Robustness Analysis of Phoenix, AZ: Heat as a Social Ecological System

Phoenix AZ is the 6th largest city in the United States by population covering over 500 square miles, it housed over 1.5 million people in 2014 (U.S. Census Bureau, 2015). It is one of the hottest cities in the country with an annual mean temperature of 75°F, and a summer average of 93°F (National Centers for Environmental Information, 2011).

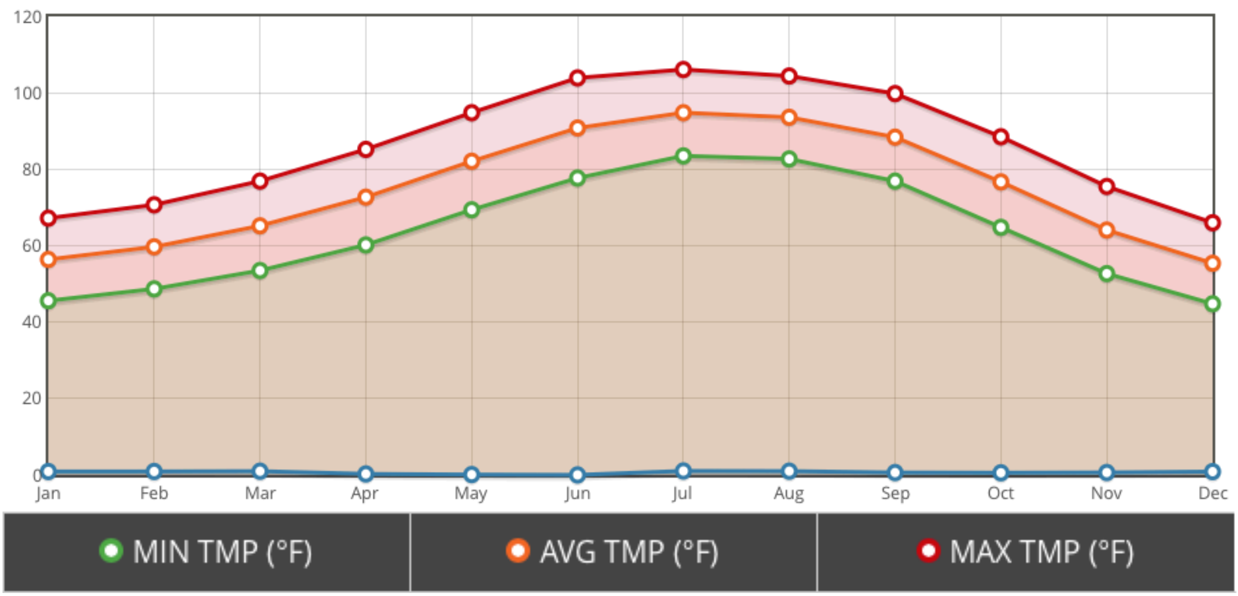

Figure 1: Annual Monthly Temperature at the Phoenix Sky Harbor Airport, AZ US
Source: (National Centers for Environmental Information, 2011).

Native Americans occupied the valley at one time, though it was abandoned in the 15th century for not fully understood reasons. European Americans resettled the valley in the 19th century. The valley was still quite hot then, but large canal projects, encouraged in part by federal reclamation money, brought in abundant water (Barney, Goldwater, Williams, 2008). This water was essential for the success of the city and afforded its new residents the potential for year-round agriculture and relief from the heat.

The mechanisms through which water and flora contribute to cooling an environment are now well understood (Baker et al 2002). Much work has been done recently on how changes in environments due to urbanization can increase city temperatures. Decreasing surface water through flood control and conservation efforts combined with reductions in natural flora and increases in anthropogenic heat sources, all contribute to making cities hotter than their surrounding environments; an effect now referred to as the urban heat island (Chow, Brennan, Brazel, 2012; Luber & McGeehin, 2008; Harlan, Brazel, Prashad, Stefanov & Larsen, 2006; Jenerette et al., 2006).

As Phoenix continued to expand and urbanize throughout the 20th and then 21st centuries room needed to be made for increasing populations, requiring more robust flood control, more water, more industry, and more cars. This meant that previously exposed canals were lined in concrete and covered in order to preserve the water inside, trees were removed from the sides of the canals in order to conserve water and were removed from many road and walk ways in order to widen streets and make room for new buildings. Slowly, this led to a modern urban landscape devoid of much of the water and shade that provided original Phoenicians relief from the heat. These effects were amplified further by changes in surface materials and activities in the city. As dirt roads and agricultural plots were replaced by asphalt and concrete, less and less incoming solar radiation was reflected back into the atmosphere, and more and more was absorbed and held in the city. At the same time, people moved away from agricultural forms of production towards more industrial forms, engaged in increasingly long commutes from expanding suburbs, and used air conditioners in homes, buildings and cars. These changes led to unprecedented amounts of heat being generated by people inside the city. At a certain point this heat became too great in too small of an area to be efficiently dissipated into the atmosphere, thus raising the temperature inside the city beyond that of the surrounding desert– creating an urban heat island.

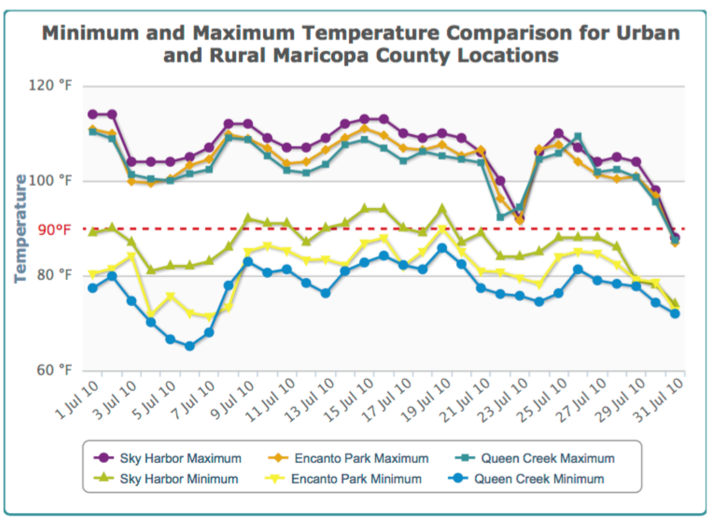

Figure 1: *Minimum and Maximum Temperature Comparison for Urban and Rural Maricopa County Locations.*
Source: NOAA's National Climatic Data Center, Satellite and Information Service (Sky Harbor); Arizona Meteorology Network [AZMET] (Encanto Park and Queen Creek).

Figure 2: Temperatures in Rural and Urban Maricopa County, AZ
Source: (Wittlinger, 2011).

Essentially, what has happened in Phoenix over the last two centuries is a classic common pool resource problem. The capacity of the atmosphere to dissipate

Phoenix's heat is a finite, non-excludable, and now scarce resource that is over appropriated by its users. There are various forms of institutional and cultural contexts, feed backs, and trade-offs, which both amplify and attenuate this problem.

There is an under provisioning of public infrastructure that could mitigate the effects of regional heat. The mechanisms through which water bodies, flora, and building materials can cool an environment via evapotranspiration (ET), solar reflectivity, and heat capacity are well understood. If there were increased public investment in this type of infrastructure there could be a decrease in the use of the heat dissipation capacity resource. This involves several decision making trade-offs. Most importantly, the benefits of this type of infrastructure would disproportionately help individuals who live and work in the densest parts of the city, and who cannot currently afford private cooling infrastructure in the form of personal landscaping, air-conditioning, and residential insulation. At the same time, it would disproportionately cost individuals in higher tax brackets who are likely to reside further away from the central business district (CBD), and already have access to private cooling infrastructure.

There are important trade-offs to consider about the mechanisms used to mitigate heat. First, by increasing our resilience to extreme heat through trees, water, and reflective building materials, we increase our vulnerability to water shortages, and finical constraints from tree maintenance and potential damage during storms. Second, a more restrictive regulatory environment has the potential to cause reduced economic activity. Lastly, technological fixes like green roofs often have large carbon footprints, which exacerbate climate change, making the original problem worse on longer timescales.

Furthermore, a feedback exists in the capacity for cooling via ET. ET generally increases in efficiency as temperatures rise, until a threshold ~104°F where ET almost completely stops. This means that as temperatures rise, cooling through ET ultimately decreases, creating a negative feedback (Baker et al 2002).

Additionally, there are other important trade-offs between pubic and private cooling infrastructure that have manifested in Phoenix over the last 60 years. With the advent of accessible personal air conditioning in the 1940's, it quickly proliferated to exist in every conceivable form: large scale commercial heating, ventilating, and air conditioning (HVAC), residential central air conditioning, window and wall single unit air conditioning, split air conditioning, portable air conditioning, and personal vehicle HVAC. The first law of thermodynamics tells us that energy cannot be created or destroyed, thus air conditioners cannot actually eliminate heat, only move it. Air conditioners are heat pumps. Due to the second law of thermodynamics no air conditioner can ever be 100% efficient; we will always be using energy to move heat. That extra energy is also manifested as heat. This is why air conditioners need to be installed along lines of insulation. They only work if the air conditioner's compressor is insulated from the space it is cooling, so it can pump heat out of an insulated space and into the greater environment, where it also pumps the extra heat it created doing the work. In this way, all air conditioners are net-heat-generating devices.

With this background the trade-off of air conditioning becomes clear: by using air conditioners inside spaces where we live and work, we heat the greater environment where those spaces ultimately exist, which then creates a linear positive feedback, making it increasingly more difficult for the air conditioner to cool the insulated area. In general practice, we rarely experience this problem because of the immense capacity the atmosphere has to dissipate the heat we create using air conditioners, however, when this resource becomes scarce, this trade-off begins to matter, and that is part of what happens inside urban heat islands. Furthermore, power generation itself creates heat through mechanical inefficiencies, exacerbating this problem. There are two coal fired plants within the urban area that contribute to heating in Phoenix; these create more heat as the demand for air conditioning rises, amplifying the positive heating feedback effect of air conditioning (Baker et al 2002).

Furthermore, though air conditioning is widespread and relatively affordable for most American's today, it is still out of reach for the lowest income households, for whom the operating costs of running a air conditioner is still too high. In light of this reality the trade-off associated with running air conditioners is even more important. Not only do we pump more heat out of our homes and offices than was there to begin with, in a place like Phoenix, AZ, we actually pump that heat into other peoples' homes and yards who are not using air conditioners, making those people's homes hotter than they would be if no one used any air conditioning. This trade-off is only becoming more prominent over past decades, as air conditioning and other private heat generating infrastructure continues to rise while public heat mitigating infrastructure continues to decline, presenting serious environmental justice and ethical concerns, as well as unique governance challenges.

a.

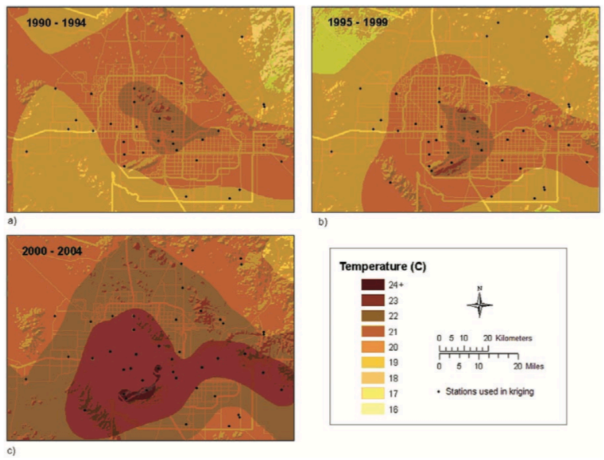

FIG. 5. Mean monthly (Jun) minimum air temperature patterns interpolated through ordinary kriging over 5-yr periods in the PMA: (a) 1990–94, (b) 1994–99, (c) 2000–04. Temperature data were taken from 37 stations distributed throughout the PMA (Source: Brazel et al. 2007). The increase in UHI spatial extent is especially evident when compared to Fig. 3.

b.

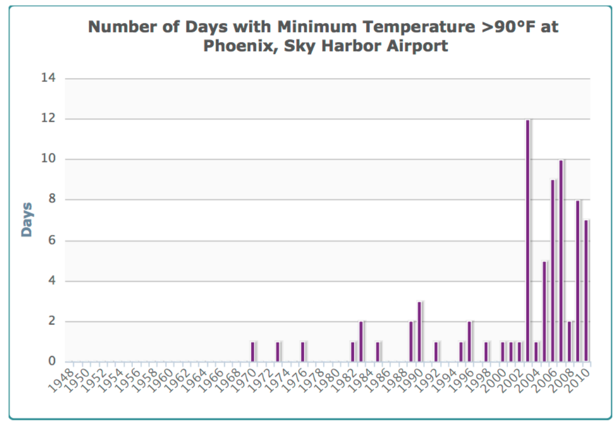

Figure 2: *Number of Days with Minimum Temperature Greater than 90°F at Phoenix Sky Harbor Airport.*
Source: NOAA's National Climatic Data Center, Satellite and Information Service.

Figure 3a: Changes in the Average Minimum June Air Temperature in the Phoenix, AZ Urban Area. Source: (Chow, Brennan, Brazel, 2012).
Figure 3b: Increasing Number of Days at the Phoenix Sky Harbor Airport with Minimum Temperatures Above 90°F. Source: (Wittlinger, 2011).

Amplifying this concern, global climate change will not only increase the annual mean temperatures in Phoenix, but will increase the number and length of extreme heat events, which have real implications for public health and well-being (Luber, McGeehin, 2008; McMichael, Woodruff, Hales, 2006).

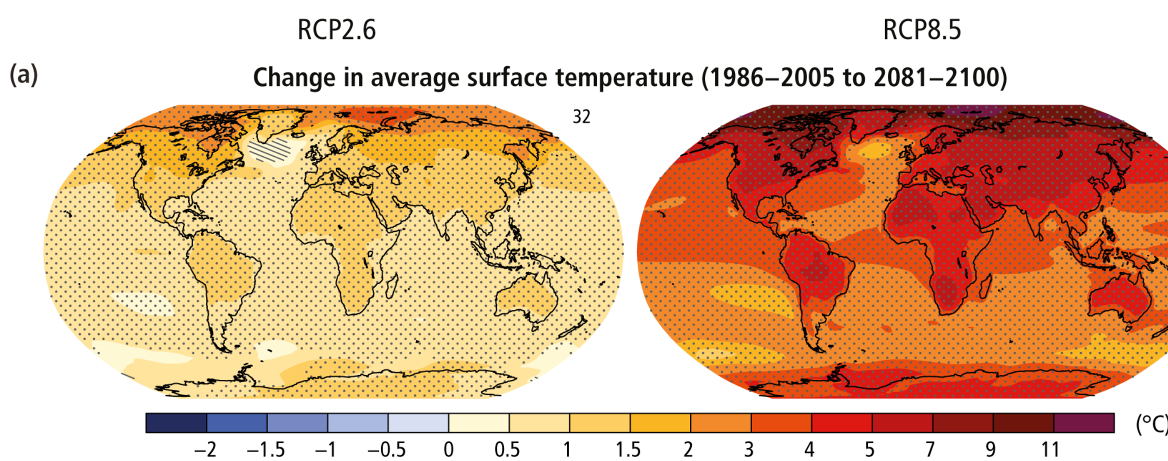

Figure 4: Projected Change in Average Global Surface Temperatures
Source: (IPCC, 2014)

Right now, a massive number of agencies are responsible for decision making that affects Phoenix's capacity to dissipate heat. The Arizona Department of Health Services and the Arizona Emergency Information Network (a service of the Arizona Department of Emergency and Military Affairs) are the main two offices in charge of managing extreme heat as a human health hazard. However, hundreds of other private and public firms affect the use of the resource and mediate the risk of the hazard (Arizona Department of Health Services 2014; State of Arizona). There is currently no government agency at any level responsible for monitoring, measuring, or allocating the use of the city's capacity to dissipate heat.

There are however several protocols in place which dictate how to mitigate the dangerous effects of extreme heat, such as opening cooling centers, giving water donations, and educational campaigns, but there are no state or city proscriptive regulations, and few general polices, that mitigate the cause of the hazard in the first place. Most policies that exist are advisory in nature, like the Town of Gilbert's guidance on cool-roofs, or the City of Phoenix's Cool Roofs Project and the Tree and Shade Master Plan Project (Town of Gilbert Planning Dept., 2006; Middel, Chhetri, Quay, 2015; City of Phoenix, 2006; The City of Phoenix. 2010). However, more recently the city has issued some new zoning that explicitly prescribes heat mitigation infrastructure. The Green Construction Code passed by the city council in 2005, and Chapter 12 of the current zoning ordinance, have requirements for reflective roofing, shade trees, and cooler building materials. Chapter 12 of the current zoning ordinance section E, "Shade Standards" indicates that:

"All buildings over 5,000 square feet shall provide the following: A minimum of 75 percent of public sidewalks shall be shaded [and] a minimum of 50 percent of all accessible public and private open space areas shall be shaded, of which 50 percent of the shade shall be provided by trees or trellised vines (City of Phoenix, Arizona 2015)."

Section J, "Streetscape Guidelines," of the current Phoenix Zoning Ordinance indicates:

"Alternative paving materials should be used on private property to reduce urban heat island effect, and to allow natural drainage and filtration (City of Phoenix, Arizona 2015)."

And section G, "Landscape and Hardscape Guidelines," indicates:

"Alternative paving materials such as permeable pavers, porous concrete or similar materials should be used for on-site hardscaping to reduce urban heat island effect, and to allow natural drainage and filtration (City of Phoenix, Arizona 2015)."

While section R, "General Building Form Guidelines" indicates:

"The proposed building orientation should respect climate conditions by minimizing heat gain and considering the impact of shade on adjacent areas (City of Phoenix, Arizona 2015)."

And finally, section S, "Window Guidelines" indicates:

"Windows placed above 30 feet in height should be designed to reduce summer solar heat gain and reflectivity. Windows shall have a Solar Heat Gain Coefficient (SHGC) of .40 or lower (City of Phoenix, Arizona 2015)."

Though these are effective steps in the right direction, without monitoring and regulation of the use of the primary resource that these laws are intended to conserve, it is my belief that in the long run there will continue to be problems of over appropriation. As can be seen in ongoing research, changes in building materials and landscape cover can only do so much. The City of Phoenix's own publication acknowledges:

"However, trees and cool roofs are only part of the solution and need to be included in a broader, more comprehensive mitigation and adaptation plan. Our research thus far indicates that there is no simple solution to mitigating the UHI [urban heat island]. A complex balance of strategies will be necessary so that efforts to lower the daytime temperatures do not increase the nighttime temperatures or shift UHI impacts to more vulnerable populations (Middel, Chhetri, 2014)."

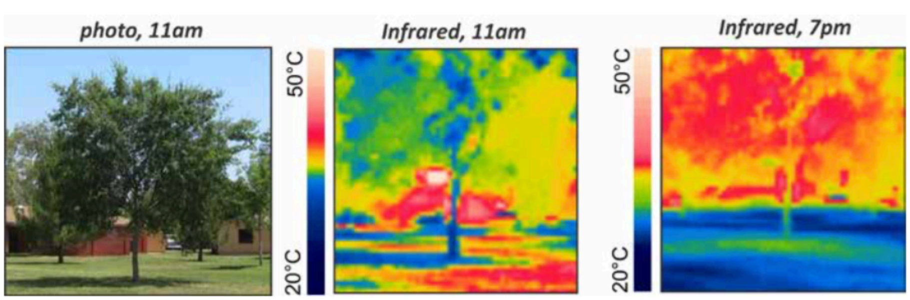

Figure 5: Thermographic image of an elm tree on grass, June 21, 2012. Note how the cooler (blue/green) areas follow the shade patterns during the day, and how the trees capture and hold the heat released from the grassy areas underneath in the evening.

Figure 5: Trees That Provide Cooling During the Day Contribute to Heating at Night
Source: (Middel, Chhetri, 2014)

A growing city and certain climate change induced warming makes these issues absolutely pressing. Managing these governance challenges while making considerations for the various resiliency trade-offs and feedback systems that heat mitigation interventions create will be essential for city planers moving forward.

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