also included in Fig. 2 are the time series of the observed relative frequency of occurrence of these same high temperature events. To remove some of the year to year fluctuations attributable to sampling error, smoothed versions of these time series obtained by repeated use of hanning (i.e., a local smoother involving weights ¼, ½, and ¼; see Tukey 1977) were produced as well (see Fig. 2). It is evident that the extent of overestimation noted by Balling et al. (1990) is somewhat diminished when a trend in the standard deviation is permitted. Some of the remaining overestimation might be attributable to the right-hand tail of the distribution of daily maximum temperature being "lighter" than the normal (as was mentioned in section 2). Another way to possibly improve the models would be to fit more complex, nonlinear trends to the mean or standard deviation.

The probabilities of the extreme low temperature events listed in Table 1 were also estimated under Models 1 and 2. Figure 3 shows the results for one particular threshold value $c = 24.7$°C. The decrease in relative frequency is much more rapid than the corresponding rates of increase in Fig. 2 for extreme high temperatures. Nevertheless, Model 1 matches the observed trend reasonably well. Because the observed trend in standard deviation is so small, Model 2 is virtually indistinguishable from Model 1 and is not included in Fig. 3. The results presented are consistent with those obtained for other extreme low and high temperature event thresholds.

## 4. Concluding remarks

The urban heat island provides a real-world application in which trends in variability need to be taken into account to anticipate changes in the frequency of extreme events. Being situated in a desert region, the heat island effect for Phoenix is not necessarily typical of that for other urban areas. It would be of interest to determine whether other urban environments have experienced comparable trends in the standard deviation of minimum or maximum daily temperatures. Given that a decrease in mean diurnal temperature range has also occurred outside of urban areas (Karl et al. 1993), it would be worthwhile to examine whether these regions have experienced corresponding trends in standard deviations and in the frequency of extremes.

This example does provide convincing evidence of the need for a statistical model for climate change that allows for changes in variability, as well as in average conditions [as previously argued by Katz (1993)]. It calls into question the use of statistical models for climate change in which simply the mean is changed [e.g., as employed by Hansen et al. (1988)]. The urban heat island, of course, is not necessarily perfectly analogous to other climate changes such as the enhanced greenhouse effect. Ideally, more attention should be focused on whether the variability of temperature changes in experiments with general circulation models, as well as in the observed records of stations, has not been contaminated by the heat island effect. Nevertheless, the general value of analogs in assessing the impact of climate change on society has been recognized by Glantz (1988), with Changnon (1992) having advocated the use of the urban heat island.

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