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Urbanization and warming of Phoenix (Arizona, USA): Impacts, feedbacks and mitigation

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Abstract. This paper examines the impacts, feedbacks, and mitigation of the urban heat island in Phoenix, Arizona (USA). At Sky Harbor Airport, urbanization has increased the nighttime minimum temperature by 5°C and the average daily temperatures by 3.1°C. Urban warming has increased the number of "misery hours per day" for humans, which may have important social consequences. Other impacts include (1) increased energy consumption for heating and cooling of buildings, (2) increased heat stress (but decreased cold stress) for plants, (3) reduced quality of cotton fiber and reduced dairy production on the urban fringe, and (4) a broadening of the seasonal thermal window for arthropods. Climate feedback loops associated with evapotranspiration, energy production and consumption associated with increased air conditioning demand, and land conversion are discussed. Urban planning and design policy could be redesigned to mitigate urban warming, and several cities in the region are incorporating concerns regarding urban warming into planning codes and practices. The issue is timely and important, because most of the world's human population growth over the next 30 years will occur in cities in warm climates.

Keywords: urban ecosystems, urban heat island, feedbacks, temperature, heat index

Introduction

Helmut Landsberg (1970) wrote in *Science* 32 years ago "... by far the most pronounced and locally far-reaching effects of man's activities on microclimate have been in cities... ". "Urban atmospheres have already demonstrated the strongest evidence we have of the potential for human activities to change climate"(Oke, 1997). Evidence of climate change in cities—particularly the formation of urban "heat islands"—is irrefutable (Changnon, 1992). The magnitude of climate change that has already occurred in many cities is comparable to future projected global or regional change. For example, the expected change in aver age regional temperatures over the next 50 years for the southwestern United States is ca. 2–4°C (Hinkley, 2000). Temperature increases of this magnitude have already taken place over a shorter time frame for major cities, e.g., a city of one million is about 2°C warmer than the rural areas in the region (Karl *et al*., 1988). As multidisciplinary teams initiate research on urban ecosystems, understanding feedbacks from human activities is becoming a central theme (Grimm *et al*., 2000; Collins *et al*., 2000). This emerging emphasis on urban ecosystems coincides with rapid growth in the world's urban population, which is expected to double over the next 30 years (WRI, 1998). This paper addresses the question: what are the impacts of heating from urbanization on humans and their support systems? Developing this understanding is timely and important because much of the urban growth will occur at low to mid latitudes, where the consequences of local heating are likely to be negative.

This paper examines impacts, feedbacks, and considerations regarding mitigation of the heat island of the Phoenix, Arizona metropolitan area. The region has mild winters and hot summers: mean monthly temperatures in the rural desert range from 10°C in December to 32°C in August. The Phoenix metropolitan area is an ideal site for studying the urban heat island because it has grown from a small agricultural center (population ∼300,000) to a major metropolis (population ∼2.6 million) in the past 50 years, a period for which there is a continuous, detailed climate record. Urban land has increased five-fold over this period, replacing both agricultural land and natural desert (figure 1). Because it has developed quickly, the urban area is a heterogeneous patchwork of impervious surfaces (roads and buildings) and artificial amenity landscapes (mesic and xeric lawns, golf courses, parks, and urban lakes), interspersed with remnants of Sonoran desert, pasture, and irrigated cropland. The heat island is well defined (figure 2) because there are many clear, calm days each year (Balling and Brazel, 1987; Brazel *et al*., 2000).

Methods

We analyzed both temporal and spatial data sets with frequent and nearly uninterrupted observations. Temporal data were obtained from the National Weather Service (NWS) Phoenix Sky Harbor Airport First Order Station, which has been in continuous operations since 1948. Observations were hourly from 1948 through 1964, 3-hourly from 1965 through 1972, and hourly from 1973 to the present. From 1948 through 1995, the station was located in the center of the airport property, in the middle of an asphalt parking lot. In 1995, after a one-year overlap, the old station was replaced by an Automated Surface Observing System, (ASOS) at the Northeast edge of the airport property, over a dirt/gravel surface. The new

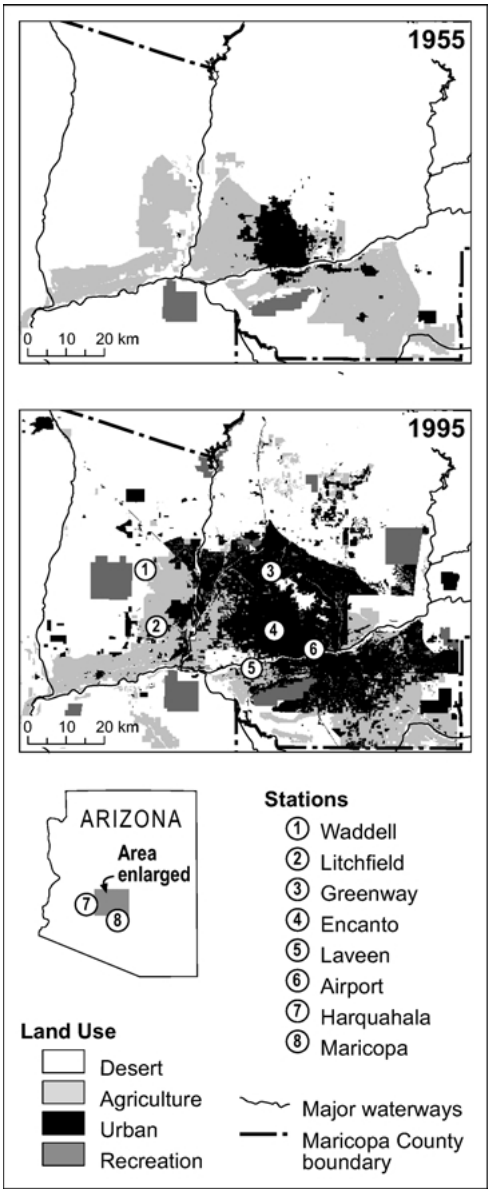

Figure 1. Land use in the Phoenix metropolitan area in 1955 and 1995. The location of Arizona Meterological (AZMET) locations and the Sky Harbor Airport National Weather Service station are shown on the 1995 map.

location and instrumentation contributed to a 0.5°C decrease in air temperature and no discernible change in dew point temperature. Wind speed and direction also appear to be unaffected by the change. As all first order stations, temperatures are measured at shelter height, while winds are measured at 10 meters.

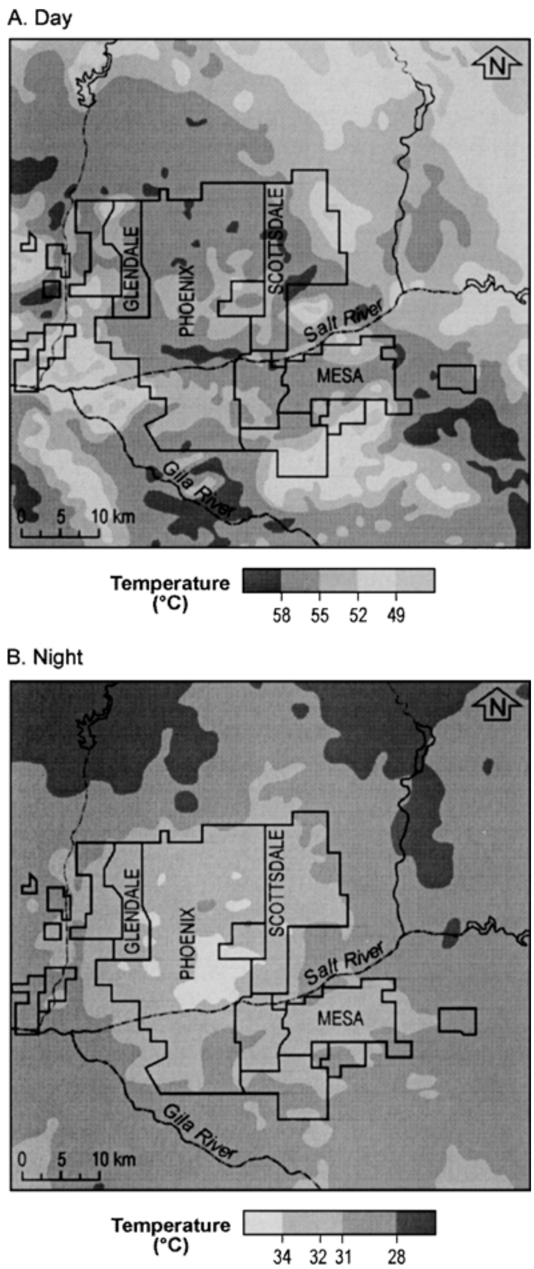

Figure 2. Advanced Very High Resolution Radiometer (AVHRR sensor system on NOAA-9 polar orbiting satellite, using Band 4—10.3–11.3 microns) 1.1 km resolution earth surface apparent temperature pattern averages for A. daytime (1400 hrs) for five days in summer 1986 (6/5, 6/15, 7/12, 7/31, and 8/9, wind less than 4 m/s, cloud-free) and B. nighttime (0220 hrs) for four nights in summer 1985 (6/5, 7/4, 8/10, 9/17, wind less than 3 m/s, cloud-free). After Balling and Brazel (1988) and (1989).

Spatially distributed data were obtained from the Arizona Meteorological (AZMET), operated by the University of Arizona Cooperative Extension, with 32 stations in central and southern Arizona. The stations are designed to provide meteorological data to assist in crop and irrigation management. Air temperature, relative humidity, soil temperature, solar radiation, wind speed, and wind direction are measured (http://ag.arizona.edu/azmet/sensor.html). The network began in 1987, with stations added each year. Hourly data were used in computations.

The AZMET stations were selected for this study based on three criteria (1) their location relative to Phoenix, (2) elevation, and (3) completeness of data. All but one of the stations was selected to be in or near the Phoenix metropolitan area. One site (Harquahala) was selected specifically because it was located 100 km west of the urban area and was unaffected by the urban heat island. Sites were selected to be within about a 100-m elevation range so that elevation would not be a major factor affecting meteorology. As a compromise between desirable features of a high degree of data completeness and a long data record, we selected the four-year time period of 1997–2000.

Based on these criteria, seven stations were selected (Table 1). Two, Phoenix Encanto and Phoenix Greenway, are located within the urban area. Both are located on golf courses. All of the other sites are located on agricultural land. Three others stations (Litchfield, Waddell, and Laveen) are located at agricultural sites immediately on the fringe of the urban area and area affected by the urban heat island (see figure 1). The Maricopa site is located about 20 km south of the urban area (figure 1). All are located within an elevation range of 307 to 409 m above mean sea level. Data completeness was >98% of all sites, with no large

Table 1. Site characteristics, including average daily, average minimum, and average maximum temperatures, 1997–2000

Site	Location, latitude and longitude	Elevation (m)	Average mean temp (°C)	Ave. max. (°C)	Ave min. (°C)
Sky Harbor	33°26′N 112°00′W	337	23.3	29.4	17.3
Phoenix Greenway	33 37 17 N 112 06 30 W	401	21.7	28.3	15.2
Phoenix Encanto	33 28 45 N 112 05 47 W	335	21.6	29.0	14.2
Waddell	33 37 05 N 112 27 35 W	407	21.7	29.5	13.9
Litchfield	33 28 02 N 112 23 53 W	309	21.3	29.2	13.5
Laveen	33 22 35 N 112 09 00 W	315	20.7	29.1	12.4
Maricopa	33 04 07 N 111 58 18 W	361	20.9	29.3	12.5
Harlquahala	33 29 00 N 113 07 00 W	350	20.1	29.1	11.2

contiguous missing data blocks. Interpolation of data from adjacent time periods was used to replace missing values.

Analyses focused on quantification of direct temperature effects to humans, their support systems, and the surrounding biota. Based on review of such algorithms, we selected the following: heating and cooling degree days, human comfort, violent crime, hot and cold plant stress, arthropod activity, cotton planting and harvest dates, cotton heat stress, and dairy cow heat stress, and dairy milk production. All algorithms were computed for each site, because land uses are intermixed. For example, climate data at Sky Harbor is relevant to agricultural production, because the nearest dairies and cotton fields are only a few kilometers from the airport. Conversely, climate in agricultural areas is relevant to human comfort because the urban fringe is rapidly expanding into agricultural areas.

Human heat stress

The widely used Temperature-Humidity Index (THI), also known as the Heat Index (Thom, 1959) or "apparent temperature" was used as a measure of human comfort:

$$\mathrm{THI} = 0.55\mathrm{T} + 0.2T_d + 17.5 \quad (1)$$

where: T = dry bulb temp (°F), T_d = dew point temp (°F).

There is no one absolute apparent temperature that produces "misery" for all people at all levels of activity. We picked 100°F (38°C) because it is within the 90°F–105°F "danger" range in which sunstroke, heat cramps, and heat exhaustion are "possible" with prolonged exposure and/or physical activity (NWS, 2002). The THI was computed hourly. The number of "misery hours per day" were summed for all hours in which the THI was >100.

Temperature and crime

Elevated temperatures increase irritability and aggression in controlled laboratory experiments and numerous studies have shown positive correlations between temperature and violent crime (Anderson, 2001). Using crime statistics from 50 U.S. cities, Anderson *et al*. (1997) estimated that violent crimes (defined as murders + assaults) increased by 4.58/100,000 for each 1°F increase in annual temperature. We used current violent crime rates in Maricopa County (BJS, 2002) as a baseline for computing the effects of increasing temperature.

Heating and cooling degree-days

Heating and cooling degree-hours were calculated using the difference between the temperature for that hour and 18°C (65°F). If the temperature was above 18°C, the difference contributed to cooling degree-hours, and if the temperature was below 18°C, the difference contributed to heating degree-hours. Heating and cooling degree-hours were summed to compute heating and cooling degree-days.

Plant temperature stress

Hourly temperature data were used to compute the number of hours of plant cold stress ($<4°C$) and heat stress ($>40°C$) per day. The hours of heat or cold stress were then summed over various time periods.

Arthropod activity window

Arthropod activity is constrained within a so-called "thermal window" that usually lies between 15–38°C for most taxa, with an optimum environmental temperature ~26°C, regardless of biome or habitat (Whicker, 1983; Whicker and Tracy, 1987). Hours within this window were tabulated for each day and summarized by month and year.

Heat stress for dairy cows

Excess heat has a negative impact in dairy cows, particularly when there is little opportunity for thermal recovery at night (Kabuga, 1992). Heat stress occurs when $T_{max} > 27°C$ and the cooling period ($T < 21°C$) is short or absent. As an overall metric for heat stress to dairy cows, we computed the number of hot days with short cooling periods, days with $T_{max} > 27°C$ that also had less than six hours of temperature below 21°C (Kabuga, 1992).

The effect of temperature on dairy milk production was estimated using a series of regression equations developed for an uncooled dairy located on the fringe of the Phoenix metropolitan area (K&L Dairy, in Gilbert) (Igono *et al.*, 1992). No one equation appeared to be superior in all ways to the others, so we computed milk production using all six equations.

For all six equations, y = milk production, kg/cow-day

$$y = 110.2745 - 8.7089x + 0.3109x^2 - 0.0037x^3 \quad (2)$$

where x = maximum ambient temp.,°C

$$y = 44.7404 - 3.0443x + 0.1926x^2 - 0.004x^3 \quad (3)$$

where x = minimum ambient temp, °C

$$y = 70.033 - 5.7718x + 0.2671x^2 - 0.0041x^3 \quad (4)$$

where x = mean ambient temperature

The next three equations utilized a temperature-humidity index, where $THI = t_{db} - [(0.55 - 0.55\ RH)(t_{db} - 58)$; t_{db} = daily ambient temperature, °F, and RH = relative humidity.

$$y = 1180.9802 - 48.1969x + 0.6713x^2 - 0.0031x^3 \quad (5)$$

where x = maximum THI

$$y = 201.1992 - 8.9405x + 0.1566x^2 - 9.226 \times 10^{-4}x^3 \quad (6)$$

where x = minimum THI

$$y = 277.507 - 11.6688x + 0.1848x^2 - 9.852 * 10^{-4} * x^3 \quad (7)$$

where x = mean THI

Cotton planting and harvest dates; heat stress index

The time of cotton planting was estimated from the accumulation of heating units (HUs) above a 55°F (12.8°C) threshold (Silvertooth and Norton, 1998; Silvertooth, 2001). The accumulation of 400 HUs is needed for planting of early season cotton varieties. Accumulation of heating units after planting (HUAPs) was based on a dual threshold heat unit concept, with a lower threshold of 55°F and an upper threshold of 86°F (30°C) (Silvertooth, 2001). Harvest date for early season cotton was considered to be the date on which 2500 HUAP had accumulated. Accumulation of heating units utilized the single sine method (Zalom *et al*., 1983) for daily maximum and minimum temperatures.

Brown (2001) developed a heat stress unit (HSU) concept for cotton grown in Arizona from mean daily canopy temperature. Brown developed an empirical relationship between temperature measured at the AZMET stations (air temperature) and canopy temperature of the cotton crop, making it possible to use AZMET temperature data to estimate HSUs:

$$\mathrm{CT_h} = 0.52 + T_a - 1.43\mathrm{VPD} \quad \text{(daytime)} \quad (8)$$

$$\mathrm{CT_h} = -5.93 + T_a + 1.95\mathrm{e_a} \quad \text{(nighttime)} \quad (9)$$

where

$\mathrm{CT_h}$ = hourly canopy temperature,°C
T_a = mean hourly air temperature,°C
VPD = mean hourly vapor pressure deficit, in kilopascals
e_a = mean hourly vapor pressure in kilopascals

Hourly estimates of CT_h were then averaged to compute mean daily canopy temperatures. HSUs for each day were computed by subtracting 28°C (the heat stress threshold) from the mean daily canopy temperature. Accumulation of HSUs was calculated by summing positive daily values over time.

Results

Temperature patterns and trends

The major effect of urban heat islands is increased daily minimum temperatures (Table 1 and figure 2). Based on average daily minimum temperatures during 1997–2000, Sky Harbor was the hottest site (17.3°C). The two other urban sites, Phoenix Encanto and Phoenix

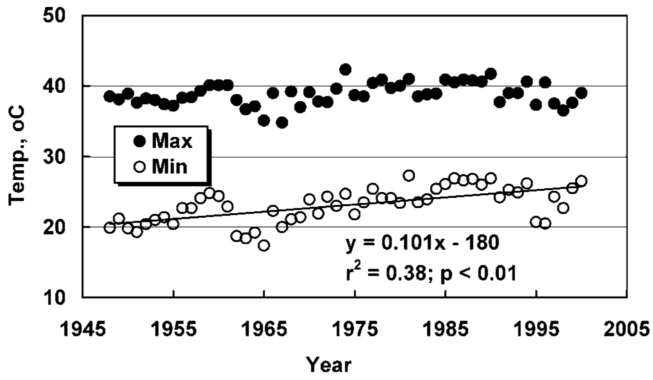

Figure 3. Average daily June temperature at Sky Harbor Airport, 1948–2000. The slope of the T_{max} line is not significantly different from 0.

Greenway, were a bit cooler (14.2°C and 15.2°C, respectively), in part because they are located on golf courses. Three agricultural sites, Litchfield, Waddell, and Laveen (13.5°C, 13.9°C, and 12.4°C, respectively) were on the fringe of the urban heat island (figure 1). One agricultural site (Maricopa, 12.5°C) is in a rural location about 20 km from the urban fringe. Harquahala (11.2°C), located about 100 km west of Sky Harbor Airport, is a non-urbanized agricultural site surrounded by desert. Based on regression analysis, the average daily minimum temperature at Sky Harbor Airport increased by 5.0°C between 1948 and 2000 and the average daily average temperature rose by 3.1°C. The average minimum temperature in June rose by 0.1°C/year (significant at the $p < 0.01$ level), whereas the average daily maximum rose by only 0.03°C and was not statistically significant (figure 3).

The temporal trend during the period of urbanization is substantiated by the present day urban-rural gradient. During 1997–2000, the average daily minimum was 6.1°C higher at Sky Harbor than at Harquahala (Table 1). Average monthly minimum daily temperatures were 4°C to 8°C lower at Harquahala than at Sky Harbor (data not shown). By contrast, the two sites had nearly identical average daily temperature maxima throughout the year.

Misery hours per day

Because minimum daily temperatures have increased, it takes less time to reach uncomfortable temperatures during the day and longer to cool off. At Sky Harbor, the average number of hours with effective temperature over 38°C per day, between May and September nearly doubled since 1948, from 1.8 to 3.4 (figure 4). The number of hours with $T > 38°C$ per day during the two hottest months (July and August) also doubled, from 3.6 to 6.4.

Hot days take a toll on human life, resulting in about 30 heat-related deaths per year in Arizona, about 13 times the national rate. The mechanism of heat-related deaths in Arizona may be different than in temperate climates. Nearly everyone in Arizona has air-conditioning, so it appears that most heat-related deaths are related to outdoor exertion, especially early in the summer (W. Humble, Arizona Department of Health Services, per.

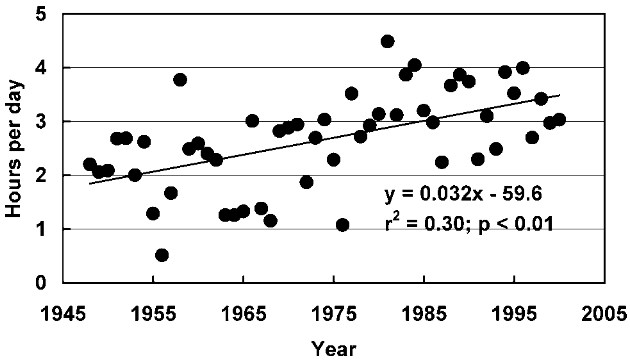

Figure 4. Trend in average number of hours per day with effective temperature >38°C from May–September at Sky Harbor Airport, 1948–2000.

comm.). This hypothesis is supported by the observation that 73% of heat-related deaths occur among males. We postulate that the increase in the number of misery hours per day has likely increased the risk of heat-related deaths, but more research would be needed to test this hypothesis.

Crime rate

Using the algorithm of Anderson *et al*. (1997), the 3.1°C (5.5°F) increase in annual average temperature at Sky Harbor since 1948 would theoretically account for an additional 25 violent crimes/100,000, about 7% of the 1998 total (382/100,000). There is controversy over whether there is a downturn in the temperature-crime relationship at very high temperatures (Craig Anderson, Iowa State University, per. comm.). If so, the calculated increase in crime associated with elevated temperature in Phoenix may overestimate the effect of temperature.

Heating and cooling degree days

Urban warming since 1948 has increased the number of cooling degree-days from 1,560 to 2,130, a gain of 569 degree-days. The number of heating degree-days has declined from 695 to 364, a loss of 331 degree-days (figure 5). A model of energy utilization for several types of buildings developed by Matuusa (1995) shows that the 3°C increase in mean annual temperature at Sky Harbor Airport since 1948 would have increased net energy consumption in a hypothetical "small office building" and "two-unit townhouse" by 16% and 30%, respectively. Because energy costs are higher in summer than winter, the overall cost of energy consumption for heating and cooling a given home would have been greater than the increase in energy consumption.

Because of urban warming, most people run their air conditioners continuously, day and night throughout the extended summer. This was not the case several decades ago, when nighttime temperatures were cool enough to sleep with open windows. For comparison,

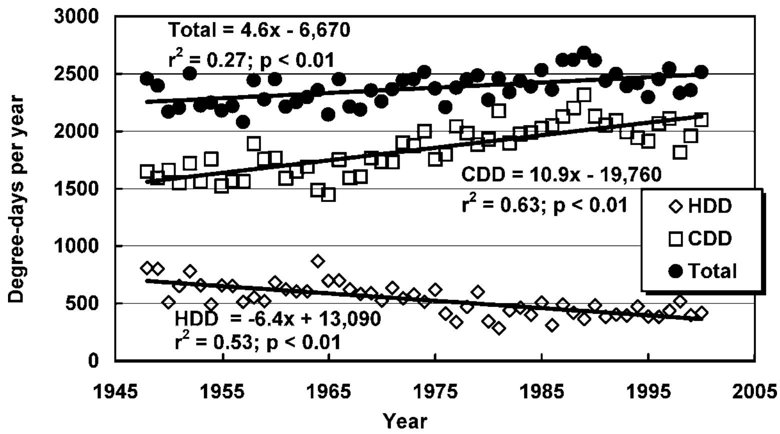

Figure 5. Heating degree-days (HDD), cooling degree-days (CDD), and total degree days at Sky Harbor Airport, 1948–2000.

the average June-September minimum temperature is 27°C at Sky Harbor, compared with 21°C at Harquahala.

Plant heat and cold stress

Spatial and temporal expansion of urban heating in the Phoenix metropolitan area has increased the annual number of summertime degree-hours above 40°C and decreased the annual number of wintertime degree-hours below 4°C (figure 6). Urban warming is likely having mixed effects on vegetation productivity and water loss, and both summer and winter temperature trends are physiologically significant with respect to exacerbation or alleviation

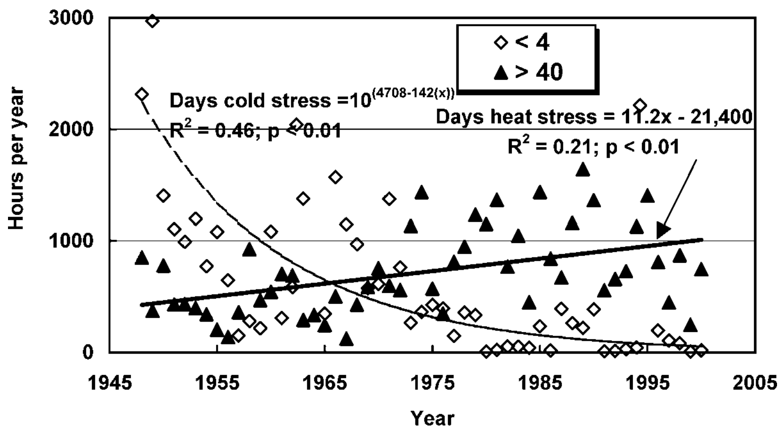

Figure 6. Hours of plant cold stress (<4°C) and heat stress (>40°C) per year at Sky Harbor Airport, 1948–2000.

of indirect heat and chilling stress plant injuries (Levitt, 1980), respectively. Vegetation in the metropolitan area is a mixture of broad and narrow leaf woody trees and shrubs, warm and cool season grasses, and a few cacti and succulents, which have three different methods for photosynthesis. Exposure to supraoptimal, sublethal temperatures above 40°C has the most negative impact on photosynthesis of the dominant vegetation in the urban area, broad and narrow leaf woody trees and shrubs, and cool season grasses (Farrar and Williams, 1991). Supraoptimal temperatures inhibit photosynthesis by decreasing the efficiency of photosynthetic enzymes (Huxman *et al*., 1998; Rokka *et al*., 2000; Crafts-Brandner and Salvucci, 2000) and increasing photorespiration (Law and Crafts-Brandner, 1999; Jordon and Orgen, 1984). Supraoptimal temperatures also increase growth and maintenance respiratory costs (Van Iersel and Linstrom, 1999), lower water-use efficiency (Martin *et al*., 1995), and the lower ET cooling potential of urban vegetation by stomatal inhibition of leaf transpirational water loss (Martin and Stabler, 2002). The latter response is particularly important with regard to climate feedback (see Discussion). Urban heating in the Phoenix area is less likely to inhibit productivity of warm season grasses like Bermuda grass and cacti and succulents because of their spatial or temporal photosynthetic adaptations (Cushman and Bohnert, 1997). Long-term decline in the annual number of wintertime degree-hours below 4°C enables greater productivity of evergreen species during the winter and fosters introduction of greater numbers of subtropical and tropical plant species into the city.

Arthropod thermal window

Among animal groups, arthropods are likely to be most influenced by climate change because they are ectotherms with short lifespans and even shorter reproductive periods, making them vulnerable to changes in diurnal and seasonal temperature patterns (Walker, 1991; McGeoch, 1998). Arthropods are also abundant, diverse, and conspicuous members of the urban ecosystem's fauna (McIntyre *et al*., 2001). Using regression analysis, we estimated that the duration within the 15–38°C thermal window at Sky Harbor increased by nearly a month since 1948, from 236 days to 262 days. During 1997–2000 there were 41 more days in the arthropod thermal window at Sky Harbor than at Harquahala (Table 2). During

Table 2. Duration of the arthropod thermal window (15°C < T < 38°C)

Site	Days per year
Sky Harbor	260
Phoenix Greenway	250
Phoenix Encanto	240
Waddell	236
Litchfield	231
Laveen	227
Maricopa	229
Harlquahala	219

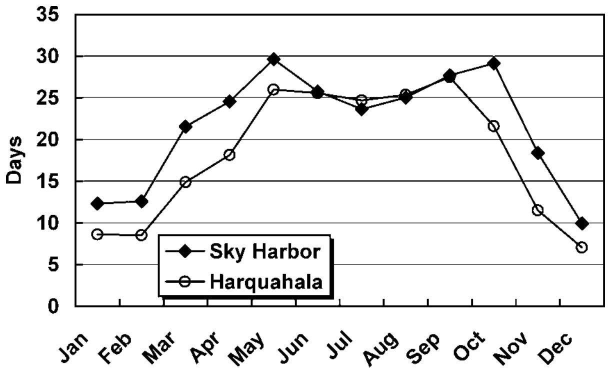

Figure 7. Average number of days per month within the arthropod thermal window (15°C < T < 38°C) at Harquahala (coolest site) and Sky Harbor Airport (warmest site), 1987–2000.

the two hottest months (July and August), all sites had between 49 and 54 days within the thermal window. Differences among sites occurred during the "shoulder months", periods of warming (March and April) and cooling (October and November) (figure 7). During these four months, the number of days within the thermal window ranged from 66 (Harquahala) to 94 (Sky Harbor).

Possible outcomes from an increased thermal window from climate warming include changes in the distribution and abundance of disease vectors (Gratz, 1999), increased agricultural pests (Walker, 1991), and greater arthropod populations in general (Hill *et al.*, 1999; Bryant *et al.*, 2002). Therefore, the significance of an additional month of arthropod activity extends beyond simply the need for extended pesticide use by farmers or homeowners.

Cotton planting and harvest

The urban heat island has dramatically changed the planting and harvest dates for cotton, the major cash crop in the region. Longitudinal analysis shows that the time to reach 400 HU at Sky Harbor Airport has decreased by 23 days ($r^2 = 0.33$; $p < 0.01$), moving the date to reach 2500 HUAP forward by 22 days ($r^2 = 0.32$; $p < 0.01$). For 1997–2000, the average planting was 14 days earlier and the average harvest date was 22 days earlier at Sky Harbor than Harquahala (Table 3). Late season heat stress reduces the quality and quantity of harvest. Cotton grown at agricultural sites near the urban fringe suffer far greater heat stress (average HSUs = 36 ± 12) than cotton grown at Harquahala (12 ± HSUs) (Table 3). One effect of heat stress is to lower the quality of the local cotton crop (measured in "micronaires", a measure of loftiness, lowering its value (Silvertooth, 1999; 2002).

Dairy heat stress and milk production

The number of days with $T_{max} > 27$°C was about 200 days per year at all sites (Table 3). However, rural sites cooled off more at night than did the urban sites, reducing the overall heat stress to dairy cows. At Sky Harbor only one-fourth of the hot days ($T_{max} > 27$°C) had

Table 3. Climate variables for cotton growth and dairy cow heat stress. Data are averages for 1997–2000

	Cotton			Dairy	
Station	Julian days to 400 HU	Julian days to 2500 HUAP	HSUs at 2500 HUAP	Days with $T_{max} > 27°C$	Days with $T_{max} > 27°C$ and <6 hours with $T < 21°C$
Sky Harbor	70	190	–	204	158
Phoenix Greenway	79	196	28	199	140
Phoenix Encanto	76	198	28	206	131
Waddell	76	199	51	205	131
Litchfield	80	202	31	205	125
Laveen	83	205	27	204	121
Maricopa	81	202	22	208	118
Harlquahala	84	212	12	203	101

long cooling periods (six hours with $T < 21°C$). At Harquahala, half of the hot days had the requisite cooling period needed to reduce heat stress (Table 3). All sites had some hot days without long cooling periods during the mid-summer. As with the arthropod thermal window, the effect of urban warming was greatest in shoulder months. For dairy thermal effects, the shoulder months were April-June (warming months) and September-October (cooling months).

Equations (2)–(7) predicted 1 to 6% less milk production at the near urban agricultural sites (Waddell and Litchfield) than at Harquahala and 1 to 16% less milk production at Sky Harbor than at Harquahala. Some dairy farmers in the region now cool their dairy cows using evaporative coolers to increase milk production during the summer (Armstrong, 1994).

Discussion

Positive and negative impacts of urban warming, on balance

Urban warming in the Phoenix region has profound implications for dynamics of the urban ecosystem. The key effects are (1) increased minimum daily temperatures throughout the year, (2) a longer warm period and shorter cool period within a given day, and (3) an extended hot season. The climate of the Phoenix ecosystem has become far less comfortable to humans in the summer than it was in the past, and may even have increased the risk of heat-related deaths and the rate of violent crime. On balance, the energy requirement to maintain comfortable dwelling temperatures has increased, raising the cost of living in the ecosystem, and most residents use air conditioning 24 hours per day from May through October. Urban warming appears to have a generally deleterious affect on both agricultural and non-agricultural plants, although the effect is not entirely negative: one can now grow oranges and Bougainvillaeas within the urban area with little risk of frost damage. On balance, elevated temperatures and decreased cooling periods have probably had a negative effect on cotton harvest and dairy production within the urban heat island. We speculate that the impact of urban warming might hasten land conversion by decreasing profitability for agriculture on the urban fringe and encouraging farmers to sell their land for urbanization. Warming extends the thermal window for arthropods, but with little research on arthropod populations in urban areas, the actual impact of urban warming on arthropod populations is unknown (McIntyre, 2000).

Feedback loops

Several feedback loops affect urban warming. First, evapotranspiration (ET) plays an important role in temperature control in urban areas, particularly those located in hot arid climates. Lougeay *et al*. (1996) (also discussed in Brazel *et al*., 2000) showed that the irrigated urban areas in the Phoenix region are cooler than the surrounding desert during the daytime, with irrigation creating an "oasis" effect. The effect of temperature on ET is complex. To a point, increasing temperature increases ET, which utilizes solar energy and slows the rise in temperature. However, as noted earlier, photosynthesis of non-adapted plants is severely inhibited at temperatures above 40°C. At temperatures above this threshold, much of the cooling effect from plant ET is lost. Thus, the feedback is negative with a well-defined threshold at 40°C.

High temperatures also increase the need for air conditioning, increasing the generation of mechanical (sensible) heat. In Phoenix, sensible heat is generated by both power production and by air conditioning systems that use this power. On the power production side, power to supply peak demands (i.e., hot days) is produced at two coal-fired power plants within the urban area. Mechanical energy lost during power production therefore contributes to urban warming. On the power consumption side, heat is produced by air conditioners (nearly every home and car is air-conditioned). In both cases, mechanical heat production increases in direct proportion to temperature (i.e., a linear response), exacerbating the warming effect at the hottest times of the day and year, a positive feedback loop.

Over longer time scales, we speculate that the impact of urban warming might hasten land conversion by decreasing profitability for agriculture on the urban fringe and encouraging farmers to sell their operations. Since there is far more ET in agricultural fields than in urban land, the conversion from agricultural land to residential land would decrease ET and associated cooling on the urban fringe.

Complex effects

In this paper we examined only direct effects of temperature and not the full complexity of climate impacts and feedbacks. The actual situation is more complex. For example, the more rapid rise in morning temperatures and prolonged hot period may promote more rapid ozone formation (Olszyna *et al*., 1991). Urban warming may therefore have an indirect adverse impact on both humans and plants, via elevated ozone levels. CO_2 levels are also elevated in the Phoenix metropolitan area as the result of combustion processes (Koerner and Klopatek, 2002), adding complexity to the temperature-plant response. We also did not attempt to address the social ramifications of increased temperatures, apart from a possible effect on crime rates and heat-related deaths. Other social consequences of urban heating on social behavior have not been as thoroughly studied. Although it quite clear that children stay indoors during the hot part of summer days (the misery hours), we do not know what impact this has on their social development, or what it means to neighborhood social interactions when it is too hot for an evening walk. Understanding secondary impacts of urban warming on human psychology and social interactions is a very fruitful area for further research.

Is urban warming inevitable?

Although some increase in temperature is probably unavoidable during urbanization, until recently urban planning and design practices have exacerbated local warming by strictly applying zoning, land-use regulations and design standards and practices developed in cooler temperate climates to a hot arid climate. For example, almost all subdivisions are designed to accommodate long hook-and-ladder trucks, with widths up to 32 feet for streets and 40 feet for collector roads, even though most housing in the Phoenix region is single story with very little housing more than two stories that would require hook-and-ladder trucks. Furthermore, because most housing was built after widespread automobile ownership became the norm, nearly all residents have off-street parking in garages or carports. Commercial land use regulations often require excessive parking lot sizes because of the ratio of building square footage to the number of parking spaces is based on the busiest shopping days of the year; the same regulations have scant requirements or incentives for shading. The overabundance of high heat storage materials such as concrete, black asphalt, brick and stone are keys to nighttime urban warming because these surfaces have high absorption rates during the day and also high heat storage capacity to retain heat at night (Oke, 1981). The link between urban form and climate change is being made in several cities. For example, high-resolution thermal imagery, collected by the National Aeronautical and Space Administration (NASA) for Atlanta, illustrated the relationship between single-family residential design and the emission of radiant heat energy (Stone and Rogers, 2001). The NASA research showed that lower density housing patterns contribute more radiant heat than higher density development within the Atlanta region. As a result, Stone and Rogers suggested that "Compact moderate-to-high-density new construction and area-based tree ordinances . . . [can mitigate] the effects of urban development on regional climate change".

Mitigation of the urban heat island

Urban planning and design policy could be redesigned to mitigate urban warming. Construction of narrower roads, development of greater green spaces interspersed among built-up areas, more use of high-albedo materials for roofs and streets, and greater use of shading are among practices that could mitigate warming or reduce its impact (Arendt, 1996; Calthorpe and Van der Ryn, 1986; Pijawka and Shetter, 1995; Steiner, 2000; Thayer, 1994; Thompson and Sorvig, 2000; Rydin, 1992). Such practices were once common in desert cities worldwide, but have fallen out of favor with contemporary architectural design and urban planning. Specific experiments and research linking climatic factors to design and mitigation of the urban heat island are becoming more abundant in the ecological, climatological, and planning literature (e.g., Bonan, 2002; Gomez *et al*., 2001; Mills, 2000;

McPherson, *et al.*, 1988; Akbari, *et al.*, 1993; Garbesi, *et al.*, 1989; Pearlmutter and Berliner, 1998; Heisler, *et al.*, 1995).

Cities throughout the world are warmer than their surroundings because of human activities, yet little is known about how this warming affects urban ecosystems and human well being. This research is needed not only to understand the consequences of global warming, but also local warming. Research can develop strategies to mitigate and adapt to these changes where they are deleterious, as they are in the Phoenix metropolitan area and much of the developing world (Thoman and Bierbaum, 1995). Several cities in the Phoenix metropolitan area now have mitigation strategies in their city general plans to address some of the issues mentioned above, in order to reduce the heat island effect. For example, it is recognized in the City of Phoenix General Plan's Goal 7 (www.ci.phoenix.az.us/PLANNING) the UHI leads to increased human discomfort, increased energy costs during the cooling season, and increased stress on urban vegetation. Policies and recommendations have been developed to explore UHI mitigation. They revolve specifically around: (a) options for building materials and paving surfaces that minimize the absorption of heat, and (b) the encouragement of tree planting to provide more shade. Under (a), 7 recommendations are in existence; under (b) there are 5 that have been accepted (Table 4). As these recommendations are followed in the future in various areas of the metropolitan environment, it is incumbent upon urban ecologists to study the effects of UHI mitigation.

Applying this understanding to future urban development poses a significant challenge to urban planners, architects, and urban climatologists (e.g., Bonan, 2002; Emmanuel, 1997; Mills, 1997, 2000). At the beginning of the 21st century, nearly half of the world's population

Table 4. Goal 7 of the City of Phoenix General Plan

Building materials and paving surfaces that minimize the absorption of heat.

A. Study and explore options to increase shade canopy, by developing street design standards to increase the number of trees planted along all new public streets.
B. Retrofit existing streets where possible, to increase the shade canopy along each side of the street for both pedestrians and vehicles.
C. Encourage the use of light-colored building and roofing materials on municipal, commercial, industrial, and multiunit residential structures. Consider a recommended standard for solar reflectivity for roof systems.
D. Research alternative paving materials that absorb less heat.
E. Explore methods for restricting the use of reflective glass on commercial properties above the second floor, whenever the commercial structure is adjacent to a residential area.
F. Consider amended street cross sections, which decrease the amount of paving required.

Encourage the planting of mature trees (and other vegetation) as a method to provide shade and help reduce temperatures.

A. Study an ordinance change that would require public and private development to plant and maintain an adequate number of trees that will achieve 50% shading on parking lots and the non-building portion of a site in 15 years.
B. Encourage constructing medians with size-appropriate shrubs and trees in new streets of four or more lanes.
C. Encourage shaded open space in private development to reduce heat impacts.
D. Develop a program to educate the public regarding the heat island effect.
E. Explore developing a citywide program to promote tree planting as a method to help reduce the urban heat island effect.

lives in cities. Two-thirds of the world's population will live in cities by 2030 (WRI, 1998), so there is an enormous opportunity to apply new concepts of urban design to the benefit of billions. Cities are where humans have the greatest impact on climate, and where the impacts of climate change have been and will be most profoundly felt by humans.

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