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How do variations in Urban Heat Islands in space and time influence household water use? The case of Phoenix, Arizona

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[1] This paper explores how urbanization, through its role in the evolution of Urban Heat Island (UHI), affects residential water consumption. Using longitudinal data and drawing on a mesoscale atmospheric model, we examine how variations in surface temperature at the census tract level have affected water use in single family residences in Phoenix, Arizona. Results show that each Fahrenheit rise in nighttime temperature increases water consumption by 1.4%. This temperature effect is found to vary significantly with lot size and pool size. The study provides insights into the links between urban form and water use, through the dynamics of UHI.

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1. Introduction

[2] In recent years there has been an emerging interest in examining how global climate change may impact future water resources in rapidly growing cities around the world [*Ellis et al.*, 2008; *Gleick*, 2006; National Research Council, Colorado River Basin water management: Evaluating and adjusting to hydroclimatic variability, 2007, available at http://dels.nas.edu/dels/rpt_briefs/colorado_river_management_final.pdf]. A linked but somewhat less widely examined issue relates to how the process of urbanization itself may already be impacting water consumption through its influence on local temperature patterns. Of particular significance here is the phenomenon of Urban Heat Island (UHI) which arises when roads, buildings, and other urban built structures with high heat absorption capacities take in the sun's radiant energy during the day and release it at night. This nighttime emission of heat by urban built structures leads to elevated nighttime temperatures within the urban core and a prominent gradient along the urban-rural boundary [*Oke*, 1987]. The purpose of this study is to use panel data on the incidence of UHI in the city of Phoenix as a case study to examine how the spatial and temporal variations in surface temperature impact urban residential water consumption.

[3] Although the phenomena of UHI is physically quite distinct from warming due to climate change, some scholars have suggested that "it offers a useful natural experiment" [*Gober et al.*, 2010b, p. 110] to study the impacts of temperature variation and to design policies and practices for mitigating its impact [*Rosenzweig et al.*, 2005; *Solecki et al.*, 2005; *Chagnon*, 1992]. In the rapidly growing metropolitan region of Phoenix, UHI has been linked to an increase in summer nighttime temperatures of almost 10°F between 1948 and 2000 [*Brazel et al.*, 2000, 2007], which is regarded as being comparable to the most pessimistic climate predictions for the American Southwest [*Baker et al.*, 2002; *Gober et al.*, 2010b; *Christensen and Lettenmaier*, 2007; *Karl et al.*, 2009]. A recent National Research Council report on Colorado River Basin Management warns that "steadily rising population and increasing urban water demands in the Colorado River region will inevitably result in increasingly costly, controversial, and unavoidable trade-off choices to be made by water managers, politicians, and their constituents" (National Research Council, 2007, pp. 2–3; see paragraph 3 for details). The impact of temperature variation on water management due to the combined effect of UHI and climate change in this region has thus assumed special significance.

[4] Previous studies on the impacts of UHI have largely focused on its effects on energy consumption [*Ewing and Rong*, 2008] and on health through the morbidity and mortality effects associated with heat stress [*Kovats and Hajat*, 2008; *Kalkstein et al.*, 2009; *Harlan et al.*, 2006]. The relation between UHI and urban water consumption has been somewhat less systematically explored except for a couple of recent studies on Phoenix [*Guhathakurta and Gober*, 2007, 2010]. In particular, *Guhathakurta and Gober* [2007] found that the UHI has a significant effect on residential water consumption with each Fahrenheit rise in nighttime temperatures estimated to increase water consumption of single-family residences by 3.8%.

[5] All of the above studies on the relation between UHI and water consumption are based on cross-sectional data from a single year. UHI is, however, a dynamic phenomena

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and there is strong evidence to suggest that with growing urbanization, both the intensity of UHI (in terms of urban-rural temperature gradient) as well as its spatial distribution has changed significantly over the past few decades in Phoenix [*Brazel et al.*, 2000, 2007]. This raises the question of whether and to what extent has the relationship between UHI and water consumption changed over the years. Dynamic relationships of this kind can be studied through longitudinal studies that collect data on the same set of observational units over time. Longitudinal studies can also help overcome some important estimation problems associated with cross-sectional data, and reveal relationships that are often quite different from that emerging from cross-sectional studies. For instance, an important estimation problem associated with the above cited studies on UHI and water consumption is that of endogeneity, which leads to inconsistent estimates because of the breakdown of the assumption of no correlation between the explanatory variables and the error terms. The problem of endogeneity in this context arises because temperature and water consumption are likely to be jointly determined (simultaneity) and there may be unobserved variables that affect both temperature and water consumption (unobserved heterogeneity) that are difficult to control for in cross-sectional data.

[6] To understand how the problem of endogeneity may arise and how it may lead to misleading results consider the following example. Several studies have found residents to sort into different types of neighborhoods, with some evidence suggesting that wealthier families tend to locate away from transportation corridors and into older neighborhoods with mature trees [*Jenerette et al.*, 2007]. Both of these characteristics (greater distance from transportation corridors and a mature tree canopy) contribute to lower local temperatures in these neighborhoods. These neighborhoods may also be associated with lower water use because of the mature vegetation or it may be true that residents of these upscale neighborhoods have greater awareness about conservation issues. In either case, one would observe lower temperatures and lower water use relative to other neighborhoods. This correlation, however, does not imply causation in terms of higher temperatures leading to higher water use. Since data for some of these variables (such as resident attitudes/awareness or maturity of tree canopy) may not be observed and hence omitted out, it would lead to inconsistent estimates.

[7] The basic idea here is that temperature variation and water use are linked by a complex set of biophysical and behavioral relationships. Longitudinal data can help tease out some of these effects to the extent that using information from repeated observations over different years helps control for time invariant unobserved heterogeneity and thus provides more consistent estimates of the impact of heat islands on residential water use. In this study we use panel data from 1990, 1995, and 2000 for the city of Phoenix. Within this time period, it is reasonable to assume that some of the underlying heterogeneity associated with some of the slow-changing ecological variables (such as soil thermal properties) and institutional factors (such as zoning and Home Owner Association regulations), may have remained relatively constant, and hence can be controlled for. At the same time, this period is long enough to capture some of the key dynamics of urban settlements in the context of a fast growing city like Phoenix. To at least partially address the problem of simultaneity, we use simulated temperatures from a meso-scale atmospheric model as proxies for the actual temperatures. Drawing on this atmospheric model we are able to capture intracity temperature variation at a much more spatially disaggregated level (census tract level) than previous statistical studies that have relied on recorded temperatures from weather stations.

[8] Our study thus contributes toward efforts to get consistent estimates of the impact of local temperature variation, due to UHI, on water consumption. Although the focus is on intracity variation, knowledge of urban climate modifications and their impacts has important lessons for global climate change as well [*Chagnon*, 1992]. Recent studies have shown that climate change has the potential to significantly alter the intensity and spatial extent of UHI [*Rosenzweig et al.*, 2005], thus this study is especially timely. Getting consistent estimates of temperature elasticity has also assumed particular significance given current efforts to use them to build simulation models for estimating future water consumption under different climate scenarios [*Blokker et al.*, 2010; *Ines et al.*, 2009] and to study water-energy tradeoffs in urban policy.

[9] The rest of the paper is organized as follows. Section 2 reviews the related literature on the incidence of UHI and its impact, particularly with reference to the Phoenix region. We also review related theoretical and empirical literature on water demand studies here. Section 3 presents the empirical model and section 4 discusses the associated data and measurement issues. Results are presented in section 5 and section 6 contains the conclusions and policy implications.

2. Review of Related Literature

[10] As cities expand and water resources become scarce, interest in examining the functioning and efficacy of alternative instruments for urban water demand management has grown [*Griffin*, 2006]. In particular, in recent years, a lot of attention has focused on estimating elasticities under different price structures (increasing and decreasing block rates) and on addressing the problem that the choice of the price structure itself may be endogenous [*Olmstead et al.*, 2007]. In a meta-analysis of 124 estimates covering the period 1963 to 1993, *Epsey et al.* [1997] found a mean price elasticity of -0.51 with a short run median of -0.38 and long run median of -0.64. *Olmstead and Stavins* [2008] argue that in spite of this rather low elasticity, price mechanisms have been found to be more cost effective than nonprice mechanisms (such as technology standards and mandatory or voluntary conservation programs, and outdoor water restrictions). However, as they point out, raising water prices to promote conservation is often politically difficult and in many places water rate-setting officials are constrained by law from raising prices, particularly during droughts when these might be most urgently needed. Thus the need for some form of independent and objective regulatory agency separate from the policy-making body is often advocated as an essential part of water reforms [*Rouse*, 2007].

[11] In the above cited studies, climate variables—and in particular, temperature—is introduced as a control variable

rather than as a variable of interest. For instance, the approach followed in most such studies is to introduce dummies for different seasons or estimate different demand functions for different seasons, thus indirectly controlling for the effect of temperature and other weather related variables. When actual temperature data is available, it has been introduced as a level effect (for instance, see the survey by *Worthington and Hoffman* [2008]). As *Hanemann* [1998] observes, temperature may also influence the other slope coefficients (such as lot size, living area and pool size) and could be used to derive separate elasticity estimates of indoor and outdoor use. To the best of our knowledge, these interaction effects of temperature with other housing characteristics have not been systematically studied.

[12] Among studies that introduce temperature as a level effect, the results vary quite a bit as expected, depending on the location of the study and the type of specification. Studies conducted in west European countries, for example, do not find much of an effect [*Schleich and Hillenbrand*, 2009]. On the other hand, studies conducted in US cities (particularly, in the Southwest, where outdoor component of water use is high), have found temperature to have a significant effect on water use. Some examples here include the study by *Olmstead et al.* [2007] based on cross-sectional household level data for several cities in the Southwest and *Guhathakurta and Gober* [2007] who used cross-sectional census tract level data for the City of Phoenix. Nonlinearities and threshold effects in the relation between temperature and water use are likely to be important but have been less systematically examined in empirical studies. An important exception is the study by *Maidment and Miaou* [1986] of daily water use in nine US cities, which used a physics-type transfer function and excluded price and income effects. They found that there is a nonlinear response of water use to temperature changes, with no response for daily maximum air temperatures between 39°F–70°F and an increase in water use with temperatures above 70°F.

[13] A somewhat different stream of literature gaining ground in recent years is interested in exploring the role of longer term structural considerations of how the form of urban development, patterns of land use and land cover, and design of new master planned communities may impact water consumption [*Guhathakurta and Gober*, 2007, 2010; *Yannas*, 1998; *Jabereen*, 2006]. These studies recognize that a large proportion of urban residential water use in the US (particularly in the arid Southwest) is for outdoor purposes. In Phoenix, for instance, an estimated two-thirds of all residential water consumption is for outdoor purposes [*City of Phoenix* (*COP*), 2005] and this segment is highly influenced by factors such as lot sizes, presence of swimming pools, and vegetation structure [*Guhathakurta and Gober*, 2010; *Wentz and Gober*, 2007]. This outdoor use of water is also highly sensitive to climatic factors, particularly temperature variation, thus underscoring the need for studying the impact of UHI on residential water use.

[14] UHI effect is generally characterized by the temperature gradient along the urban-rural boundary and since this gradient is most pronounced at night, differences in minimum temperatures are generally used as the primary indicator of the magnitude of UHI [*Rosenzweig et al.*, 2005]. Previous studies have examined how this intraurban distribution of temperature is determined by natural and anthropogenic factors including variations in land use, building materials and heights, street geometry, and spacing between buildings [*Eliasson*, 2000; *Unger*, 2004]. Several of these studies have explored varied urban forms and their differential effect on UHI formation [*Akbari and Rose*, 2001; *Rose et al.*, 2003; *Brazel et al.*, 2007]. The primary aspects of urban form that are implicated in UHI are the distributions and concentrations of roofing, impervious surfaces, and vegetation. In general, standard roofing and paving materials are dark and solid, which tend to increase their heat absorption capacities. In contrast, trees and green vegetation have a cooling effect on surface temperatures through evapotranspiration [*Gartland*, 2011]. In addition, a World Meteorological Organization study defined and ranked seven types of urban development zones' effects on climate at the local scale, observing that higher density areas tended to have more severe UHI conditions [*Oke*, 2006].

[15] The phenomena of UHI has been widely studied in the context of the metropolitan area of Phoenix since the early 1980s because of its rapid rate of urbanization and its warm and dry climate coupled with the large number of clear days that create conditions that are conducive to the development of UHI [*Balling and Brazel*, 1987; *Brazel et al.*, 2000, 2007]. Table 1 shows the recorded average monthly temperature difference between a typical urban site within Phoenix (Sky Harbor Airport) and a rural site (Maricopa) located about 20 km south of the urban area for the study years: 1990, 1995, and 2000. As shown here, the average monthly temperature difference varies between years. Temperature records from 12 weather stations across Phoenix between 1949 and 1985 showed rapid increases in minimum temperatures in the central portions of the city and a significant expansion of the areas affected by UHI [*Balling and Brazel*, 1987]. More recent studies have examined how the location of new subdivisions and the pace of development affect nighttime temperatures in Phoenix. For instance, it was found that the low temperatures recorded by the weather stations included in the study rose by an average of almost 2°F for every 1000 new homes built within a radius of 0.5 km [*Brazel et al.*, 2007]. These temporal and spatial variations in temperature in Phoenix make it an interesting case for the purposes of this study.

Table 1. Average Monthly Temperature Difference Between Representative Urban Site and Rural Site During the Study Years[a]

Month	1990	1995	2000
Jan	4.8	2.8	4.9
Feb	4.6	4.2	4.9
Mar	5.4	4.1	4.0
Apr	5.3	5.5	4.6
May	5.9	4.3	4.8
Jun	6.0	5.5	5.2
Jul	4.1	5.3	3.8
Aug	5.1	4.7	3.1
Sept	4.7	5.2	4.5
Oct	6.9	6.7	2.9
Nov	6.8	5.1	4.4
Dec	5.2	5.9	5.6

[a] The average monthly temperature difference is shown in Celsius. The urban site is at Sky Harbor Airport and the rural site is at Maricopa.

3. Data and Measurement Issues

[16] The coverage of this study is restricted to the municipal boundaries of the City of Phoenix, which is the nation's sixth largest city (U.S. Bureau of the Census, Urbanized Areas in 2000, 2006, available at http://www.census.gov/geo/www/ua/ua2k.txt). The City of Phoenix Water Services Department covers the entire Phoenix incorporated area (546 square miles) and services around 1.4 million customers [*COP*, 2005]. Under normal, nondrought conditions, the City has access to approximately 163 billion gallons of water per year, around 90% of which comes from surface water through the Salt River Project and the Central Arizona project [*COP*, 2005]. Municipal water records from the City of Phoenix were not available at the household level for the 3 years of this study. So we use the census tract level as the unit of our analysis in order to match the available water records with an expanded census data set and other data (such as on vegetation and temperature) that was also available at the tract level. The drawback of using this aggregate data is that it fails to account for heterogeneity across individual households. Since our main interest in this paper is in studying the impact of temperature variations due to UHI, which is a mesoscale phenomenon, taking the census tract as the unit of analysis seems to be an appropriate alternative.

[17] Residential customers, including single family homes and apartments, comprised almost 90% of the 403,000 accounts served by the City and almost two-thirds of the water consumption in 2010 [*COP*, 2011]. Single-family homes accounted for about 50 percent while apartments and other multifamily housing accounted for approximately 16 percent of total City water use. These two types of units generally have different patterns of water use [*Hanemann*, 1998]. An important reason for this is that there tends to be less outdoor space per household in multifamily units. Thus, in the month of June when water use for outdoor irrigation is high, the difference in average water consumption between these types of dwellings is also large. In June 2010, for instance, it was found that single family units consumed on average about 16,000 gallons, while multifamily unit consumed only a quarter of this amount [*COP*, 2011]. In contrast to this, in the month of February when outdoor irrigation needs are low, the difference in water use between these two types of dwellings is also observed to be much lower: 8000 gallons for single family and 3000 gallons for multifamily units. In many areas, residents of multifamily units are not metered and billed individually and the maintenance of landscaping (including irrigation) are often controlled by a building manager rather than by the residents individually. Given these different motivations and their confounding effects, only data on water consumption by single family residential units was considered for the purposes of this study. The data on single family water use was obtained from the Water Services Department, City of Phoenix for the month of June for all the study years. Table 2 lists the data sources of the variables used in the study along with the associated summary statistics for pooled data. Table 3 shows the summary statistics for the different years separately and Table 4 shows the correlation matrix.

[18] The City of Phoenix is serviced by a single water supplier and all residential consumers within the city face the same water rate which consists of a monthly fixed service charge, volume charge, and environmental charges. The volume charge for any given season is a fixed price per unit of consumption and does not vary according to the amount of consumption. However, the volume charge does vary somewhat across seasons with the summer rate being the highest. Water rates for residential consumers for the study years are given in Table 5. As shown here, inflation-adjusted water rates have not changed much over the study period. Apart from these water charges, utilities also often use other monetary and nonmonetary instruments to achieve specific goals, such as that of conservation. For instance, rebates may be offered to replace toilets or convert to desert landscaping. No such rebates were offered on a large scale during the study period to residential customers in the City of Phoenix (Western Resources Advocates, 2007, Arizona Water Meter: A Comparison of Water Conservation Programs in 15 Arizona Communities, available at http://www.westernresourceadvocates.org/azmeter/report.pdf). Beginning in 1992, certain limitations on watering landscaping plants were set but single family dwellings were exempted.

[19] It is noteworthy that the City's annual water use has been relatively stable since 1996 although population has grown by more than 25% during this period [*COP*, 2011]. It is estimated that per capita water use has declined by 25% in the last 15 years [*COP*, 2011]. According to the latest report by the City of Phoenix Water Services Department, the key factors that have contributed to this decline include, improved plumbing fixture standards, smaller residential lots, fewer new pools, growing acceptance of desert landscaping in both new and existing homes and increased customer awareness [*COP*, 2011].

[20] The City of Phoenix has engaged in a number of educational programs over time to promote water conservation.

Table 2. Summary Statistics and Sources of Data[a]

Variable	Mean	SD	Minimum	Maximum	Source
Water consumption per single family unit in Jun (gallons)	17463.03	5057.906	5829.725	58842.67	Water Services Department, City of Phoenix
Water prices (constant 1990 prices)	1.203	0.0437	1.17	1.26	Water Services Department, City of Phoenix
Household size	2.813275	1.0470	1.0	13.99	US Census Bureau
Age of unit (years)	41.5922	16.2013	9.3718	91.6410	Maricopa County Assessors Data
Median household income ($)	34957.3	22,693	0	135,432	US Census Bureau
Temperature at 05:00 local time (°F)	75.2256	2.8702	67.55	80.51	WRF model simulation
NDVI	0.51549	0.0292	0.4444	0.62	Landsat imagery
Pool size (sq. feet)	110.7395	99.1387	0	519.7917	Maricopa County Assessors Data
Lot size (sq. feet)	10420.13	6764.701	0	74417.66	US Census Bureau
Living area (sq. feet)	1505.988	441.1141	0	3050.284	US Census Bureau

[a] All the statistics reported here relate to the census tract level.

Table 3. Summary Statistics by Sample Years[a]

Year	Mean	Standard Error	[95% Confidence Interval]	
	Water Consumption per Single Family Unit in June (Gallons)			
1990	17990.06	325.5084	17351.14	18628.97
1995	16328.13	247.8148	15841.72	16814.55
2000	18252.96	315.6713	17633.36	18872.57
	Household Size			
1990	2.844259	0.0882367	2.671067	3.017452
1995	2.666232	0.0511131	2.565907	2.766558
2000	2.961505	0.0403679	2.88227	3.04074
	Age of Unit (Years)			
1990	43.14402	0.8845667	41.40778	44.88026
1995	41.70267	0.9706044	39.79754	43.60779
2000	40.48508	1.020794	38.48145	42.48872
	Median Household Income ($)			
1990	23650.42	1155.487	21382.41	25918.43
1995	32291.36	1045.601	30239.03	34343.68
2000	47979.98	1360.74	45309.1	50650.87
	Temperature at 05:00 Local Time (°F)			
1990	76.51207	0.1296917	76.25751	76.76664
1995	72.20864	0.1210896	71.97096	72.44631
2000	76.81154	0.0954229	76.62424	76.99884
	NDVI			
1990	0.5306296	0.001608	0.5274734	0.5337858
1995	0.516338	0.001682	0.5130365	0.5196396
2000	0.4999163	0.0015029	0.4969663	0.5028663
	Pool Size (sq. feet)			
1990	115.1583	6.283549	102.8248	127.4918
1995	109.243	5.717435	98.02067	120.4653
2000	109.3394	5.905482	97.74799	120.9308
	Lot Size (sq. feet)			
1990	11330.94	529.2054	10292.21	12369.68
1995	10304.51	382.1345	9554.452	11054.57
2000	9868.613	286.1533	9306.946	10430.28
	Living Area (sq. feet)			
1990	1477.88	25.5278	1427.773	1527.986
1995	1509.4	25.9827	1458.401	1560.399
2000	1536.763	27.4235	1482.935	1590.59

[a] The number of observations = 833.

Table 5. Price Structure in City of Phoenix During Study Years for Single Family Residential Units (at constant 1990 prices)[a]

	1990	1995	2000
Monthly service charge ($)	5.12	4.652	3.882
Volume Charge (per unit)			
High season (Jun–Sep)	1.17	1.174	1.264
Low season (Dec–Mar)	0.74	0.762	0.959
Medium season (Apr–May, Oct–Nov)	0.90	0.908	0.993

[a] Here, 1 unit = 748 gallons = 100 cubic feet. Monthly service charge includes: 4488 gallons in Oct through May (6 units); 7480 gallons in Jun through Sept (10 units). The source City of Phoenix Water Services Department. Inflation adjusted prices were calculated using Consumer Price Index Series for Western US region from Bureau of Labor Statistics.

These include various community outreach and classroom programs and distribution of conservation information through its water conservation website and free bilingual brochures. The most significant and coordinated large-scale conservation/educational campaign during the study period was the Water Use it Widely (WUIW) campaign launched in April 2000. This campaign employed a colorful and simple message that "there are a number of ways to save water using common but unexpected items" [*Behavior Research Center* (*BRC*), 2001, p. 1]. Since our study period only extends up to June 2000, it is unlikely that the WUIW campaign would have had any significant effect on water consumption within this short period. While awareness and (possibly) attitudes toward water conservation may undergo a change within a short period of time, behavioral change leading on to actual changes in water use (if any) generally takes a longer time. We do not have data on awareness and attitudes toward water conservation to be able to incorporate these variables in our model. However, it is worth noting that a number of studies were commissioned by the Arizona Water Users Association at different points in time to assess the impact of this campaign. In particular, a study based on random telephone surveys of 1400 households in 2007 found that although awareness toward water conservation had changed significantly from 2000 to 2007, there was no statistically significant relationship between awareness of WUIW and observed water use [*BRC*, 2007].

[21] Indoor and outdoor water uses are influenced by very different set of factors. However, data on water consumption does not distinguish between these two types. Thus, the estimated parameters relate to the sum of water used for outdoor and indoor purposes. While indoor residential water usage depends on household size, living feet, the types of appliances owned and how these are used; outdoor residential water usage depends crucially on the interaction between climate, lot size, type of landscaping, irrigation system used, pool characteristics, and management practices. The Maricopa County Assessor's database was used to get information on age of house, amount of living space in square feet, lot size, presence of evaporative coolers, percentage of pools, and average size of pools. Indoor household use is expected to be positively related to

Table 4. Correlation Matrix

	Water Use	Median Income	Age of Unit	Household Size	Living Feet	Temperature	Lot Size	Pool Size	NDVI
Water consumption	1.0000								
Median income	0.3607	1.0000							
Age of unit	0.1116	−0.5807	1.0000						
Household size	0.0593	−0.1565	0.0847	1.0000					
Living feet	0.4589	0.7471	−0.5281	0.0847	1.0000				
Temperature	0.1897	0.0102	0.1498	0.2282	−0.2094	1.0000			
Lotsize	0.3395	0.1673	−0.0938	−0.1091	0.3903	−0.1048	1.0000		
Pool size	0.5523	0.7049	−0.4465	−0.2438	0.8926	−0.1656	0.3416	1.0000	
NDVI	0.2817	0.1869	−0.0073	−0.2321	0.3557	−0.1590	0.2447	0.3655	1.0000

household size and amount of living space, although the relation may not be linear. To account for the nonlinearity, we tried including squared terms of both these variables in the demand equation. Evaporative coolers are used in several Phoenix homes as an efficient and cheaper alternative to air conditioning [*Guhathakurta and Gober*, 2007]. The cooling effect in these devices is achieved through evaporation and so census tracts with higher percentage of evaporative coolers are expected to have higher water consumption.

[22] The age of housing can influence water consumption through various ways. The most direct effect is through the vintage of the appliances and fixtures that use water. Newer appliances and fixtures are likely to be more resource efficient and exhibit less wear and tear resulting in less leakage of water. In 1990, the city amended its plumbing code to require water-conserving fixtures (including high-efficiency toilets) in new construction and renovation. All this would suggest that newer homes are likely to consume less water *ceterus paribus*. However, it is also true that new homes come equipped with newer more water intensive appliances like Jacuzzis and dishwashers than older homes. Previous studies have hypothesized a nonlinear relationship, with both very old and newer homes likely to have lower water consumption than middle aged homes [*Olmstead et al.*, 2007]. To test for this hypothesis we included both linear and squared terms of age of housing unit.

[23] As discussed before, outdoor water use is likely to be most sensitive to temperature. Here two main categories of water use can be distinguished. The first is for landscaping and the other is for swimming pools. For a given type of groundcover, irrigation requirements per square foot depend on soil type, the slope of the land, the amount and timing of precipitation, temperature, wind, and other factors. Actual water used, however, may or may not be closely related to these requirements. The actual amount of water used is likely to depend on the irrigation system and how it is used as well as on resident knowledge and attitudes. For instance, drip systems and in-ground turf irrigation systems are often postulated to be more efficient than hand watering with a hose as the former can be put on timers and programmed to deliver the right amount of water when needed. However, previous studies conducted in the state have found that in practice it is not clear which irrigation system is more efficient because management of the system is as important as the system hardware. For instance, *Martin* [2001] found that although mesic vegetation is postulated to be more water intensive than xeric vegetation, there are no significant differences in the actual water applications between these two vegetation types.

[24] To capture the effect of vegetation type and density at a spatially disaggregated scale to match the water records, we use data on Normalized Difference Vegetation Index (NDVI) from spectral signatures in Landsat imagery. NDVI is widely used to determine the density of green on a patch of land and to monitor evapotranspiration rates. We expect NDVI to be positively associated with outdoor water use. The other major outdoor use is associated with the presence of swimming pools. The average percentage of single family housing units with swimming pools in the census tracts in our study area was found to be 25%, with the average size of an individual pool being around 450 square feet. The average evaporation rate from swimming pools in Phoenix is estimated to be approximately 6 feet per year, most of which occurs in summer (Arizona Department of Water Resources (ADWR), Technologies—Pools, Spas and Water Features, 2011, available at http://www.azwater.gov/AzDWR/StatewidePlanning/Conservation2/Technologies/Tech_Pools_Spas_Waterfeatures.htm). Other sources of water loss in addition to evaporation are filter backwashing, pool draining, splashing, and leaks. The evaporation rate has been found to depend on the surface area of the pool, the temperature, the relative humidity, and the wind (ADWR, 2011, online). Thus to capture the effect of swimming pools on water consumption we included the percentage of pools in a census tract, average pool size, and interaction terms between these pool characteristics and temperature in our specifications.

[25] Getting accurate temperature data at the appropriate spatial resolution is critical for characterizing the UHI phenomena. For this study, we used estimated (instead of observed) temperatures from a meso-scale atmospheric model of the region because data on actual recorded temperature from the weather station network in Phoenix is not of sufficient spatial detail to match with the water records we have at the census tract level. The simulated temperatures were obtained from the Weather Research and Forecasting (WRF) model version 2 [*Skamarock et al.*, 2005], which numerically solves a set of differential equations that govern the evolution of the state of the atmosphere in space and time in terms of air temperature, pressure, specific humidity and wind speed. This model examines the influence of land use and land cover changes, radiation trapping, heat storage and anthropogenic heat flux (due to traffic combustion and electricity consumption by air conditioners) on surface temperatures. WRF is a community model of the atmospheric sciences and used worldwide for research and weather forecast (See here for details: http://www.wrf-model.org/index.php).

[26] A global 30 s land use/cover database classified according to the 27-category USGS Land Use/Land Cover (LULC) System [*Anderson et al.*, 1976] is provided with WRF. Urban areas were added to the data after being extracted from the Digital Chart of the World [*Defense Mapping Agency*, 1992]. In this data, the LULC coverage of Phoenix metropolitan area is underrepresented. *Stefanov et al.* [2001] developed a classification methodology to derive more recent 12 category land cover data for the Phoenix metropolitan region based on Landsat TM reflectance data using visible to short wave infrared spectral data. These land cover data were incorporated into WRF to give three Phoenix specific urban LULC categories: urban built-up, urban mesic residential and urban xeric residential, which were mainly distinguished by the type of vegetation and irrigation (no vegetation, well-watered flood or overhead irrigated, and drought-adapted vegetation with drip irrigation, respectively). Besides the LULC data, the model also incorporates determinants of anthropogenic heat flux calculated from hourly profiles of anthropogenic heat based on resident and working population density data, electricity consumption, and vehicle miles traveled [*Grossman-Clarke et al.*, 2005].

[27] The model was used to simulate temperatures two meters above the surface (T2m) on a 2 km × 2 km grid for the periods 24–27 June 1990, 23–26 June 1995, and 14–17

June 2000 for the Phoenix metropolitan region. As explained earlier, UHI in Phoenix is largely a nighttime phenomena so spatial variation in temperature at 05:00 local time has been used to characterize the UHI effect [see also *Grossman-Clarke et al.*, 2005]. From the simulated temperature profiles we extracted information on temperature at 05:00 local time for all the 3 years. The model performances were tested against data from the National Weather Service at Sky Harbor Airport located in the Center of Phoenix and a network of 15 weather network stations across a range of land uses. For all the three simulation periods, WRF performed sufficiently well with simulated air temperatures being within 2°C and less of the observed temperatures at all times. The WRF model's ability to capture rural and urban temperatures, and specifically the UHI phenomena in Phoenix, is discussed in a number of published studies (see in particular, *Grossman-Clarke et al.* [2005, 2010] and the studies cited therein). While hourly T2m data calibrated to land observations are also available through other sources, such as the Global Land Data Assimilation System, the resolution is much lower (0.25 × 0.25 degree level or about 30 km × 30 km). Hence it is not very useful for the purposes of this study.

[28] Figure 1 provides an overlay of surface temperatures derived from this simulation, applied at the level of the census tract, for two of the 3 study years. As the second fastest growing city in the US over this time period, Phoenix has witnessed a significant conversion of agricultural and desert land to urban uses over the past few decades. This has contributed to significant temporal variation in surface temperatures. *Baker et al.* [2002] found that the average daily minimum temperature at Sky Harbor Airport (in the center of the city) increased by about 9.4°F between 1948 and 2000 and the average daily maximum temperature rose by 5.9°F. Using regression analysis, they found that the average daily minimum temperature in June has increased by 0.2°F year^{-1} (significant at the $p < 0.01$ level). This study also found a significant rural-urban gradient in the Phoenix metropolitan area, with the average daily minimum temperature at Sky Harbor Airport observed to be 11.4°F higher than that in a nonurbanized agricultural site surrounded by desert. In our study, which covers only the City of Phoenix and not the entire metropolitan area, the spread in surface temperature was found to be around 9.3°F in 1990. As urbanization expanded to the outlying areas, the spread in surface temperatures reduced somewhat to 7.6°F in 2000. However, as Figure 1 shows, the heat island is not a smooth urban-to-rural gradient in sprawling urban areas [see also *Jenerette et al.*, 2007; *Gober et al.*, 2010a]. The intensity of heat island and its impact have been found to be highly correlated with place-specific measurements of ecological variables, such as vegetation density and open space [*Grossman-Clarke et al.*, 2005; *Gober et al.*, 2010a]. The spatially disaggregated nature of our study helps to capture some of this underlying variation in temperature and thus contributes toward a better understanding of the effects of temperature.

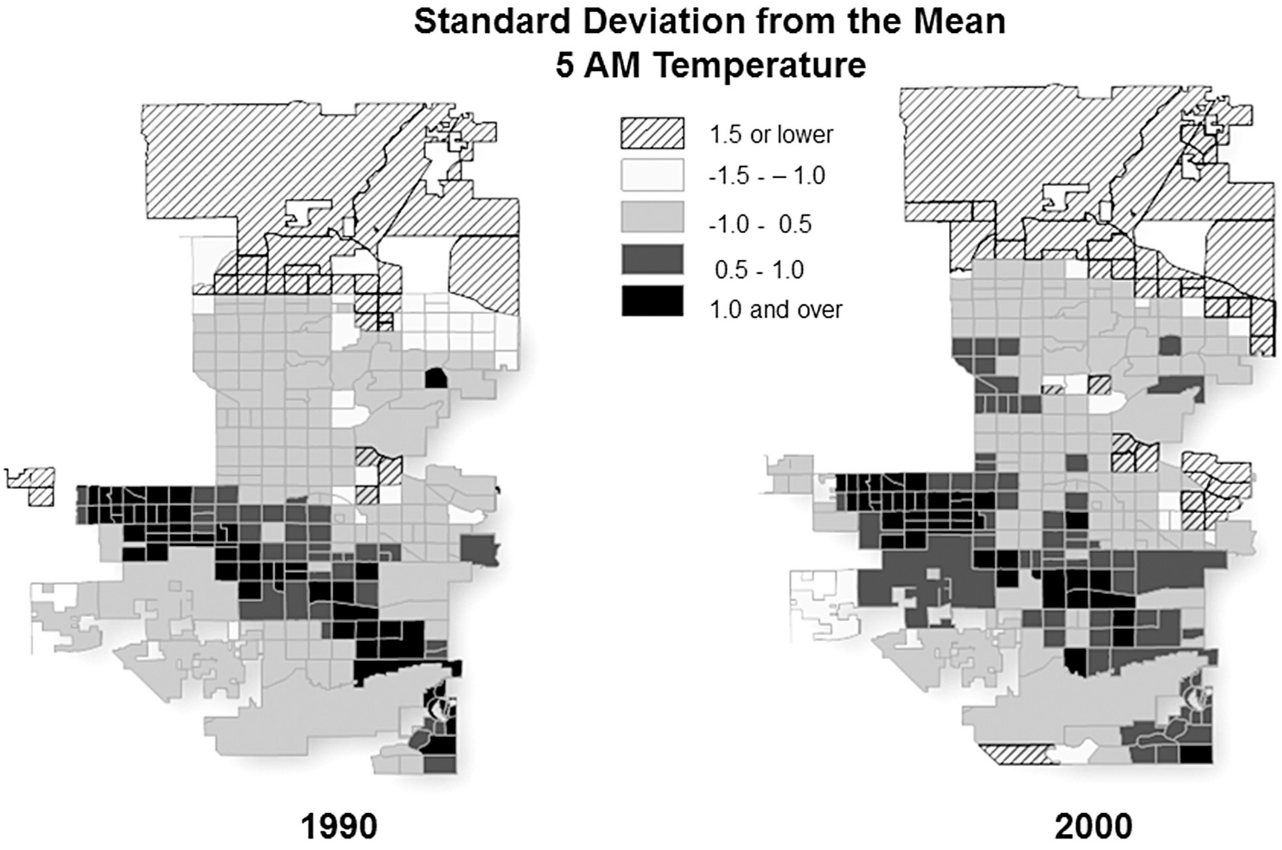

Figure 1. Spatial and temporal variation in surface temperature (at 05:00 local time) in City of Phoenix at census tract level.

4. Empirical Model

[29] The household consumption of water can be viewed as a composite of direct use for drinking and indirect use of water as a complement to different household activities such as cooking, cleaning, washing, personal hygiene, recreation, and landscaping [*Höglund*, 1999]. To model the impacts of the varied factors that influence water consumption, researchers have used linear, log-log or semilog specifications of the demand equation. *Hanemann* [1998] points out that all of these functional forms, although often applied in a rather ad-hoc manner, can be shown to be potentially consistent with economic theory of utility maximization. The estimated coefficients, however, are likely to be quite sensitive to the form of specification, as several empirical studies have confirmed (see *Worthington and Hoffman* [2008] for a survey). A log-log model has the advantage that elasticities can be directly obtained from the parameter estimates. A log specification also makes the range of variables more comparable to each other. However, the log-log specification assumes that elasticities are constant for the entire domain of variable values, which may not be a defensible assumption for many of the effects.

[30] In this study we did not start with any a priori preference for a specific functional form. Instead we tried different specifications with the dependent and independent variables specified in both log and level forms, as explained in greater detail in section 5. For expositional ease, a generic form of the water demand equation (with all variables entering as levels) can be represented as follows

$$\mathrm{W}_i = \mathrm{K} + \mathrm{aH}_i + \mathrm{bD}_i + \mathrm{cT}_i + \mathrm{dV}_i + \mathrm{e}_i, \tag{1}$$

where i denotes the census tracts;

W_i = average single-family water consumption in census tract i;

H_i = Characteristics of the housing units in census tract i (such as lot size, living area, pool characteristics);

D_i = demographic characteristics of population in census tract i (such as income, education, median age, among others);

T_i = minimum temperature on a typical summer day in census tract i;

V_i = normalized difference vegetation index (NDVI) (a measure of vegetation cover); and

e = the random error term that captures the effect of all the unobserved variables.

[31] Ordinary least squares (OLS) estimation of the above model would give consistent estimates if it is assumed that the error term (e) is uncorrelated with the explanatory variables. However, as discussed before, there is a potential endogeneity problem in the above specification because temperature and water consumption are likely to be jointly determined (simultaneity) and there are unobserved variables that affect both temperature and water consumption (unobserved heterogeneity). Some examples of such unobserved effects include residents' awareness and attitudes about water conservation, Homeowner Association (HOA) regulations (which specify rules regarding vegetative cover and influence property values), physical and ecological characteristics (water table, soil moisture and thermal properties, elevation, vegetation type).

[32] To understand how such unobserved effects could bias the estimated coefficients, consider the effect of soil quality, which is omitted from the above specification. Suppose we have two census tracts that are identical in every respect except for their soil type. In particular, suppose census tract A has a soil type that has lower water retention capacity than the soil type in tract B. It is likely that tract A has higher surface temperature (due to lower rates of evapotranspiration from the soil). It is also likely that water intake (for any given vegetation type) is higher for tract A. Note that the direct effect of surface temperature on water use in this case is exacerbated by the indirect effect of soil type on water use. Thus if the effect of soil type is omitted from the analysis, we will be overestimating the effect of temperature change on water use.

[33] By utilizing information on both the intertemporal dynamics of change and the individuality of the entities being investigated, one can better control for the effect of unobserved effects. Using data from 1990, 1995 and 2000 we estimate both the fixed effects and random effects model. As *Green* [2008, p. 183] points out, the "crucial distinction between fixed and random effects is whether the unobserved individual effect embodies elements that are correlated with the regressors in the model, not whether these effects are stochastic or not." Random effects assume that the entity's error term is not correlated with the predictors, which allows for time-invariant variables to play a role as explanatory variables. In the random-effects model, however, one needs to specify those individual characteristics that may or may not influence the predictor variables. The problem with this is that some variables may not be available therefore leading to omitted variable bias in the model. In the fixed effects model, the effect of all time-invariant effects is differenced away. The resulting estimates are consistent but the problem is that the effect of time-invariant or slow changing characteristics (some of which may be of interest to the investigator, like NDVI) are swept away. In section 5 we report estimates obtained from both the fixed and random effects model and the results of the Hausman test to examine which specification fits the data better.

[34] While using these longitudinal data techniques helps address the problem of unobserved heterogeneity the problem of simultaneity still remains and is quite challenging to address given the complexity of the relation between surface temperatures and water use. This complexity arises due to the multiple feedback effects among characteristics of the built environment, vegetation intensity, nighttime temperatures, and water use. While local temperatures affect water consumption, these local temperatures are in turn determined by the interaction of irrigation practices with soil type and vegetation; evaporation from water bodies (pools and artificial lakes); as well as other characteristics of the built environment. For example, as *Guhathakurta and Gober* [2010] point out, while higher vegetation intensity and presence of pools is expected to increase the amount of water demanded, it may also reduce nighttime temperatures, thereby moderating the amount demanded. Using a microclimate model of energy flux, *Gober et al.* [2010a] found that heavily vegetated surfaces promote nighttime cooling by preventing the buildup of heat during the daytime hours. However, they found this relation to be nonlinear with threshold effects.

[35] It is beyond the scope of this paper to structurally model this complex relation between temperature and water use. Instead, we think that our use of simulated as opposed to observed temperatures helps at least partially address the problem of simultaneity. This is because the simulated temperatures are derived from a mesoscale atmospheric model that incorporates variables such as, land use and land cover as well as determinants of anthropogenic heat flux (as explained in section 3), which can be interpreted as instruments for T_i in the water demand equation (1). The most efficient way of combining multiple instruments is usually through a two-stage least squares (TSLS) procedure, originally developed by *Theil* [1953]. In the first stage of this procedure, the "endogenous" right hand side variable (observed temperature in this case) is regressed on all instruments. In the second stage the predicted value is plugged into the equation of interest [*Angrist and Krueger*, 2001]. Note that we do not have observed temperature readings at the census tract level and so we cannot follow a complete TSLS procedure. Thus the simulated temperatures are not strictly speaking an Instrument Variable (IV) estimator. However, following *Angrist and Krueger* [2001, p. 17], simulated temperatures can be "interpreted as an application of instrumental variables" because these meet two important requirements for instruments: (1) highly correlated with actual temperatures, as discussed in section 3 and (2) uncorrelated with the error term.

[36] Note that the use of simulated as opposed to observed temperatures in (1) could also be seen as potentially introducing an "error in variables" or "measurement error" problem. In linear models, measurement error in explanatory variables has been shown to lead to a downward bias in the estimated coefficient. In our case, the measurement problem arises because of the mismatch between the spatial support of the explanatory variable (temperature measured at a few weather stations) and the dependent variable (water use measured at the census tract level). In such cases of spatial mismatch, a common procedure is to interpolate using procedures such as kriging, which lead to measurement error. In our case, however, the estimated temperatures are not derived from a kriging process but from an underlying spatially explicit atmospheric model, and thus serve as instruments for the actual temperatures (as explained above). Instrument variable methods are commonly used to overcome measurement error problems in explanatory variables (see for example, *Hausman* [2001]).

[37] Finally it is possible that there is spatial dependence in residential water consumption. To the extent that this spatial dependence is not captured by the explanatory variables of the model, it could lead to spatial autocorrelation in the error terms [*Anselin*, 1988]. In the case here, we expect much of the spatial dependence in water consumption equation (1) to arise from the spatial distribution of temperature and other location specific factors such as land use and land cover, NDVI etc. As explained earlier, our simulation of surface temperature using georeferenced data on land use and land cover accounts for a number of these location specific factors. Once these location dependent factors are accounted for, the predicted water consumption did not show presence of significant spatial dependence (based on calculation of Moran's I, which is generally used as indicator of spatial association, see *Anselin* [1988]).

5. Results

[38] Table 6 shows the results of the different specifications of the water demand equation. This includes the results from the estimation for the different years (1990, 1995, and 2000) separately (model I, II and III, respectively) as well as the pooled regressions (model IVA and IVB). Results from the fixed effects (FE) and random effects (RE) estimation are also presented (models V and VI, respectively). To see if fixed effects are needed, we conducted an F test of the joint significance of these effects. The null hypothesis of these effects being equal to zero was rejected, thus confirming that the FE model does better than the pooled OLS model. To test for random effects we conducted a Lagrange Multiplier test with the null hypotheses that variances across the individual effects are zero, i.e., there is no significant difference across units (census tracts) [*Hsiao*, 1986]. The null hypothesis was rejected at 1% level thus confirming the importance of the random effects. Finally, to decide between the FE and RE models, we conducted the Hausman specification test, which tests whether the unit specific errors are correlated with the regressors. The null hypothesis is that the errors are not correlated, which implies that the preferred model is RE versus the alternative of FE [*Green*, 2008; *Hsiao*, 1986]. The null hypothesis was rejected at 1% level, and thus in the ensuing discussion we focus on the results from the FE model although all the other models are also presented and their results compared with the FE model. As noted before, the FE model does not capture the effect of invariant or slow changing variables (like vegetation density) and this is another reason for including results from the other specifications.

[39] As mentioned before, all single family residents within the City of Phoenix face the same prices for water in any given season of a year. Therefore in this study we are not able to estimate the effect of cross-sectional variation in water prices. In Table 6, we have presented two versions of the pooled model, one with inflation adjusted water prices (model IVB) and the other without (model IVA) to compare how prices may affect estimation of water demand. As shown in Table 6, the effect of water prices is not found to be statistically significant. As discussed before, water prices are quite low in Phoenix and have not varied much over the study years, thus it is not entirely surprising that water prices do not play a significant role in estimation of the water demand function.

[40] The impact of nighttime temperature, the most important variable of interest here, is found to be statistically significant in all the different models. As discussed before, we included the temperature variable as both an intercept/level effect and a slope effect (through its interaction with other variables). To capture the possibility of potential nonlinearities in the level effect, we tried including linear, square, and cubic terms for temperature in the regressions. However, the square and cubic terms were not found to be statistically significant in any of the models while the linear term was found to be highly significant ($p < 0.01$) in all the models. The coefficient for the intercept effect was found to lie in the range of 0.01 to 0.03. In the pooled regressions (models IVA and IVB) we included separate dummies for the level effect of temperature in different years. The

Table 6. Water Demand Model Estimates[a]

Variable Name	Model I 1990	Model II 1995	Model III 2000	Model 1VA Pooled (without price)	Model IVB Pooled (with price)	Model V FE	Model VI RE
Log median income	0.0066	0.0334	0.2322[b]	0.0668[c]	0.0682[c]	0.0751[b]	0.0695[b]
	(0.0559)	(0.0298)	(0.0443)	(0.0320)	(0.0317)	(0.0277)	(0.0258)
Age of house	0.0049[b]	0.0069[b]	0.0089[b]	0.0069[b]	0.0068[b]	0.0017	0.0069[b]
	(0.0013)	(0.0008)	(0.0007)	(0.0005)	(0.0005)	(0.0050)	(0.0007)
Household size	0.0300[b]	0.0493[b]	0.1094[b]	0.0477[b]	0.0473[b]	0.0078	0.01845[c]
	(0.0110)	(0.0129)	(0.0153)	(0.0147)	(0.0147)	(0.0059)	(0.0077)
Living area (linear term)	−0.00002	−0.0003	−0.0002	−0.0003[c]	−0.0003[c]	−0.0003	−0.0004[c]
	(0.0002)	(0.0002)	(0.0002)	(0.0001)	(0.0001)	(0.0010)	(0.0002)
Living area (squared term)	5.63e-08	6.07e-08	9.1e-08[b]	9.04e-08[b]	9.19e-08[b]	8.07e-09	9.26e-08[c]
	(00.0062)	(4.60e-08)	(3.57e-08)	(2.81e-08)	(2.83e-08)	(3.28e-07)	(4.65e-08)
NDVI	−0.3690	1.2208[b]	0.8102[c]	0.7166[b]	0.7016[b]		−0.1183
	(0.4972)	(0.4355)	(0.3684)	(0.2470)	(0.2496)		(0.2608)
Temperature	0.0227[b]	0.0240[b]	0.0299[b]			0.0105[b]	0.0113[b]
	(0.0062)	(0.0055)	(0.0060)			(0.0022)	(0.0014)
Lot size * temperature	9.60e-08[b]	8.53e-08[b]	8.31e-09	7.94e-08[b]	7.91e-08[b]	1.4e-07[b]	1.02e-07[b]
	(2.35e-08)	(2.46e-08)	(2.57e-08)	(2.56e-08)	(2.57e-08)	(6.53e-08)	(2.70e-08)
Pool size * temperature	0.00001[b]	0.00003[b]	0.00002[b]	0.00002[b]	0.00002[b]	0.00002[b]	0.00002[b]
	(4.05e-06)	(3.51e-06)		(1.77e-06)	(1.79e-06)	(9.99e-06)	(2.70e-06)
Temperature 1990				0.0185[b]	0.0173[b]		
				(0.00349)	(0.0040)		
Temperature 1995				0.01904[b]	0.0180[b]		
				(0.0037)	(0.0041)		
Temperature 2000				0.0188[b]	0.0227[b]		
				(0.0035)	(0.0059)		
Log water price (inflation adjusted)					−5.0399		
					(6.6480)		
Constant	7.5680[b]	7.2825[b]	3.8435[b]	6.8094[b]	7.6912[b]	8.1700[b]	7.9222[b]
	(0.7635)	(0.5427)	(0.6837)	(0.4666)	(1.3634)	(1.0566)	(0.34487)
Adj. R square	0.5163	0.5263	0.7325	0.6006	0.6008	0.8872[1]	0.5881[1]
Number of observations/groups	200	282	279	761	761	290	290

[a] Dependent variable: Log of gallons of water consumed by a typical single-family unit by census tract in June. The calculation and interpretation of adjusted R square in panel data models is different from that in purely cross-sectionals or time series models and hence is not strictly comparable. See STATA manual for details. Robust standard errors are in parentheses.

[b] Denotes significance at 1% level.

[c] Denotes significance at 5% level.

estimated coefficients differ somewhat across the different years but a t test of linear combination of these coefficients revealed that the differences are not statistically significant. This suggests that that the level effect of temperature has remained stable across the years.

[41] Interestingly, the estimated coefficient of temperature in the panel models (model V and VI) is around 0.010 (with 95% confidence interval of 0.005 to 0.016), which is almost half of that in the single year models and the pooled regression, although still positive and statistically significant. This suggests that the unobserved census tract effects are important and that previous work using cross-sectional data may have overestimated the effect of temperature on water use. For instance, the study by *Guhathakurta and Gober* [2007], which used the same climate model to get simulated temperatures but used cross-sectional data for a single year (1998) for the City of Phoenix, found the level effect of temperature on water consumption to be around 0.04. This is higher than our panel estimates but close to our estimated coefficient for 2000 (model III). Among the other studies that have estimated the impact of temperature on water consumption, the one that comes closest to our study is *Olmstead et al.* [2007], which used cross-sectional household level data for several cities in the Southwest. Their estimated coefficient for the temperature level effect was also around 0.04, which is close to what we found in our cross-sectional models.

[42] Neither of the above two cited studies reported any interaction effects of temperature with other housing characteristics. In our study, we also interacted temperature with several other housing characteristics, such as lot size, living feet, pool size, and NDVI. Only the interaction of temperature with lot size and pool size was found to be significant. In both cases, the estimated coefficient had a positive sign suggesting that the effect of pool size and lot size magnifies as temperature increases. This is consistent with the physical science literature we reviewed earlier and suggests that each degree rise in temperature not only increases water consumption directly (intercept effect) but also indirectly through its effect on lot size (which after controlling for living area proxies for outdoor non/pool use of water) and pool size (which affects the extent of evaporation losses from pools). Taking into account these interaction effects, the total effect of temperature on water consumption is somewhat higher. In the FE model, the total temperature effect (estimated at the average of pool size and lot size) is 0. 014 (with 95% confidence interval of 0.006 to 0.022), as opposed to 0.010 with just the intercept effect. This means that each degree rise in nighttime temperature (in Fahrenheit) increases monthly water consumption by 1.4% or 180.6 gallons for an average single family residence in the study. Although the interaction effects are small, they provide us some insights into how higher temperatures, through their role in magnifying the effect of

outdoor water intensive activities, would impact residential water consumption. In Table 7 we have summarized the intercept and slope effects of temperatures under different models, and the associated elasticities and compared them with the estimates found in other studies.

[43] Among the other outdoor variables, the effect of NDVI was found to vary across the different models. The effect was found to be positive and significant in almost all the cross-sectional models but not significant in the panel models. NDVI shows very limited variation within census tracts across time and thus its effect could not be estimated in the FE model. In the RE model, its effect is not significant. It is highly likely that only a fraction of pixels are irrigated at single-family residences and some public parks and other green spaces are irrigated using nonpotable (reclaimed) water. Census tract level NDVI may thus be a poor indicator of single family residential, potable water use. Previous studies by *Guhathakurta and Gober* [2007, 2010] have also pointed out that NDVI does not capture the specific role of vegetation in moderating heat island effects or in increasing water use. Turning next to other housing characteristics, age of the housing unit has a positive and significant effect in almost all the models, as expected. Squared term for age of unit was also included but it was not found to be significant in any of the models. The square footage of living space is hypothesized to capture indoor water use once we have controlled for lot size and household size. The effect of this variable was significant in some models, including the RE model where the linear term is negative and the squared term is positive. This suggests that controlling for lot size, as square footage of living space increases, water consumption first declines up to a certain level and then increases. The turning point is reached around the mean of the sample and implies that for houses with larger than average square footage, water consumption gets associated with more water intensive lifestyles through greater number of bathrooms and/or more intensive appliances such as dishwashers and Jacuzzis. The percentage of evaporative coolers was found to have a significant positive effect on water consumption in the work of *Guhathakurta and Gober*'s [2007] study but was not found to be significant in any of our models.

[44] Next let us turn to demographic and socioeconomic variables. The effect of income is positive and significant in almost all of the models. The estimated income elasticity is about 0.07 in the panel models and the pooled OLS regressions. In their survey of residential water demand models, *Worthington and Hoffman* [2008] observe that income elasticities are almost universally less than one and rather small in magnitude. Our estimate is lower than the range reported in other studies of about 0.2 to 0.6 but this may be largely because few of these other studies have included housing characteristics which are likely to be strongly correlated with income [*Olmstead et al.*, 2007; *Hanemann*, 1998]. Among the demographic characteristics, the size of the household is found to have a positive and significant effect, as expected.

6. Conclusions and Policy Implications

[45] Climate and water use are linked by a complex set of biophysical and behavioral relationships operating at different scales. In this paper we have examined the changing configuration of UHI in space and time as a "natural experiment" to disentangle some of the complexities in the dynamics of urban microclimates and water use. Our paper is perhaps the only one to date that uses longitudinal data to examine the temporal variation in UHI and its impact on water consumption at the census tract level. Conducting research at the census tract level is of critical importance—particularly for urban planners and water managers—in terms of contributing toward an enhanced understanding of how the form of urban development and patterns of land use and land cover may impact water consumption through their effect on microclimates. The longitudinal nature of our study has enabled us to more effectively tease out the effect of multiple determinants of water consumption, and to specifically control for the effect of those unobserved ecological and institutional factors that vary across cross-sectional units but are likely to have remained relatively stable over the study period. Not controlling for these unobserved effects may have led to biased estimates in previous studies based on cross-sectional data.

[46] Our results show that each degree rise in nighttime temperature (in Fahrenheit) contributes to 1.4% increase in water consumption. This effect is considerably smaller than what was found in previous studies (3.8%) but still highly significant and robust across alternative specifications of the model. Our estimates suggest that water use in single family residences increases by 180.6 gallons in the month of June for each degree Fahrenheit rise in nighttime temperature. This is about 30% of earlier estimates that have been as high as 647 gallons per household for similar temperature increase during roughly the same period [*Guhathakurta and*

Table 7. Estimated Effect of Temperature Across Different Models[a]

Specification	Temperature Intercept	Temperature * Pool Size Interaction	Temperature * Lot Size Interaction	Temperature Total Effect	Temperature Elasticity
		This Study			
Model I (1990)	0.0227	0.0015	0.0011	0.0253	1.9357
Model II (1995)	0.0240	0.0029	0.0009	0.0277	1.7339
Model III (2000)	0.0299	0.0019	0.0001	0.0319	2.4507
Model V (FE)	0.0105	0.0020	0.0015	0.0140	1.0538
Model VI (RE)	0.0113	0.0025	0.0011	0.0148	1.1676
		Other Studies			
Guhathakurta and Gober [2007]	0.038			0.038	
Olmstead et al. [2007]	0.036			0.036	

[a] The effects are estimated at sample means.

Gober, 2007]. Even with the smaller losses, we estimate that an additional 3338 single family units could be added to Phoenix without incurring any additional pressures on existing water resources by reducing the nighttime temperature by a degree. This is a conservative estimate given that single family water consumption has been declining over the past two decades. Assuming a 2% annual growth rate in single family units in Phoenix, which has been the case between 2000–2008, almost half the new units each year can be accommodated without any additional water supplies if in fact the nighttime temperatures reduced by one degree Fahrenheit.

[47] These results, however, should be interpreted with caution because of a couple of reasons. First, given our interest in examining intraurban variation in temperatures, we had to use simulated instead of actual observed data. Although the simulated temperature data we have used for the study comes from a state of the art mesoscale atmospheric model, it is still captive to the specific assumptions made in the model. Second, the large computational resources required to run such a model also forced us to confine our study to 3 year data from a single city for the month of June. To contextualize these findings, it is worth noting that the average minimum temperature in the month of June in the City of Phoenix is about 50% higher than the annual average minimum temperature and average water consumption for single family units is about 30% higher than the average for the year. More importantly, looking at water consumption for a single month presents only a partial view of water consumption dynamics. For instance, recent work by *Scott et al.* [2009] in Tucson, Arizona found that warming due to UHI extends the growing season for landscaping vegetation and thereby increases total annual water consumption while also intensifying peak (monthly) irrigation.

[48] We hope that our work provides an opening for future studies to investigate the impact of UHI on water consumption more extensively using data from more years and across different seasons for a range of different cities to provide a comparative perspective. As *Chaganon* [1992, p. 620] observes, "the heat island aspect of urban climate is very important to the global change issue, both as an analog and as an effect" that needs to be explored in-depth. Over the next 50 years, Arizona could face a temperature increase of between 4 to 9°F according to the IPCC climate models (Arizona Department of Environmental Quality (AZDEQ), Climate Change Action Plan, 2006, available at www.azclimatechange.gov/download/O40F9347.pdf). Annual precipitation is likely to decrease in addition to a significant decline in the annual runoff into the Colorado River system resulting in a 40% decrease in basin storage. In other words, Arizona will get hotter and drier and thus will be facing serious water shortages, under current projections. Our study shows that controlling and limiting heat island effects could have a significant impact on saving water resources, and thus should be an important part of our policy tools set.

[49] Over the past two decades, extensive research on UHI has shown several potential means of reversing its adverse effects. For instance, simple changes in material used for construction and better design of outdoor spaces can result in substantial reduction in UHI. One popular technique has been the use of "green roofs." Another solution often suggested is the use of trees and shrubs, and sometimes community gardens, that also help limit the nighttime temperatures. All these solutions, however, entail important tradeoffs. For instance, increased vegetation to mitigate the UHI entails the use of scarce water resources. While it is possible to find drought resistant varieties of plants that can control heat island effects, the specific costs and benefits of using vegetation of particular types have not yet been examined. Similarly, the trade-offs between elevated water consumption due to evaporation from pools and large water bodies and their amenity value (including relief from uncomfortably large high temperatures) need to be examined further. Investigating these tradeoffs will require both new conceptual and methodological tools (particularly those that help us better integrate biophysical and behavioral relationships), as well as more extensive spatial and temporal data to disentangle the complex feedback processes entailed at different scales.

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