Vol. 55: 201–215, 2013
doi: 10.3354/cr01130

CLIMATE RESEARCH
Clim Res

Published online January 10

Historical threshold temperatures for Phoenix (urban) and Gila Bend (desert), central Arizona, USA

D. Ruddell[1,*], D. Hoffman[2], O. Ahmad[3], A. Brazel[4]

[1]Spatial Sciences Institute, University of Southern California, Los Angeles, California 90089-0374, USA
[2]School of Natural Resources and Environment, University of Michigan, Ann Arbor, Michigan 48109-1041, USA
[3]School of Sustainability, Arizona State University, Tempe, Arizona 85287-5502, USA
[4]School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, Arizona 85287-5302, USA

ABSTRACT: Several critically important temperature thresholds are experienced in the climate of the desert southwest USA and in central Arizona. These thresholds present significant and increasing challenges to social systems. Utilizing daily surface air temperature records from Phoenix and Gila Bend regional weather stations from 1900–2007, we examined 3 temperature thresholds: (1) frost days (minimum temperature < 0°C); (2) misery days (maximum temperature ≥43.3°C); and (3) local characteristics of heat waves. We investigated historic climate patterns in addition to considering the human implications associated with these changes. Analyses also integrated multidecadal modes of the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Key findings of this study were (1) uneven warming trends among temperature thresholds between the Phoenix (pronounced warming) and Gila Bend (modest warming) weather stations; (2) disjointed associations between ENSO and PDO with frost and misery days, signaling anthropogenic interference between temperature thresholds and historic atmospheric processes; (3) variable effects of ENSO and PDO modulations on annual frost and misery days; (4) evidence of urbanization suppressing local effects of global climate systems (i.e. ENSO, PDO); and (5) potentially significant and widespread adverse impacts on many local environmental, economic, and social systems as a result of changes in threshold temperatures.

KEY WORDS: Temperature thresholds · Urban heat island · Phoenix · Gila Bend · Coupled natural-human systems

1. INTRODUCTION

The Sonoran Desert of central Arizona (Fig. 1) experiences temporal variability of critically important threshold temperatures during the temperate winter months as well as the warm summer season. Although freezing temperatures (which occur throughout the region; Meehl et al. 2004) rarely last for more than a few hours in a given day, frost days are vital to Sonoran Desert vegetation because they help regulate competition amongst the drought-resistant species that can survive in the region (Shreve 1934, Weiss & Overpeck 2005). In contrast to frost days, summers in central Arizona are characterized by extremely hot temperatures. Daily maximum temperatures regularly reach and exceed 43.3°C (110°F), which are locally referred to as misery days, because they exceed a threshold of excessive exposure to heat (Karl et al. 2009), stressing local natural and social systems. For instance, high summer temperatures inhibit photosynthesis and reduce both water-use efficiency among local vegetation (Martin et al. 1995, Huxman et al. 1998) and agricultural productivity (Brown 2001), while increasing human vulnerability to heat stress (Baker et al. 2002, Harlan et al. 2006).

While scientists commonly analyze minimum, maximum, and average temperature in climate change and/or urban heat island research, recent studies have also considered weather and climate extremes

*Email: druddell@usc.edu

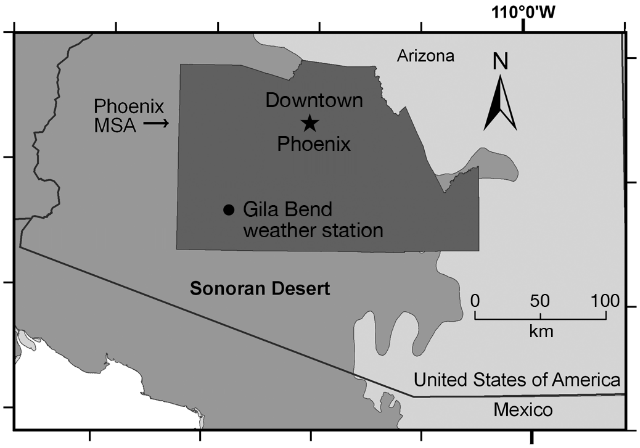

Fig. 1. Metropolitan Phoenix, Arizona (dark gray: Phoenix metropolitan statistical area [MSA]) and surrounding area. Mid-gray: Sonoran Desert

(e.g. freezing temperatures, heat waves), in order to better understand physical changes in climate as well as the likely effects of a changing climate on social and ecological systems (Kunkel et al. 1999, Parmesan et al. 2000, Meehl et al. 2004, Ebi & Meehl 2007). Meehl et al. (2004), for instance, examined trends in the number of frost days throughout the contiguous USA and found a decreasing trend throughout the study area, particularly in the western and southwestern regions of the USA. The authors identified changes in sea level pressure, regional scale atmospheric circulation changes, and increased soil moisture and clouds as leading drivers of changes in the occurrence of frost days. Frost days are particularly important in terms of controlling disease and pest outbreaks, so a significant reduction in frost days is likely associated with increased numbers of insects and pests as well as increased breeding days (Gage et al. 2008).

Baker et al. (2002) investigated historical changes in the occurrence of intense heat, partially explained by urban heat island effects, in metropolitan Phoenix, Arizona. The study employed the Temperature-Humidity Index (THI), also known as the Heat Index (Thom 1959), as a measure of human comfort. Although there is no one exact temperature that correlates with heat-related illness for all people in all locations, Baker et al. (2002) used 38°C (or 100°F) as the temperature threshold, a value which the National Weather Service (NWS) classifies as within the range of 'danger' with regard to sunstroke, heat cramps, and heat exhaustion, in association with prolonged exposure and/or physical activity (NWS 2002). Baker et al. (2002) examined the number of so-called misery hours when the THI was >38°C at Sky Harbor (Phoenix's regional weather station) from 1948–2000, and found that the average number of misery hours per day nearly doubled from 1.8 to 3.4 between May and September. This analysis was highlighted in the report on global climate change impacts in the USA as illustrating the importance of heat extremes to quality of life in the southwest (Karl et al. 2009, p. 103). Thus, exposure to elevated and potentially dangerous temperatures significantly increased throughout Phoenix over the second half of the 20th century (Booth et al. 2011).

Increasing attention has been paid to the physical and social conditions of heat waves. For example, Meehl & Tebaldi (2004) modeled spatial and temporal characteristics of heat waves in Europe and North America and found projected warming trends throughout the 21st century. Their analyses projected that heat waves are likely to be more intense, more frequent, and longer lasting by the second half of the 21st century. The study concluded that areas already experiencing strong heat waves (e.g. the US Midwest, southwest and southeast USA, and the Mediterranean region) will likely experience more intense heat waves in the future, while areas not well adapted to heat waves (e.g. northwest USA, France, Germany, and the Balkans) could see an increase in heat wave intensity which may thus have adverse effects.

Research also shows that extended periods of elevated temperatures can have severe impacts on human health and well-being. For instance, more people die in the USA from extreme heat than any other weather-related phenomenon (CDC 2006, Kalkstein & Sheridan 2007) and very hot weather increases mortality rates as well as hospital admissions for cardiovascular, respiratory, and other pre-existing illnesses (Semenza et al. 1999). Two recent heat waves illustrate the dangerous impacts of excessive exposure to extreme heat: (1) the Chicago heat wave in July of 1995 claimed over 700 lives (Semenza et al. 1996, Klinenberg 2002); and (2) the 2003 heat wave in Europe resulted in between 22 000 and 52 000 deaths, many of them in large cities (Larson 2006).

Global climate patterns help explain the seasonal and historical variability of threshold temperatures. Modes of variability such as the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) express identifiable characteristics at spatially and temporally explicit scales of analysis, which are highly correlated with historical temperature trends throughout the southwest USA (Cayan & Redmond 1994). In general, the influence of ENSO is such that the warm phase (El Niño) corresponds with heavy precipitation throughout the southwest, while the cool phase (La Niña) is associated with drier conditions (Cayan et al. 1999, Brazel & Ellis 2003). High precipitation is associated with warmer seasonal and annual temperatures while low precipitation is correlated with cooler temperatures (Pagano et al. 1999, Brazel & Ellis 2003). Similarly, the PDO index records significant fluctuations in North Pacific sea surface temperature (SST) (Mantua & Hare 2002). The PDO is a widely used measure of decadal variability and climate anomalies in the Northern Hemisphere, and conforms to one of 2 general patterns: the warm (positive) phase and the cool (negative) phase (Schneider & Cornuelle 2005). The PDO signature in the southwest is such that the warm phase coincides with anomalously wet periods; the cool phase has no definitive influence on temperatures in the region (Mantua & Hare 2002). ENSO and PDO modulations have been found to significantly impact North American climate (Mantua et al. 1997, Gershunov & Barnett 1998; Newman et al. 2003).

In addition to these fluctuations, the urban heat island (UHI) effect must also be considered when investigating trends in threshold temperatures in a large metropolitan environment. There are 2 principal drivers of the UHI: land-use/land-cover change, and anthropogenic heat. The conversion of native landscapes into urban land-uses (parking lots, buildings, neighborhoods) alters the surface energy balance and inhibits surface cooling. Engineered surfaces and building materials absorb and retain heat throughout the day via high heat capacity and thermal conductivity, which translates to warmer near-surface air temperatures in the city compared to areas with the natural land cover and agricultural land uses that preceded urbanization (Oke 1982, Arnfield 2003, Brazel et al. 2000). The second driver of UHI is anthropogenic heat (e.g. automobiles, industrial plants, air conditioners, among other sources), which emit heat into the air near the urban surface (Grossman-Clarke et al. 2005). Combined, these processes have been found to significantly raise nighttime temperatures (Lowry 1967, Oke 1997, Voogt 2002). Daytime temperatures may be less than nearby desert temperatures due to moist, vegetated land cover (Brazel et al. 2000). A study by Brazel et al. (2007) found strong correlations between urban development and increased warm season daily minimum and maximum temperatures throughout metropolitan Phoenix. Thus, urbanization is partially responsible for increased daily maximum temperatures in Phoenix.

The aims of this study were twofold: (1) to investigate temporal variability in the occurrence of threshold temperatures in central Arizona by comparing temperature trends from Phoenix (an urban site) and Gila Bend (a desert site); and (2) to consider the effects that changes in the occurrence of threshold temperatures may have on social and ecological systems. Germane to this research effort was appreciating both the physical and social dimensions of historical temperature thresholds between the study sites. This study was part of a larger coupled natural and human systems project that is investigating urban vulnerability to climate change using a systems dynamic modeling approach. This study also represents one of few studies (to our knowledge) examining the combined effect of local-scale climate phenomena (UHI) and regional-scale teleconnections on climate vulnerability metrics (Brazel & Ellis 2003). Research questions informing this study were (1) What historical (annual and decadal) trends occurred in the number of frost days and misery days for the Phoenix and Gila Bend weather stations between 1900 and 2007? (2) What were the historical temperature thresholds of heat waves (as defined by Meehl & Tebaldi 2004) during this period? (3) To what degree do global climate circulation patterns (ENSO and PDO) explain historical variability of frost days and misery days?

2. RESEARCH METHODOLOGY AND DATA

2.1. Study area

Central Arizona is predominantly undisturbed native Sonoran Desert; however, large portions of the region have been, and continue to be, converted to urban development. This study focused on 2 particular locations within central Arizona: Phoenix and Gila Bend.

The city of Phoenix was established in 1865 near the confluence of the Salt and Gila Rivers. With a climate and terrain favorable for agriculture production, the federal government's 1902 National Reclamation Act helped establish a local economy based on cotton and citrus farming, which stimulated local population growth and land-use/land-cover change (Reisner 1986). The population of Phoenix grew from 240 people in 1870 to over 4.2 million residents throughout the metropolitan statistical area (MSA) in 2008 (Table 1). As Phoenix developed, agricultural cropland gave way to suburban development and a new economy based on technology and telecom-

Table 1. Historic population of Phoenix (Arizona) metropolitan statistical area (MSA) from 1870–2008

Year	Population: City of Phoenix	Population: Phoenix MSA	Percent change: City of Phoenix	Percent change: Phoenix MSA
1870	240	–	–	–
1880	1708	–	611.7	–
1890	3152	–	84.5	–
1900	5544	–	75.9	–
1910	11 314	–	104.1	–
1920	29 053	–	156.8	–
1930	48 118	–	65.6	–
1940	65 414	–	35.9	–
1950	106 818	–	63.3	–
1960	439 170	726 183	311.1	–
1970	581 572	1 039 807	32.4	43.2
1980	789 704	1 599 970	35.8	53.9
1990	983 403	2 238 480	24.5	39.9
2000	1 321 045	3 251 876	34.3	45.3
2008	1 567 924	4 281 899	18.7	31.7

munications companies, research institutions, and tourism (Gober 2006). Although Phoenix has been transformed from a natural desert environment to an urban oasis, large-scale population growth and urban development have been a mixed blessing. While growth has provided a valuable economic base for the city, the transformation of the fragile Sonoran Desert ecosystem into an urban metropolis has resulted in significant changes in regional temperatures. Phoenix's UHI, for example, has steadily expanded and intensified over the last forty years, and these changes in physical conditions present serious risks and challenges to the health and well-being of local residents (Balling & Brazel 1987, Harlan et al. 2006, Brazel et al. 2007, Grossman-Clarke et al. 2010).

Gila Bend is a small town 52 miles southwest of Phoenix. Founded in 1872, Gila Bend served as an important nexus for trade and transportation throughout the greater southwest. Although trade was central to the development of Gila Bend, the area has remained native desert landscape and has consistently supported a small population (1980 people reported in the 2000 Census). Gila Bend was selected as a comparative site to Phoenix for 3 reasons: (1) the desert (non-urban) landscape; (2) the relative proximity to Phoenix (52 miles); and (3) the long-standing temperature records (1892 to present).

2.2. Temperature records

The study used data from NWS's regional weather stations at Phoenix and Gila Bend (Table 2). The Phoenix data were provided by the Arizona State Climate Office and represent a threaded dataset from 1900–2007. The data were reconstructed from Phoenix's first-order weather station, Sky Harbor International Airport (1933 to present), and from the Phoenix City weather station (1895–1998). The 2 weather stations are in close proximity and the environmental characteristics were nearly identical until Phoenix's rapid urban expansion began in the 1950s. Records from the 2 weather stations were used to construct the threaded dataset for Phoenix, with the Phoenix City station providing daily data from 1900 to the end of 1953, while temperature readings from Sky Harbor were used from 1954 onwards to present (2007). Data from the period of overlap between the 2 weather stations (1933–1953) show a strong association, with a Pearson's bivariate correlation coefficient of 0.996 for maximum temperatures and 0.990 for minimum temperatures. Data for Gila Bend were accessed from the National Climatic Data Center (www7.ncdc.noaa.gov/CDO/dataproduct). Minimum and maximum temperatures were examined from 1900–2007.

The 108-yr temporal period offers insight into historical patterns of threshold temperatures throughout the region. Specifically, we examined 3 temperature indices: (1) frost days, (2) misery days, and (3) heat waves. The 108-yr data record was also divided into 3 discrete time series to investigate potential effects of urbanization at the Phoenix weather station. The 3 temporal periods are (1) the full historical dataset; (2) the era before large-scale urban development, when the population of metropolitan Phoenix was <1 million (Period 1: 1900–1969); and (3) the era following large-scale urban development (Period 2: 1970–2007). Analyses therefore provide insight into the occurrence of threshold temperatures over time in addition to elucidating an urban effect in temperature trends. This partitioning between pre- and post-urban peri-

Table 2. Characteristics of Phoenix City, Sky Harbor, and Gila Bend weather stations

Weather station	Operational period	Latitude	Longitude	Elevation (m)	Land use
Phoenix City	1895–1998	33° 27′ N	112° 05′ W	334	Urban
Sky Harbor	1933–Present	33° 26′ N	112° 00′ W	337	Urban
Gila Bend	1892–Present	32° 56′ N	112° 42′ W	224	Desert

ods was also adopted in a detailed analysis of the Phoenix Sky Harbor Airport NWS temperature record by Svoma & Brazel (2010).

2.3. Frost days and misery days

Frost days are defined as days when the nighttime minimum temperature is <0°C (<32°F) (Meehl et al. 2004, Weiss & Overpeck 2005). Misery days are defined as days when the maximum temperature is ≥43.3°C (110°F). The daily maximum temperature of 43.3°C is a metric of excessive heat in metropolitan Phoenix commonly used by the NWS, and the THI classifies exposure to 43.3°C, at all humidity levels, as provoking 'extreme danger' in the context of heat-related illness (NWS 2002).

2.4. Threshold temperatures of heat waves

In addition to examining frost days and misery days, we also analyzed threshold temperatures of heat waves, as defined by Meehl & Tebaldi (2004). Although the literature currently lacks a generally accepted method for determining heat waves, we used the approach introduced by Meehl & Tebaldi (2004) as it takes historical temperatures and local temperature variability into consideration when calculating local temperature thresholds, which are then used to identify extreme heat events. This method also enables researchers to study important characteristics of heat waves, such as the intensity, frequency, and duration of heat events, as opposed to some other methods which simply examine the 3 hottest days for a given year.

The process of identifying heat waves was divided into 3 steps: (1) determine historical temperature variability; (2) compare a given year to historical temperatures; and (3) identify extreme heat events based on 3 temperature threshold criteria (see below, this subsection). Step 1 in the analysis was to examine historical temperature records to determine normal conditions. Normal conditions were calculated with the dataset divided into 30 yr blocks (e.g. 1901–1930). For Step 2, we compared the distribution of observed temperature readings for each year in a given decade to the preceding 30 yr normal. In Step 3 we identified extreme heat events, which was accomplished by comparing temperature readings within a given decade to threshold temperatures associated with the preceding 30 yr normal. For instance, all the years from 1941–1950 were compared to the 30 yr normal of 1911–1940. To qualify as an extreme heat event, threshold temperatures T1 (the 97.5 percentile of normal conditions) and T2 (the 81 percentile) must satisfy all 3 of the following conditions: (1) daily maximum temperature must be above T1 for at least 3 d; (2) average daily maximum temperature must be above T1 for the entire period; and (3) daily maximum temperature must be above T2 for the entire period.

2.5. Teleconnection indices

Trends in ENSO and PDO indices were investigated and compared with the occurrence of threshold temperatures. ENSO data from El Niño Region 3.4 (120–170° W and 5° S–5° N) were examined from 1900–2007 (Trenberth 1997); data were provided by the National Center for Atmospheric Research (NCAR) Climate Analysis Section (CAS). PDO data for the years 1900–2007 were provided by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) (http://jisao.washington.edu). ENSO and PDO index values were reported at a monthly time-step, and moving averages were calculated from mean average sea surface temperature.

2.6. Hurst rescaling analysis

Hurst rescaling can be used to find regime shifts for time-series data (Mandelbrot & Wallis 1969, Outcalt et al. 1997, Runnalls & Oke 2006). Runnalls & Oke (2006) show this technique adequately reveals details about local changes at a particular weather station (to location or surrounding land cover), in addition to signaling larger-scale changes such as regional land-cover change (urbanization) or major atmospheric regime shifts (e.g. PDO). The method is similar to the Rodionov (2004) and Rodionov & Overland (2005) regime shift detection method that has been used to determine impacts of large-scale climate system regime shifts and impacts on ecosystems; and has been applied by Elliott & Kipfmueller (2011) in a multiscale study of intraregional variability and bioclimatic thresholds in response to 20th century warming of the southern Rocky Mountains region. Both the Hurst and the Rodionov method employ cumulative sums of normalized deviations from the mean value of a time series to detect regime shifts.

The Hurst rescaling method involves subtracting the mean of a time series from each of the observations (the present study examined frost days and misery days per year). The deviations from the mean of the time series are accumulated, which then produce a transformed time series, Q_i. For the time series of misery days or frost days (A,F), for example:

$$Q_i = \sum_{i=1}^{i}(A_i, F_i - A, F) \tag{1}$$

By definition in the Hurst rescaling approach, $r_n = Q_{max} - Q_{min}$, where r_n is the adjusted range of the series of n observations and Q_{max} and Q_{min} are the maximum and minimum values of Q_i. The rescaled range is r_n/s, where s is the standard deviation of the original time series. The rescaled range increases asymptotically with the square root of the number of observations, i.e. $r_n/s \sim n^H$, and H, the Hurst exponent, can be approximated (Outcalt et al. 1997) as $H = \log(r_n/s)/\log(n)$.

H normally has a value of 0.5 for a stationary series, indicating the cumulative series is a random walk. A value of H between about 0.6 and 0.9 yields a situation termed the Hurst phenomenon (Outcalt et al. 1997). These higher H values are typical of persistence and nonstationarity in the record mean, or of having pooled samples with different distribution characteristics (Outcalt et al. 1997). The cumulative deviations from the mean, when normalized by the adjusted range of the series $(Q_i - Q_{min})/r_n$, can be plotted and visually inspected to identify distinct physical regimes (Outcalt et al. 1997). Regime transitions can be seen as inflection points in the normalized series. A period of above-average values is seen as an ascending trace, due to positive differences from the mean accumulating. A change to below-average values is marked by an inflection point. Typically, a steeper slope results from larger deviations from the mean. Therefore, changes in either the magnitude or sign of the slope signal regime transitions. If, for a series, $H = 0.5$, then inflection points on the rescaled trace are not significant; that is, the series are considered homogeneous (Runnalls & Oke, 2006). However, if $H > 0.5$, the rescaled trace of inflections signals a significant change in the series. Changes in the size or sign of the slope mean there are either regime shifts or changes in station characteristics of some kind (e.g. surface type, equipment, locale change).

2.7. Procedures

Data analyses were organized into 3 phases, as explained above. The first phase of the analysis tabulated the 3 measures of temperature thresholds for the 108 yr climate record for both the Phoenix and Gila Bend regional weather stations. The annual occurrence of frost and misery days was calculated in addition to local heat wave thresholds. The second phase of analysis investigated correlations between ENSO and PDO indices and the historical occurrence of temperature thresholds. The frost and misery days data were detrended (i.e. residuals were calculated from the regression line for each year), and a Pearson's bivariate correlation was calculated between the ENSO and PDO and the detrended frost and misery days at the monthly time step from 1900–2007. A paired-sample t-test was used to test for statistical differences between the pre-urban (1900–1969) and post-urban (1970–2007) variable pairs. The influences of ENSO and PDO phases on annual frost and misery days were also examined. The Hurst rescaling procedure was the third and final phase of analysis, which investigated data homogeneity among the time series.

3. RESULTS

3.1. Frost and misery days

Fig. 2 shows a time series of the annual number of frost days and misery days recorded at Phoenix and Gila Bend weather stations from 1900–2007 while Table 3 provides summary statistics. Results showed 3 distinct findings. (1) Absolute temperatures are considerably different between the 2 regional weather stations: Phoenix, compared to Gila Bend, experienced considerably fewer frost (670 vs. 1310) and misery (1190 vs. 4266) days. (2) Higher variability in the annual number of frost and misery days at Gila Bend, compared to Phoenix. Annual frost days varied from as many as 31 (1964) to as few as zero (25 times) at Phoenix, while Gila Bend experienced a low of zero (1980 and 1986) and a high of 47 (1916). Similarly, the number of misery days varied annually: Phoenix had a minimum of zero (1911) and a maximum of 32 (2007); Gila Bend had a low of 7 (1913) and a high of 87 (1926). (3) A contrasting pattern of threshold temperatures when comparing historical trends for the 2 weather stations. Phoenix showed high variability in both frost and misery days from 1900–1970. Beginning in the 1970s, however, there was a pronounced divergence from the historical pattern of annual frost and misery days: frost days markedly declined while misery days steadily rose. In contrast, threshold temperatures at the Gila Bend station showed continuous variability throughout the period of analysis.

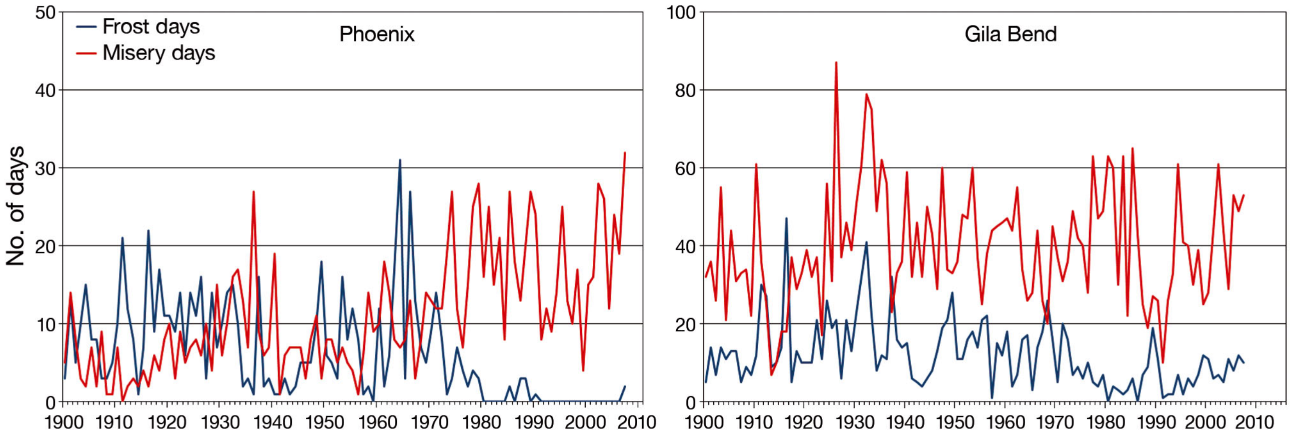

Fig. 2. Annual number of frost days and misery days recorded at Phoenix and Gila Bend weather stations from 1900–2007

3.2. Regional threshold temperatures of heat waves

Table 4 shows threshold temperature characteristics of heat waves at the Phoenix and Gila Bend regional weather stations from 1900–2007. Analyses indicate that the threshold temperature defining a heat wave steadily increased by decade at Phoenix while threshold temperatures of heat waves at Gila Bend largely remained stable. Between the 1920s and 2000–2007, T1 and T2 increased, respectively, by 1.7 and 2.2°C, at the Phoenix weather station, in contrast to the 0.6°C increase for both T1 and T2 at Gila Bend.

Table 3. Total number and annual mean of frost days and misery days measured by decade at Phoenix and Gila Bend regional weather stations

Decade	Frost days No.	Frost days Mean	Misery days No.	Misery days Mean
Phoenix weather station				
1901–1910	80	8.0	54	5.4
1911–1920	119	11.9	41	4.1
1921–1930	104	10.4	73	7.3
1931–1940	67	6.7	131	13.1
1941–1950	56	5.6	61	6.1
1951–1960	67	6.7	69	6.9
1961–1970	120	12.0	106	10.6
1971–1980	46	4.6	173	17.3
1981–1990	9	0.9	198	19.8
1991–2000	0	0	127	12.7
2001–2007	2	0.25	157	19.6
Total	670	6.3	1190	11.1
Gila Bend weather station				
1901–1910	105	10.5	363	36.3
1911–1920	175	17.5	252	25.2
1921–1930	171	17.1	433	43.3
1931–1940	203	20.3	533	53.3
1941–1950	121	12.1	395	39.5
1951–1960	148	14.8	437	43.7
1961–1970	126	12.6	359	35.9
1971–1980	84	8.4	448	44.8
1981–1990	64	6.4	380	38.0
1991–2000	54	5.4	333	33.3
2001–2007	59	7.4	333	41.6
Total	1310	12.2	4266	39.9

Table 4. Heat wave characteristics by decade for Phoenix and Gila Bend weather stations from 1921–2007. For definition of threshold temperatures T1 and T2, see Section 2.4. Frequency is the total number of heat waves that occurred during each decade

Decade	T1 (°C)	T2 (°C)	Frequency (no.)	Intensity (°C)	Average duration (d)
Phoenix weather station					
1921–1930	42.2	37.8	10	42.7	9.0
1931–1940	42.2	37.8	18	43	9.3
1941–1950	42.8	38.3	6	43.1	5.8
1951–1960	42.8	38.9	6	42.9	9.2
1961–1970	42.8	38.9	14	43.2	8.4
1971–1980	42.8	38.3	21	43.3	10.8
1981–1990	43.3	38.9	15	43.8	9.2
1991–2000	43.9	39.4	4	44.6	10.8
2001–2007	43.9	40	7	44.6	6.6
Average	43	38.7	11.2	43.5	8.8
Gila Bend weather station					
1921–1930	45	40.6	7	45.6	17.3
1931–1940	45.6	41.1	13	46.2	9.9
1941–1950	46.1	41.7	4	46.2	8.5
1951–1960	46.1	41.7	2	46.9	6.5
1961–1970	45.6	41.7	8	46.2	5.6
1971–1980	45.6	41.1	6	45.9	8.2
1981–1990	45.6	41.1	7	45.9	10.9
1991–2000	45.6	41.1	5	45.9	12.2
2001–2007	45.6	41.1	4	46.2	6.3
Average	45.6	41.2	6.2	46.1	9.5

Table 4 also shows decadal trends in the frequency, intensity, and duration of heat waves that occurred from 1900–2007 at the Phoenix and Gila Bend weather stations. Frequency refers to the total number of heat waves that occurred during each decade. Phoenix reported a low of 4 (1990s) of heat waves and a high of 21 (1970s) while the low at Gila Bend was 2 (1950s) and the high was 13 (1930s). The average number of heat waves per decade was 11.2 and 6.2, at Phoenix and Gila Bend, respectively. Heat wave intensity represents the average maximum temperature of heat waves for a given decade. For Phoenix, the maximum intensity was 44.6°C (1991–2000 and 2001–2007), the minimum was 42.7°C (1921–1930), and the average was 43.5°C. Gila Bend recorded a maximum intensity of 46.9°C (1951–1960), a minimum of 45.6°C (1921–1930), and an average of 46.1°C. Finally, duration denotes the length (in days) of a given heat wave. The average length of a heat wave between 1900–2007, at Phoenix and Gila Bend respectively, was 8.8 and 9.5 d. Among decades, the maximum average durations, at Phoenix and Gila Bend respectively, were 10.8 d (1970s and 1990s) and 17.3 d (1920s), and the minimums were 5.8 d (1940s) and 5.6 d (1960s).

3.3. ENSO, PDO, and regional threshold temperatures

This subsection investigates correlations between ENSO/PDO and the occurrence of threshold temperatures (frost and misery days) from Phoenix and Gila Bend weather stations by examining (1) moving average indices (Fig. 3); (2) bivariate correlations between ENSO/PDO indices and the occurrence of frost/misery days; (3) a test of differences (paired sample *t*-test) (Table 5); and (4) modulations in ENSO and PDO teleconnections with frost/misery days (Table 6). Results are organized into 3 time steps: (1) 1900–2007 (the full historical dataset); (2) 1900–1969 (pre-large-scale urban development); and (3) 1970–2007 (post-large-scale urban development).

Moving averages of ENSO/PDO and threshold temperatures (frost and misery days) from 1900–2007 for the Phoenix and Gila Bend weather stations are presented in Fig. 3. Observations of ENSO and PDO periodicities indicate that both ENSO and PDO experienced multiple regime shifts during the period of analysis, although the frequency of ENSO regime shifts occurred approximately every 10 yr whereas PDO cycles were multi-decadal. Both ENSO and PDO were predominately in the positive (warm) phase during the period of 1900–2007, although both systems also experienced negative (cool) phases. A third observation is that ENSO values were less extreme than PDO values throughout the period of analysis. Associations between ENSO/PDO and frost/misery days, in general, are variable. While PDO shows a relatively strong relationship with threshold temperature at both weather stations (positive phase related to more misery days; negative phase related to more frost days; Fig. 3, lower panels), ENSO variation does not appear to be correlated with the occurrence of threshold temperatures at either station (Fig. 3, upper panels).

A bivariate correlation analysis was performed between ENSO/PDO indices and frost/misery days for Phoenix and Gila Bend. Summating the results, frost/misery days were weakly (strongly) correlated with ENSO (PDO). ENSO analyses showed no statistically significant relationships for Phoenix across all 3 time steps. Results from Gila Bend showed some statistically significant relationships. Frost days are indirectly (negatively) correlated with ENSO (which indicates that high [low] precipitation is likely correlated with a low [high] number of frost days, while misery days show statistically significant positive correlations (high [low] winter precipitation is correlated with a subsequent high [low] number of misery days). The PDO showed significant correlations with frost/misery days at both Phoenix and Gila Bend. In general, the warm (cool) phase was associated with low (high) frost days and high (low) misery days.

Correlation coefficients from the bivariate analysis were used to conduct a paired-sample *t*-test to test for statistical differences between group variables; results are summarized in Table 5. The pairs of variables examined were Period 1 (1900–1969, pre-urban) and Period 2 (1970–2007, post-urban). Results show mixed levels of statistical significance. Analyses of ENSO pairs showed significant changes in correlation coefficients for the Phoenix weather station between the 2 periods while no significant results were found for the Gila Bend weather station. Analyses of PDO pairs showed significant changes in PDO values between Periods 1 and 2. Both warm and cool PDO phases occurred during Period 1, while Period 2 coincided primarily with a warm phase. Results for misery days in Phoenix were significantly different between the 2 periods. While the PDO was historically a strong predictor of misery days in Phoenix, the correlation between misery days in Phoenix and PDO was absent in the period 1970–2007. In contrast, the Gila Bend weather station displayed a significant change in frost days between Periods 1 and 2. This

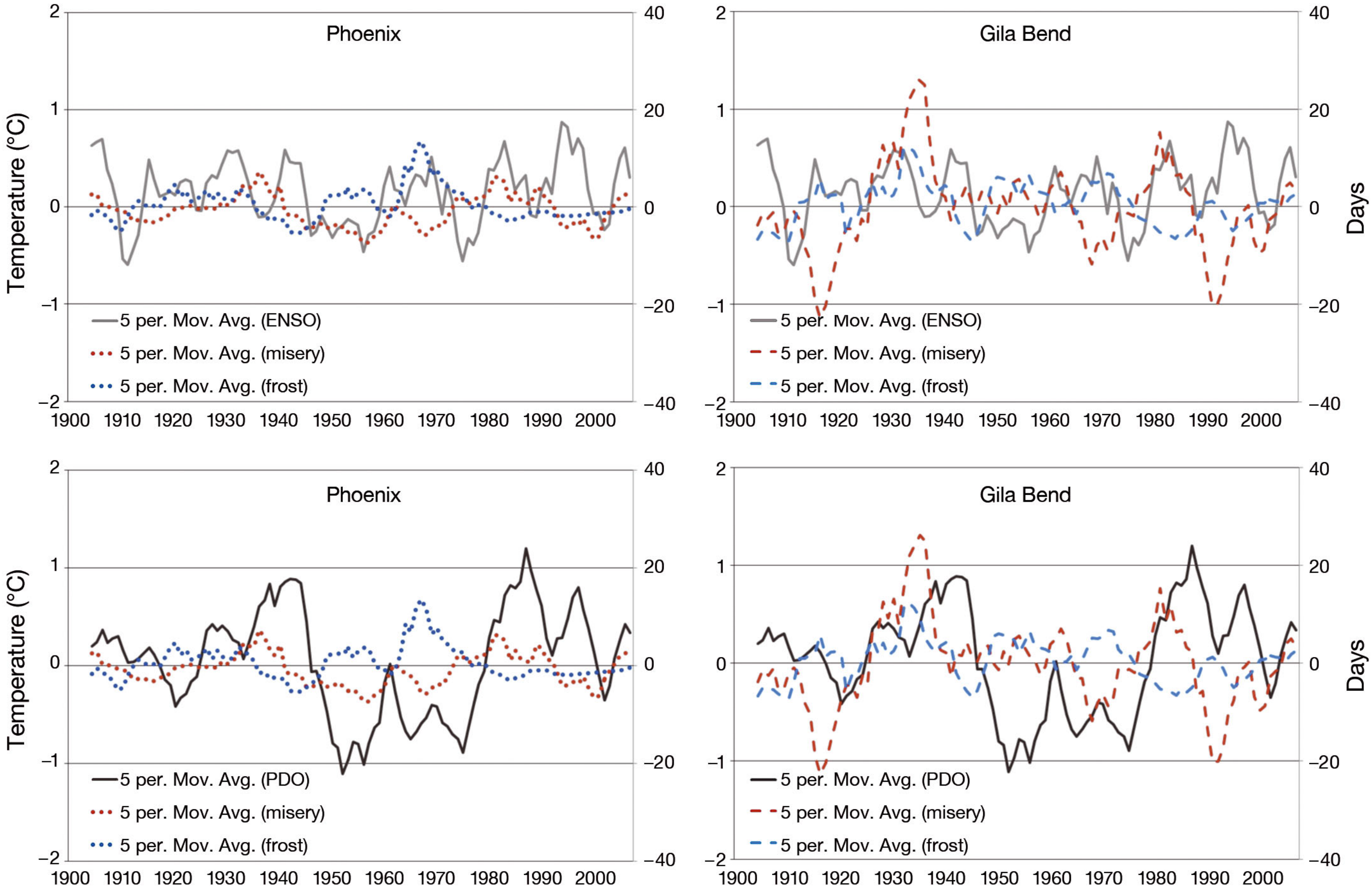

Fig. 3. Monthly values for ENSO (upper panels) and PDO (lower panels) for comparison with detrended occurrence of frost and misery days at Phoenix (left) and Gila Bend (right) from 1900–2007. Per. Mov. Avg.: periods moving average

result could be explained by the warming PDO, which corresponds to fewer frost days. One would also expect a parallel relationship for the Phoenix weather station, but agricultural development and/or urbanization may serve as a buffering influence against variations in PDO effects on temperature.

The effects of ENSO and PDO modulations on annual frost and misery days for the Phoenix and Gila Bend weather stations were examined by using a 4-cell matrix organized by winter (November–February) and summer (June–September) conditions from 1900–2007 (Table 6). Results show that ENSO modulations were weakly associated with annual frost/misery days while modulations of PDO were strongly correlated with threshold temperatures. In general, the positive ENSO phase is associated with more frost days

Table 5. Results of paired-sample *t*-test of ENSO and PDO modulations and their effects on frost and misery days at the Phoenix and Gila Bend weather stations between Period 1 (1900–1969, pre-urban) and Period 2 (1970–2007, post-urban). Row 1: index values of ENSO and PDO; Rows 2 to 5: correlation coefficients between ENSO/PDO values and the climate variables. **Bold:** significant (p < 0.05). SME: square mean error

Paired samples	Paired differences (Period 1 vs. Period2)				
	Mean	SD	SME	*t*	p
ENSO					
1. ENSO values	−0.02	0.03	0.01	−2.20	0.050
2. Misery days Phoenix	0.30	0.10	0.03	10.09	**<0.001**
3. Misery days Gila Bend	0.03	0.09	0.02	1.37	0.197
4. Frost days Phoenix	0.09	0.11	0.03	2.71	**0.020**
5. Frost days Gila Bend	0.15	0.30	0.09	1.70	0.118
PDO					
1. PDO values	−0.25	0.21	0.06	−4.02	**0.002**
2. Misery days Phoenix	0.27	0.12	0.04	7.444	**<0.001**
3. Misery days Gila Bend	0.07	0.14	0.04	1.67	0.123
4. Frost days Phoenix	0.05	0.11	0.03	1.69	0.119
5. Frost days Gila Bend	0.21	0.11	0.03	6.57	**<0.001**

Table 6. A comparison of winter (November–February) and summer (June–September) conditions at Pheonix and Gila Bend weather stations, i.e. the numbers of frost or misery days occurring under different combinations of ENSO and PDO phases from 1900–2007. Count: number of winters/summers in which the combination of ENSO/PDO occurred (e.g. there were 29 winters when a PDO negative phase occurred in combination with a negative ENSO)

	PDO negative phase		PDO positive phase	
	Phoenix	Gila Bend	Phoenix	Gila Bend
Winter: frost days				
ENSO negative phase				
Count	29	29	20	20
Min	0	4	0	0
Max	24	36	19	45
Sum	229	424	86	212
Mean	7.89	14.62	4.3	10.6
SD	6.33	8.45	5.43	10.26
ENSO positive phase				
Count	18	18	40	40
Min	0	0	0	0
Max	35	35	17	32
Sum	150	246	189	436
Mean	8.33	13.67	4.73	10.9
SD	9.08	9.17	5.17	8.06
Summer: misery days				
ENSO negative phase				
Count	27	27	18	18
Min	1	18	0	19
Max	25	75	32	65
Sum	249	1015	237	789
Mean	9.22	37.59	13.17	43.83
SD	6.43	12.03	10.01	13.44
ENSO positive phase				
Count	26	26	36	36
Min	2	10	1	7
Max	19	79	28	87
Sum	237	1011	463	1450
Mean	9.12	38.88	12.86	40.28
SD	4.27	14.12	8.01	17.49

and the negative phase with more misery days, regardless of PDO phase. However, the PDO appears to have a stronger influence over the occurrence of threshold temperatures. The warm phase is positively correlated with the occurrence of misery days and the cool phase with frost days. Also notable is the high variability in the number of misery days during the summer. In other words, there is great potential for extended periods of misery days during the summer, particularly during positive ENSO and PDO modulations.

3.4. Hurst rescaling results related to landscape and PDO/ENSO

As indicated above, the Hurst calculations detect stationary and nonstationary signals in the time series, and the inflections indicate various factors affecting the station time series, such as changes in the location of the station, landscape changes around a site, and larger scale regime shifts of climate. Fig. 4 shows Hurst rescaled time series for PDO, ENSO, and the frost/misery days for Phoenix and Gila Bend. The Hurst re-scaling analysis identified overall regime shifts, as well as correspondence between shifts in the occurrence of frost and misery days and the dates of some station changes (in landscape and/or location) at Phoenix and Gila Bend. The arrows in the upper panels of Fig. 4 indicate known times in station histories of each station when changes were made either to positioning of sensors over a differing surface type (e.g. gravel, grass), at a slightly different height above ground level (ground to roof or vice versa), or move to a so-called compatible station location. Virtually, all of the arrow times are coincident with inflection points on the Hurst graphs and the minor inflection points are thus traceable to station history information. Fortunately no major changes occurred around 1950 that might be coincident with breaks in the progression of temperatures through time due to the threading approach used in this study.

Hurst re-scaling calculations of the summer and winter PDO time series indicate major regime shifts in the 1940s and again in the 1970s (Fig. 4), known periods of change between the warm and cold phases of the PDO (e.g. Rodionov 2004; Goodrich 2004). The ENSO rescaled curve is also shown on Fig. 4, and major peaks are in phase with the PDO; in other words, PDO and ENSO underwent regime shifts in the winter time series which were well detected by the Hurst rescaled series and match the known physical changes of the teleconnection regime shifts.

Table 7 summarizes the relevant parameters of the Hurst calculations for all time series. Notable for the PDO are the much larger SD, Q_{max}, Q_{min}, and r_n values in winter compared to summer. This is reflected in the correspondence between both stations' rescaled frost day time series and the PDO/ENSO winter regime shifts, as shown by their respective rescaled curves. It may also explain the higher correlations with the frost day time series, compared to the misery day time series, for both Phoenix and Gila Bend (Fig. 4). The PDO and frost/misery H values

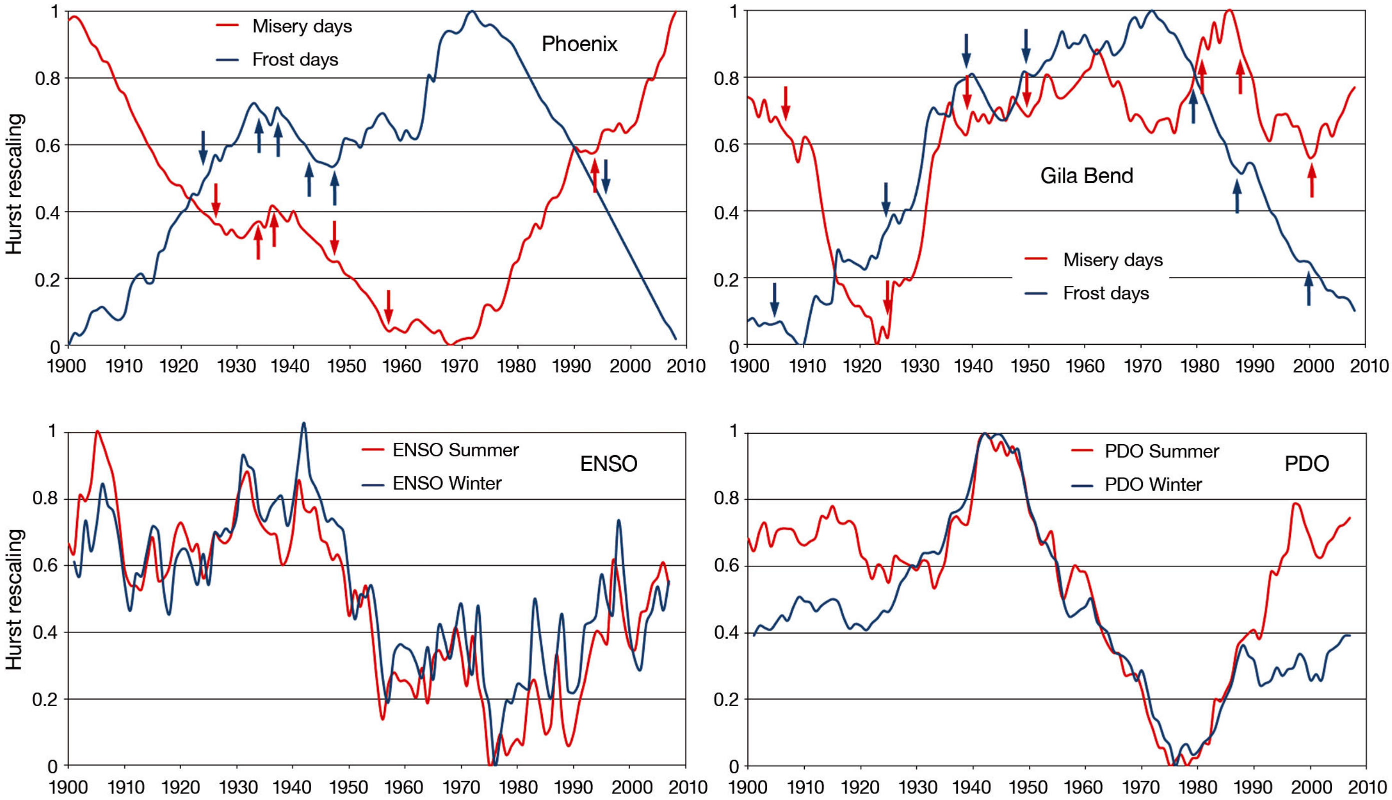

Fig. 4. Hurst rescaling analysis for frost and misery days at the Phoenix and Gila Bend regional weather stations and ENSO/PDO winter and summer values from 1900–2007. Arrows in the upper panels indicate the occurrence of changes in the station location and/or the surrounding landscape

exceed 0.5, indicating regime shifts in the time series (Outcalt et al. 1997; Runnalls & Oke 2006). For summer, as mentioned above, lower correlations were found between the misery day series and PDO/ENSO data. In the rescaled time series, a key difference is in the response noted between Gila Bend (a rural site) versus Phoenix (an urban location).

For the Phoenix record, a major regime shift is indicated by a change around 1970 for both frost days and misery days. The H values far exceed 0.5. For Gila Bend, on the other hand, there is a different and less distinct trend pattern for the misery day rescaled time series, and the H value is below 0.5. The misery day Hurst rescaled curves for Gila Bend and Phoenix resemble the patterns determined by Runnalls & Oke (2006) for a rural and urbanizing site, respectively. Therefore, it is possible that while the Phoenix rescaled frost and misery day series follows the PDO rescaled series, it is further amplified by a post-1970 period of landscape change (i.e. urbanization) influence on the misery days, much like the effect detected for the Edmonton and Regina regions in Alberta and Saskatchewan by Runnalls & Oke (2006). The oscillating pattern of Gila Bend's rescaled misery day series does not

Table 7. Summary annual statistics (N = 108, except for ENSO/PDO winter indices where N = 107) of time series for ENSO/PDO values and frost and misery days at Phoenix and Gila Bend weather stations, and results of Hurst rescaling analysis. SD: standard deviation of the original time series; Q: transformed time series values; r: adjusted range of the transformed series of n observations; H: Hurst exponent value

Time series	Mean	SD	Q_{max}	Q_{min}	r_n	H
PDO index: winter	0.04	2.84	47.99	–27.96	75.95	0.70
PDO index: summer	0.09	0.96	6.51	–12.48	18.99	0.64
ENSO index: winter	0.16	1.20	5.18	–6.94	12.12	0.48
ENSO index: summer	0.16	0.80	4.22	–5.15	9.37	0.53
Phoenix frost days	6.17	6.44	187.59	–3.17	190.76	0.72
Phoenix misery days	11.16	7.58	0.56	–257.04	257.60	0.75
Gila Bend frost days	12.11	8.46	205.87	–32.21	238.08	0.71
Gila Bend misery days	39.86	14.86	47.14	–32.86	80.00	0.36

show a monotonic progression typical of an urbanizing region, nor does it match a PDO/ENSO trend in the rescaled series. The Gila Bend pattern may follow other summer time monsoon-related characteristics, which are beyond the scope of this study. This would suggest that the Phoenix misery day pattern is driven more by landscape change at the weather station. Previous analyses of changes in the hourly misery temperature conditions at Phoenix tend to support the idea of significant changes in high temperature extremes experienced in the Phoenix area (Baker et al. 2002; and shown for Phoenix in Karl et al. 2009).

4. DISCUSSION

4.1. Historical threshold temperature trends

Temperature thresholds for frost days, misery days, and heat waves were examined from the Phoenix and Gila Bend regional weather stations from 1900–2007. Results show pronounced warming trends at Phoenix and modest warming at Gila Bend. For example, the annual number of frost days at Phoenix shows a negative linear trend for the entire study period and a decrease from 1970–2007. On the other hand, the annual number of misery days increased during the study period, and especially from 1970–2007. Heat wave thresholds also showed accelerated warming trends for Phoenix from 1900–2007. Data from the nearby non-urbanized Gila Bend weather station show slight changes among the 3 measures of threshold temperatures. Frost days showed a negative trend in the historical record and a modest decline from 1970–2007. Misery days increased slightly in the historical record but remained stable from 1970–2007. The thresholds of heat waves also remained largely stable throughout the historical record.

The findings on frost and misery day are consistent with work by Booth et al. (2011) that examined changes in climate over western North America from 1950–2005. The study area was divided into 6 subregions and 4 temperature-based indicators were examined. Results show downward trends in frost days with increased 'warm days' (defined as daily Tmax > 90th percentile) throughout southwest region (Arizona, Colorado, New Mexico and Utah). Booth et al. (2011) report a slope of 0.048167 in the linear regression of warm days, versus year. Regression analyses of misery days versus year at the 2 stations in the present study showed a slope of 0.22 for Phoenix and a slope of −0.07 for Gila Bend. Relative to results reported by the Booth et al. (2011) study, Phoenix represents a statistically significant positive anomaly while the nearby Gila Bend station is a negative anomaly. Given this perspective, it is very likely urbanization is serving to intensify misery days at the Phoenix weather station.

Analyses of ENSO and PDO provide insight into historical trends of frost and misery days. Correlations of temporal changes of ENSO values with frost and misery days show significant relationships: high (low) precipitation winters are negatively (positively) associated with frost days and positively (negatively) correlated with misery days. The analysis of PDO values with frost and misery days also showed statistically significant relationships. In general, the warm phase is negatively associated with frost days and positively related with misery days. Temperature trends were then compared between the urban environment of Phoenix and the natural land use of Gila Bend for 3 time steps. Analyses indicated a much stronger influence of PDO on regional temperatures compared to ENSO, and significant changes from the pre-urban to post-urban time steps. For instance, PDO was historically a significant indicator of misery days at the Phoenix weather station; however, this relationship disappeared in 1970–2007. It is likely that large-scale urbanization is altering the influence of PDO on local temperatures.

Teleconnection indices were then investigated to better understand the influence of ENSO/PDO modulations on the occurrence of temperature thresholds and to identify regime shifts and/or inflection points in the time series. Results show that warm PDO was associated with increased misery days, regardless of ENSO phase and that the cool PDO phase showed a modest positive correlation with frost days. The influence of ENSO phase shifts was, overall, variable on frost/misery days. The paired sample *t*-test and Hurst re-scaling analysis identified regime shifts in the ENSO/PDO and/or frost/misery day time series, but inconsistencies were found between the Phoenix and Gila Bend weather stations. Gila Bend showed nonstationary shifts (i.e. random patterns) reflective of teleconnection variability, while results from Phoenix were more pronounced and suggestive of changes in land cover and effects of other anthropogenic drivers. This finding is consistent with recent studies by Georgescu et al. (2009) and Grossman-Clarke et al. (2010) that observed trends in surface heating precipitated by large-scale urban growth and land-use change since 1970.

4.2. Potential impacts on social and ecological processes

Understanding changes in temperature thresholds is critically important due to the connections climate systems have with various environmental, economic, social, and water/energy systems. Among environmental systems, frost days help maintain balance within ecosystems by providing a natural source of pest control. Implications of reduced frost days are (1) longer breeding periods for insects and arthropods throughout the year; (2) increased insect and arthropod populations (as a result of the expanded thermal window); (3) extended need for pesticide use by farmers and homeowners; and (4) increased vulnerability through pest damage to crops and/or forest stands (Baker et al. 2002, Meehl et al. 2004).

Threshold temperatures are also intimately related to economic systems. Cotton, one of the major cash crops in Phoenix, has witnessed decreases in the quality and yield of annual harvests, which was directly attributed to increased heat stress (Baker et al. 2002). Dairy production has also declined as a function of heat stress. To combat this trend, Phoenix area dairy farmers have turned to evaporative coolers to help maintain productivity during the summer months (Baker et al. 2002). A third example relating the stress warming temperatures pose on local economic systems relates to the tourism industry. A fundamental goal of the City of Phoenix's development plan is to mitigate the UHI effect to help market Phoenix as a year round destination (Gober et al. 2009).

Human health and well-being are also highly sensitive to perturbations in the climate system. Whereas fewer frost days may translate to more temperate and pleasant outdoor conditions in the winter, increased misery days pose significant risks to human health and quality of life. The Centers for Disease Control and Prevention (CDC 2005) recently reported that Arizona led the nation in heat-related deaths from 1993–2002. It is likely that heat-related illnesses and deaths will continue to rise as the number of misery days increases. Analyses of threshold temperature of heat waves show that T1, T2, and the intensity of heat waves have all increased in a linear fashion from 1900–2008, however, the duration and frequency of heat waves reflect oscillating trends. The prospect of increases of T1 and T2 coupled with a rise in heat wave frequency is likely to produce conditions of extended exposure to increasingly extreme heat, and these physical changes may have dire effects on human health and well-being. Moreover, studies by Harlan et al. (2006) and Ruddell et al. (2010) show that minority populations and low-income residents are most at risk and possess the fewest resources to cope during episodes of extreme heat.

A warming climate in Phoenix also means increased demands on local water and energy systems. Local water demand, for example, peaks in the summer season when residents use valuable water supply to fill pools and support outdoor vegetation for shade, both of which provide relief from the intense summer temperatures (Guhathakurta & Gober 2007, Wentz & Gober 2007). A second demand on the water system relates to energy production and consumption. In Arizona, energy plants require significant amounts of water to generate electricity, although specific gallons per kilowatt hour requirements vary by fuel type (Cooley et al. 2011). One of the most energy intensive appliances is the air conditioner, which residents are using for longer periods of time and at higher settings to provide relief from intense daytime and nighttime temperatures. The implications of intensified air conditioning use are threefold: (1) increased demands on local and regional energy systems; (2) more anthropogenic heat released into the urban environment; and (3) increased air and noise pollution. In short, a warming metropolitan Phoenix has wide-reaching implications on various physical and social processes.

5. CONCLUSION

Historical trends in threshold temperatures from Phoenix and Gila Bend regional weather stations and teleconnections were examined to better understand the effects of urbanization and its potential effects on human and ecological systems. Results show accelerated warming resulting in fewer frost days, and more misery days and heat waves in Phoenix, with modest changes to stable conditions at Gila Bend. Analyses indicate that ENSO and PDO are significant predictors of historical temperature thresholds, although PDO is more strongly correlated with frost days and misery days compared to ENSO. Results suggest that human activity and urban development have disrupted the historical relationship between ENSO/PDO and temperature thresholds, which is particularly evident over the last 40 yr. The natural variation in frost days and misery days is clearly visible from 1900–1969 for both weather stations; however, beginning in 1970, Phoenix shows a departure from historical variability to a pattern of increased warming; this trend corresponds to the large-scale urban growth which has occurred throughout metropolitan Phoenix since this date. In contrast, temperature trends at the non-urban site (Gila Bend) show no disruption to natural variability during the same period of time.

Additional investigations are required to better understand climate variability and associated connections between social and ecological systems. Three particular lines of research are (1) to apply the current methodology to an expanded study area with a greater number of weather stations; (2) to examine additional teleconnection indices and teleconnection modulations on local/regional temperatures; and (3) to investigate potential mitigation and/or adaptation strategies to reduce the impacts of urbanization on the climate system.

Acknowledgements. This study is based upon research supported by the National Science Foundation (NSF) under Grant Nos. DEB-0423704 Central Arizona - Phoenix Long-Term Ecological Research (CAP LTER); SES-0345945 Decision Center for a Desert City (DCDC); and GEO-0816168 Urban Vulnerability to Climate Change (UVCC). Any opinions, findings, and conclusions or recommendation expressed in this study are those of the authors and do not necessarily reflect the views of the NSF. The authors thank Nancy Selover of the Arizona State Climate Office, Tim Lant and Benjamin Ruddell at Arizona State University, and P. Grady Dixon at Mississippi State University.

LITERATURE CITED

Arnfield AJ (2003) Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. Int J Climatol 23:1–26

Baker LC, Brazel AJ, Selover N, Martin C, McIntyre N, Steiner FR, Nelson A (2002) Urbanization and warming of Phoenix (Arizona, USA): impacts, feedback, and mitigation. Urban Ecosyst 6:183–203

Balling RC, Brazel SW (1987) Time and space characteristics of the Phoenix urban heat island. J Ariz Nev Acad Sci 21:75–81

Booth ELJ, Byrne JM, Johnson DL (2011) Climatic changes in western North America, 1950–2005. Int J Climatol, first published online 13 Dec 2011.

Brazel AJ, Ellis A (2003) The climate of the Central Arizona and Phoenix Long-Term Ecological Research Site (CAP LTER) and links to ENSO. In: Greenland D, Goodwin D, Smith R (eds) Climate variability and ecosystem response in long- term ecological research sites. Oxford University Press, Oxford, p 117–140.

Brazel AJ, Selover N, Vose R, Heisler G (2000) The tale of two climates — Baltimore and Phoenix urban LTER sites. Clim Res 15:123–135

Brazel AJ, Gober PA, Lee SJ, Grossman-Clarke S, Zehnder J, Hedquist B, Comparri E (2007) Determinants of changes in the regional urban heat island in metropolitan Phoenix (Arizona, USA) between 1990 and 2004. Clim Res 33:171–182

Brown PW (2001) Heat stress and cotton yields in Arizona. University of Arizona Agricultural Extension Service. http://ag.arizona.edu/pubs/crops/az1224/az12242b.pdf

Cayan DR, Redmond KT (1994) ENSO influences on atmospheric circulation and precipitation in the Western United States. In: Redmond KT, Tharp VL (eds) Proc Tenth Annual Pacific Climate (PACLIM) Workshop, Asimolar, CA, April 4–7, 1993. Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary, p 5–26

Cayan DR, Redmond KT, Riddle LG (1999) ENSO and hydrological extremes in the Western United States. J Clim 12:2881–2893

CDC (Centers for Disease Control and Prevention) (2005) Heat-related mortality – Arizona, 19932002 and United States, 1979–2002. MMWR Morb Mortal Wkly Rep 54: 628–630

CDC (Centers for Disease Control and Prevention) (2006) Extreme heat: a prevention guide to promote your health and safety. www.bt.cdc.gov/disasters/extremeheat/heat_guide.asp; accessed 4/29/09

Cooley H, Fulton J, Gleick PH (2011) Water for Energy: Future Water Needs for Electricity in the Intermountain West. Pacific Institute

Ebi K, Meehl J (2007) The heat is on: climate change and heatwaves in the Midwest. Pew Center for Climate Change, Arlington, VA

Elliott GP, Kipfmueller KF (2011) Multiscale influences of climate on upper treeline dynamics in the Southern Rocky Mountains, USA: evidence of intraregional variability and bioclimatic thresholds in response to twentieth-century warming. Ann Assoc Am Geogr 101:1181–1203

Gage KL, Burkot TR, Eisen RJ, Hayes EB (2008) Climate and vectorborne diseases. Am J Prev Med 35:436–450

Georgescu M, Miguez-Macho G, Steyaert LT, Weaver CP (2009) Climatic effects of 30 years of landscape change over the greater Phoenix, Arizona, region: 1. Surface energy budget changes. J Geophys Res 114:D05110, doi: 10.1029/2008JD010745

Gershunov A, Barnett TP (1998) Interdecadal modulation of ENSO teleconnections. Bull Am Meteorol Soc 79: 2715–2725

Gober PA (2006) Metropolitan Phoenix place making and community building in the Desert. University of Pennsylvania Press, Philadelphia, PA

Gober PA, Brazel AJ, Quay R, Myint S, Grossman-Clarke S, Miller A, Rossi S (2009) Using watered landscapes to manipulate urban heat island effects: how much water will it take to cool Phoenix? J Am Plann Assoc 76:109–121

Goodrich GB (2004) Influence of the Pacific decadal oscillation on Arizona winter precipitation during years of neutral ENSO. Weather Forecast 19:950–953

Grossman-Clarke S, Zehnder JA, Stefanov WL, Liu Y, Zoldak MA (2005) Urban modifications in a mesoscale meteorological model and the effects on near surface variables in an arid metropolitan region. J Appl Meteorol 44:1281–1297

Grossman-Clarke S, Zehnder JA, Loridan T, Grimmond CSB (2010) Contributions of land use changes to near surface air temperatures during recent summer extreme heat events in the Phoenix metropolitan area. J Appl Meteorol 49:1649–1664

Guhathakurta S, Gober PA (2007) The impact of the Phoenix urban heat island on residential water use. J Am Plann Assoc 73:317–329

Harlan SL, Brazel AJ, Prashad L, Stefanov WL, Larsen L (2006) Neighborhood microclimates and vulnerability to heat stress. Soc Sci Med 63:2847–2863

Huxman TE, Hamerlynck EP, Loik ME, Smith SD (1998) Gas exchange and chlorophyll fluorescence responses of 3 south-western *Yucca* species to elevated CO_2 and high temperature. Plant Cell Environ 21:1275–1283

Kalkstein AJ, Sheridan SC (2007) The social impacts of the heat–health watch/warning system in Phoenix, Arizona: assessing the perceived risk and response of the public. Int J Biometeorol 52:43–55

Karl TR, Melillo JM, Peterson TC (eds) (2009) Global climate change impacts in the United States. Cambridge University Press, New York, NY

Klinenberg E (2002) Heat wave: a social autopsy of disaster in Chicago. University of Chicago Press, Chicago, IL

Kunkel KE, Pielke RA Jr, Changnon SA (1999) Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. Bull Amer Meteor Soc 80:1077–1098

Larson J (2006) Setting the record straight: more than 52 000 Europeans died from heat in summer 2003. Earth Policy Institute. www.earth-policy.org/plan_b_updates/2006/update56

Lowry W (1967) The climate of cities. Sci Am 217:15–23

Mandelbrot BB, Wallis JR (1969) Some long-run properties of geophysical records. Water Resour Res 5:967–988

Mantua NJ, Hare SR (2002) The Pacific Decadal Oscillation. J Oceanogr 58:35–44

Mantua NJ, Hare SR, Zhang U, Wallace JM, Francis RC (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. Bull Am Meteorol Soc 78: 1069–1079

Martin CA, Stutz JC, Kimball BA, Idso SB, Akey DH (1995) Growth and topological changes of *Citrus limon* (L.) Burm. f. 'Eureka' in response to high temperatures and elevated atmospheric carbon dioxide. J Am Soc Hortic Sci 120:1025–1031

Meehl GA, Tebaldi C (2004) More intense, more frequent, and longer lasting heat waves in the 21st century. Science 305:994–997

Meehl GA, Tebaldi C, Nychka D (2004) Changes in frost days in simulations of twentyfirst century climate. Clim Dyn 23:495–511

Newman M, Compo CP, Alexander MA (2003) ENSO-forced variability of the Pacific Decadal Oscillation. J Clim 16:3853–3857

NWS (National Weather Service) (2002) Heat wave. NWS, National Oceanographics and Atmospheric Administration, Internet Weather Source. www.nws.noaa.gov/om/heat/index.shtml

Oke TR (1982) The energetic basis of the urban heat island. Q J R Meteorol Soc 108:1–24

Oke TR (1997) Part 4: The changing climatic environments: urban climates and global environmental change. In: Thompson RD, Perry P (eds) Applied climatology: principals and practice. Routledge, London, p 273–287

Outcalt S, Hinkel KM, Meyer E, Brazel AJ (1997) Application of Hurst rescaling to geophysical serial data. Geogr Anal 29:72–87

Pagano T, Hartmann H, Sorooshian S, Bales R (1999) Advances in seasonal forecasting for water management in Arizona: a case study of the 1997–98 El Niño. Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ

Parmesan C, Root TL, Willig MR (2000) Impacts of extreme weather and climate on terrestrial biota. Bull Am Meteorol Soc 81:443–450

Reisner M (1986) Cadillac desert. Viking Press, New York, NY

Rodionov SN (2004) A sequential algorithm for testing climate regime shifts. Geophys Res Lett 31:L09204, doi: 10.1029/2004GL019448

Rodionov SN, Overland JE (2005) Application of a sequential regime shift detection method to the Bering Sea ecosystem. J Mar Sci 62:328–332

Ruddell DM, Harlan SL, Grossman-Clarke S, Buyanteyev A (2010) Risk and exposure to extreme heat in microclimates of Phoenix, AZ. In: Showalter P, Lu Y (eds) Geospatial techniques in urban hazard and disaster analysis. Springer, Dordrecht, p 179–202

Runnalls KE, Oke TR (2006) A technique to detect microclimatic inhomogeneities in historical records of screenlevel air temperature. J Clim 19:959–978

Schneider N, Cornuelle BD (2005) The forcing of the Pacific Decadal Oscillation. Bull Amer Meteor Soc 18:4355–4373

Semenza JC, Rubin CH, Falter KH, Selanikio JD, Flanders WD, How HL, Wilhelm JL (1996) Heat-related deaths during the July 1995 heat wave in Chicago. N Engl J Med 335:84–90

Semenza JC, McCullough JE, Flanders WD, McGeehin MA, Lumpkin JR (1999) Excess hospital admissions during the July 1995 heat wave in Chicago. Am J Prev Med 16: 269–277

Shreve F (1934) Vegetation of the northwestern coast of Mexico. Bull Torrey Bot Club 61:373–380

Svoma BM, Brazel A (2010) Urban effects on the diurnal temperature cycle in Phoenix, Arizona. Clim Res 41: 21–29

Thom EC (1959) The discomfort index. Weatherwise 12: 57–59

Trenberth KE (1997) The definition of El Niño. Bull Am Meteorol Soc 78:2771–2777

Voogt JA (2002) Urban heat island. In: Douglas I (ed) Encyclopedia of global environmental change. John Wiley & Sons, Chichester, p 660–666

Weiss JL, Overpeck JT (2005) Is the Sonoran Desert losing its cool? Glob Change Biol 11:2065–2077

Wentz EA, Gober PA (2007) Determinants of small-area water consumption for the City of Phoenix, Arizona. Water Resour Manage 21:1849–1863

Editorial responsibility: Peter Gleckler, Livermore, California, USA

Submitted: May 6, 2010; Accepted: July 30, 2012
Proofs received from author(s): December 6, 2012