Comparative Analysis of Heat Vulnerability and Response Strategies in Phoenix, Arizona, and Seattle, Washington

Garrett Kalter

Geography 499: Honors Studies in Geography

May 2024

Abstract

Heat is the most fatal environmental hazard and as such poses significant risks to public health. Seattle experiences excess mortality from heat at far lower temperatures compared to Phoenix, necessitating an investigation into this disparity. This study constructs a Heat Vulnerability Index (HVI) to analyze socioeconomic variables, assess cooling center accessibility, and evaluate government response plans. The HVI examination reveals similar vulnerability levels across Seattle and Phoenix, challenging conventional assumptions despite climate and demographic differences. Despite having fewer cooling center facilities than Phoenix, Seattle demonstrates broader coverage of cooling centers. Analysis of government response plans highlights Seattle's recent implementation efforts and Phoenix's comprehensive strategy. These findings offer insights into the complex dynamics of heat vulnerability and response mechanisms. By exploring the factors influencing vulnerability, this study contributes to discussions on climate resilience and public health adaptation strategies.

Acknowledgments

I extend my deepest gratitude to Professor Burnett for his dedication and guidance as my thesis advisor. His willingness to work with me day in and day out has been instrumental in shaping this project. Without his support and encouragement, this project would not have been where it is today. I am profoundly grateful for his mentorship and commitment. Thank you, Professor Burnett, for your invaluable contributions to this endeavor.

I am also grateful to the Geography Chair, Professor Meyer, for his willingness to be my second reader. During the process of research and writing, Professor Meyer has asked some questions that I would never have thought of myself, and these have in turn greatly shaped my project.

Lastly, I express my wholehearted gratitude to the entire faculty in the Department of Geography. Throughout my time at Colgate, the faculty in the department has constantly piqued my interest with interesting courses and sparked intellectual curiosity within me. Their passion for the subject and dedication to teaching have played a pivotal role in sculpting my academic journey.

Table of Contents

List of Figures and Tables

1. Introduction

Heat is the single most fatal meteorological hazard in North America, accounting for approximately 20% of all natural hazard deaths (Sharma et al., 2018). The 2022 Intergovernmental Panel on Climate Change (IPCC) report has shown that extreme heat events have become more common in the last 50 years (Arsad et al., 2022; IPCC, 2022). Global mean temperatures have been rising at a rate of 0.2 °C over the past few decades and are expected to rise over the coming decades (IPCC, 2013). Due to this, the IPCC has stated that extreme heat events will become both more frequent and more extreme in the near future (IPCC, 2022). Heatwaves are commonly delineated in two distinct manners: meteorologically, they are characterized as an extended duration marked by notably elevated temperatures, whereas epidemiologically, they are defined as a timeframe associated with heightened mortality rates (Boni et al., 2023). The impact of heatwaves on humans is clear, as seen through the abundance of mortalities sustained during extreme heat events (i.e., Lay et al., 2021; Davis et al., 2003; Klinenberg, 2003). Furthermore, while heatwaves can occur in various locations, they are more often most common and more extreme in urban areas (Chen et al., 2023; Coseo & Larsen, 2014). This is largely attributed to the urban heat island (UHI), wherein urban areas experience higher surface and air temperatures due to higher population densities, man-made structures that retain more heat, and reduce evaporative cooling (Chen et al., 2023; Coseo & Larsen, 2014). A prominent example of a deadly heatwave is exemplified by the 1995 Chicago heatwave. This heatwave resulted in an estimated 696 excess deaths, 514 of which were directly caused by complications related to extreme heat (Browning et al., 2006; IPCC, 2013; Klinenberg, 2003). According to the CDC, excess deaths are typically defined as “the difference between the observed number of deaths in specific time periods and expected numbers of deaths in the same time periods" (CDC, 2023). Given the large number of excess deaths, this heatwave garnered considerable scholarly attention, with one of the most notable works stemming from it being Klinenberg's 2003 publication titled *Heat Wave: A Social Autopsy of Disaster in Chicago*, in which he closely examines the different variables that lead to unequal mortality during the heatwave. Klinenberg's social autopsy revealed a crucial insight into the dynamics of heatwave-related mortalities. Rather than attributing the fatalities to random chance, his autopsy of the heatwave uncovered numerous underlying social and economic factors that rendered certain populations more susceptible. In the case of the Chicago heatwave, poor, Black, and older (to name a few variables) residents were more vulnerable. By highlighting these variables, Klinenberg's work shed light on the disproportionate impact of heatwaves on vulnerable communities, sparking crucial discussions on societal resilience, equity, and the imperative for targeted interventions to mitigate the adverse effects of extreme heat events. Since the publication of his book in 2003, there have been dozens of journal articles dedicated to discussing and uncovering vulnerable populations in the event of extreme heat.

Therefore, understanding heatwaves is crucial for several broad reasons. Firstly, it allows for effective preparedness and response measures to be implemented. By comprehending the extremity of heatwaves, government authorities can develop early warning systems, heatwave action plans, and heat-health advisories to minimize the impact on vulnerable populations (Keith et al., 2021). Secondly, understanding heatwaves can aid in identifying and addressing disparities in vulnerability. As demonstrated by Klinenberg's (2003) work on the Chicago heatwave, certain demographic groups are disproportionately affected. Recognizing these disparities enables targeted interventions and resource allocation to support those most at risk.

In recognition of these issues of vulnerability, oftentimes Heat Vulnerability Indices (henceforth HVI) are utilized to assess which geographic locations in a given area are most vulnerable. This allows governments or other entities to make adaptation plans that can appropriately target vulnerable populations (Szagri et al., 2023). These indices incorporate various factors such as socio-economic status, access to healthcare, housing conditions, and environmental characteristics to provide a comprehensive assessment of heat vulnerability at the community level (e.g. Fard et al., 2021; Nayak et al., 2018; Reid et al., 2009). By employing HVIs, decision-makers can prioritize resources and interventions toward areas and populations at the highest risk during extreme heat events. Moreover, HVIs enable the identification of underlying vulnerabilities that may not be immediately apparent, allowing for more targeted and effective strategies to enhance resilience and reduce heat-related morbidity and mortality. Despite the upsides of an HVI showing vulnerable populations, many studies oftentimes fail to look deeper for the underlying issues resulting in said vulnerability in a specific region. For instance, studies may construct an HVI using a variety of socio-economic variables (eg., Fard et al., 2021; Buscail et al., 2012; Reid et al., 2009), but they often fail to compare it to similar indices from other cities, therefore missing the opportunity to identify potential place-based strategies to reduce heat susceptibility effectively. Such adaptation strategies could be cooling centers or government response plans, aiming to provide immediate relief and support to vulnerable populations during extreme heat events.

Acknowledging this gap in comparative HVI analysis, this study aims to examine the vulnerabilities to heatwaves in Phoenix and Seattle, highlighting their differing susceptibilities and informing targeted adaptation strategies for each region. The reason for these two cities stems from a study conducted by Saha et al. (2014) that discovered that these two cities have substantially different temperatures at which excess mortality occurs - often referred to as the heat mortality threshold. Specifically, this study showed that mortality displacement (the phenomenon where heat-related deaths may be accelerated by extreme temperatures) began at 18 degrees Celsius (64.4 degrees Fahrenheit) in Seattle. By contrast, mortality displacement in Phoenix began at 37 degrees Celsius (98.6 degrees Fahrenheit) (Saha et al., 2014). The study by Saha et al. (2014) utilized apparent temperature, which accounts for windchill and humidity, a metric more colloquially known as the "feels like" temperature.

This paper attempts to understand why Seattle experiences heat deaths at far lower temperatures than Phoenix. To accomplish this, the analysis will first conduct a comparative examination of the HVIs of both cities. This comparison will uncover whether or not there are substantial socioeconomic or environmental variables that are the primary reason for the difference in heat mortality threshold. Additionally, I will explore the government heat response plans implemented in each city to see whether or not one city has more adaptive capacity than another. By juxtaposing these elements, this research aims to identify the key determinants driving the disparate heat mortality thresholds in Seattle and Phoenix.

1.1 Roadmap

This paper will begin with an examination of pertinent literature surrounding heatwaves separated into broader categories. Subsequently, the methodology section will detail the approach employed in comparing the heat vulnerability indices of Phoenix and Seattle, as well as the analysis of government heat response plans. Following this, I will present the findings of the comparative analysis, highlighting any major differences uncovered between the two cities. Finally, the implications of these findings will be discussed, including insights into targeted adaptation strategies for each region and the broader significance of enhancing resilience to extreme heat events in urban environments.

2. Literature Review

2.1. Data sources

To identify variables, methodology, and other important related information to create the vulnerability index I searched for journal articles relating to the construction, application, and validation of HVIs. All of the journal articles used were written between 1998 and 2021. All journal articles relating to the search were found on online databases such as ScienceDirect, JSTOR, PubMed Central, and Springer, as well as each city's respective government website.

In addition to the creation and analysis of HVIs, prominent literature explores various dimensions of extreme heat events, encompassing different realms of impact. Studies delve into the general effects of heat on health, while others elucidate the varying levels of vulnerability to heat through physiological adaptation, social vulnerability, access to air conditioning (AC), and adaptive capacity, often reflected in government-regulated response plans. In this section, I will briefly discuss the relevant literature in each of these categories.

2.2. Literature on physiological heat effects

An overarching theme that warrants detailed exploration within the realm of extreme heat pertains to its adverse effects on individuals. This topic serves as a critical foundation for more in-depth discussions on vulnerability, adaptation, and resilience. Such studies reveal consistent evidence of increased mortality during heatwaves and positive associations between ambient heat exposure and mortality, particularly among vulnerable populations such as the elderly, children, and those with preexisting medical conditions (Petkova et al., 2014; Basu and Samet, 2002). The vulnerability of these groups is due to “poor blood circulation and inefficient sweat glands”, which lowers the body's ability to react and adapt to temperature changes (National Institute of Health, 2018). In this realm of research, some studies have focused on the physiological vulnerability of particular populations, revealing their susceptibility solely from a biological perspective (Martens, 1998). This adds to the nuance of our understanding of the intricate interplay between individual physiology, socioeconomic factors, and environmental stressors when comparing two different geographies' vulnerabilities to heat.

As previously mentioned, the primary measure of the impact of heat on health comes from excess mortality, however, other heat-related illnesses can result in hospital visits alone, and not be fatal (Petkova et al., 2014). Despite which metric is used, it is seen clearly through existing literature that heat has adverse effects on human health, especially those more innately vulnerable. This highlights the critical need for more in-depth discussions on vulnerability, adaptation strategies, and resilience measures to mitigate the detrimental impacts of extreme heat on human health and well-being.

Additionally, heat acclimatization is an essential factor in the attempt to understand why Seattle suffers mortality at a lower temperature threshold. Martens (1998) among others (see Lim, 2020; Diem et al., 2017; Wang et al., 2016) have suggested that heat acclimatization may be playing a large role in why we see the mortality trend we do. The CDC defines heat acclimatization as the “physiological adaptations that occur during repeated exposure to a hot environment” (CDC, 2018). This concept, though not the primary focus of this paper, remains an essential consideration in understanding why Seattle experiences mortality at a lower temperature threshold. Heat acclimatization may be the contributing factor to the drastic difference in the heat mortality threshold. The concepts of physiological heat vulnerability and heat acclimatization underscore the critical need for more in-depth discussions on vulnerability, adaptation strategies, and resilience measures to mitigate the detrimental impacts of extreme heat on human health and well-being.

2.3. Socio-economic vulnerability

With knowledge of the impact of heat on human health, it is significant to understand the populations most vulnerable to make targeted resilience. It is widely acknowledged that climate change hazards do not affect everyone equally (Best and Jouzi, 2022). Therefore, one route to understanding and studying heatwaves is by determining which variables are most closely related to those who are vulnerable to extreme heat events. As mentioned previously, studies have shown that certain demographics are particularly susceptible to the adverse effects of heat (Klinenberg, 2003). In my research, these studies most often fall into two categories: predictive (i.e., Fard et al., 2021; Nayak et al., 2018; Reid et al., 2009) and retrospective studies (i.e., Klinenberg, 2003). The former, as seen in the title, are studies that map out heat vulnerability in hopes of predicting which populations are most susceptible if a heatwave were to occur. This is most often done by creating an HVI using variables comprising the most relevant factors that relate to heatwave vulnerability. The latter category, retrospective studies, often use mortality data to find any patterns in said data. Such studies pave the way for more predictive studies.

Understanding the impact of heat on human health is crucial for targeted resilience efforts, especially considering that climate change hazards disproportionately affect vulnerable groups. By understanding vulnerable populations by studying previous heatwaves and relevant data, we can develop more effective predictive models and targeted interventions to mitigate the health impacts of heatwaves, ultimately enhancing community resilience in the face of climate change.

Other types of studies that commonly appeared during my research are those pertaining to government response plans and policies aimed at addressing heat-related health risks (see Kearl and Vogel, 2023; Keith et al., 2021; Hondula et al., 2019; Bernard and McGeehin, 2004).

These studies provide insights into the effectiveness of existing strategies, identify gaps in preparedness, and offer recommendations for improving public health response to heatwaves.

3. Methods and Materials

3.1. Study area and background

The study area for this paper is Phoenix, Arizona, and Seattle, Washington. In addition to these two cities being chosen they have the biggest disparities in heat mortality threshold (Saha et al., 2014). These cities were selected based on both their similarities and differences in other geographical aspects, including their adaptive capacity, climate, and population. Phoenix has a population of 1,644,409 sprawling across 518.00 square miles (U.S. Census Bureau, 2023). Seattle is a much more compact city, spanning only 83.83 square miles, with a population of 749,256 (U.S. Census Bureau, 2023). The population density per square mile for each city is 3,104.5 for Phoenix and 8,791.8 for Seattle (U.S. Census Bureau, 2023). While apparent due to its southerly location, the average summertime temperature in Phoenix in 2023 was 95 degrees, whereas in Seattle this number is 65 (National Weather Service, 2023). These temperatures are relatively similar to what Saha et al. (2014) found to be the temperature mortality thresholds for each city.

3.1.1 Previous extreme heat events

Given the drastically different temperatures of each city, it is clear that Phoenix is far more likely to experience a heatwave or similar event. So much so that Phoenix annually reports the deaths directly from heat after each summer season. This report is generally a year delayed, which means the most recent report reports on mortality statistics from the summer prior. The 2023 heat report therefore describes the mortality statistics from the summer of 2022, which was the most fatal summer since formal tracking began in 2006, for Phoenix. The summer of 2022 resulted in a confirmed 424 heat-related deaths, which is a 25% increase from the summer of 2021 (City of Phoenix, 2023). These 424 mortalities, while not all occurring within a condensed time frame characteristic of a heatwave, remain crucial for contextualizing the background of each city's experience with extreme heat events. In addition to tracking heat-related mortality, Phoenix also measured heat-related phone calls to the Phoenix Fire Department. From April 1 to September 30, there were 1,670 such calls. Of these calls, 40% of them (574) occurred during a one-week stretch from July 11 to July 18. This same week, the average daily high temperature was 113 degrees Fahrenheit.

Conversely, Seattle has only experienced one impactful heatwave in recent times. This was the 2021 heatwave that affected many areas throughout the Pacific Northwest. From June 26 to July 2, 2021, Seattle experienced a heatwave. During this time, temperatures peaked at 108 degrees Fahrenheit on June 28, setting a new high-temperature record in the area. In this same time period, according to the Washington State Department of Health (n.d.), there were 100 heat-related deaths.

3.2. Variable selection

To create an HVI, socioeconomic variables as well as environmental variables are needed. Variables were selected based on other studies that created HVIs (Fard et al., 2021; Nayak et al., 2018 Reid et al., 2009). These studies typically use 7-15 variables (Fard et al., 2021; Nayak et al., 2018; Reid et al., 2009). Each variable that is used in the creation of an HVI is in some manner related to increased or decreased vulnerability during extreme heat events. In total, I created an HVI using 9 different factors, 8 of which are socioeconomic, and 1 of which is environmental. Table 1 shows each of the variables as well as its source. Other studies have included important variables such as diabetes prevalence and the percentage of households without central AC in their construction of an HVI (City of Seattle, 2023; Nayak et al., 2018; Reid et al., 2009). However, I was unable to use these variables since the data was not readily available. In the case of diabetes prevalence, the data is not available at a census tract level likely due to issues of anonymity. Other studies have attempted to infer diabetes prevalence based on hospital visits (Whipple et al., 2016). Given that there is no way to tell if this data is correct or not, I have purposefully left it out of my map creation due to concerns over the possibility that such data may skew the final production of the HVI. For AC data, the American Community Survey only has data on the county level, which would not be helpful for my study which examines census tracts. Similarly to the diabetes prevalence variable, authors have attempted to infer rates of AC based on other metrics (Romitti et al., 2022). While this data would be useful, it did not contain many of the census tracts for each city because “one of the underlying variables in our model was missing from the prediction data” (Romitti, 2024). For example, of the 182 census tracts in Seattle, the Romitti et al. (2022) study only contained inferred AC data for 100 of the 182 tracts. Therefore, this data was not able to be used.

The 9 variables I have decided to use are shown in Table 1. Of the variables shown in Table 1, each of the socioeconomic variables has been shown to increase vulnerability during heatwaves, with the elderly (Population over 65) being the most vulnerable (Kenny et al., 2010). This vulnerability is increased even more when they do not have easy access to help via friends or family. Poorer populations (as measured by percent below poverty) are more vulnerable since they have less adaptive capacity through methods such as AC (Nayak et al., 2018). Klinenberg’s (2003) analysis found that many victims of the 1995 Chicago heatwave died alone.

Is it important to mention that although many sources have identified children under 4 to be physiologically vulnerable to heat (Uibel et al., 2022), I did not come across any HVI’s using this variable. This is likely because children are dependent on their parents during heatwaves which may skew this factor (Huettman, 2022). Therefore, I did not use this variable in my HVI.

Table 1. Summary of each Variable for Heat Vulnerability Index

Category	**Data Source**	**Variable Definition**
Socioeconomic variables	U.S. Census	% Below poverty line % Without a high school diploma % Not White or Asian or Hispanic % Population living alone % Population over 65 % Population over 65 and living alone % 5+ Who speak English less than "very well" % People 18-64 w/ a disability
Land cover	National Land Cover Database	% Not green space

Source: Made by the author

3.3. HVI construction

Two HVIs were created for each city to see how different construction methods could lead to different results. The first construction method for each HVI for each respective city was a simple composite index. The composite index was created by first ensuring that all variables ran in the same direction on a percent scale of 100. In this case, percentages closer to 100 were more vulnerable to extreme heat events than those closer to 0. Once all variables were appropriately scaled and all unidirectional, the sum of all 9 variables was found and divided by the number of variables. Based on the methodology from Bao et al. (2015), each variable at this scale had equal weighting. However, studies at other geographies (i.e., county scale) that contain other health information, such as diabetes prevalence, tend to weigh this variable twice as much as others. Figures 1b and 1d show the outcome of this methodology.

The second HVI construction method was made by first conducting a Principal Component Analysis (PCA) on all 9 variables for all census tracts in both cities. This was done to limit the number of variables and also reduce variables from being double-counted if they correlated extremely closely with one another (Bao et al., 2015). Other authors (Fard et al., 2021; Nayak et al., 2018; Reid et al., 2009) have employed this technique as well. The PCA is used since some of the variables that go into the HVI construction may be correlated with each other. By using the PCA, it takes the variables that are correlated and makes representative components for each. This makes it so that variables that are correlated do not contribute multiple times to the final product.

3.4. Heat adaptation analysis

To evaluate the efficacy and extensiveness of heat response plans across each city I reviewed official government websites and documents. This involved a comprehensive search for related information, primarily focused on specific heat response protocols and adaptive strategies. The main sources of data found for each city were descriptions of heat response plans and information related to operating cooling centers. Cooling center data was found on each city's respective government website. However, the formats varied and both required geocoding (the process of converting either an address of coordinates to a location) since neither website had downloads for a layer of the cooling centers. In addition to examining the number of cooling centers in each city, I layer cooling centers on top of the HVI layer. Once layered, I apply a 1-mile selection radius to identify census tracts not within 1 mile of a cooling center. This allows me to see if either city has more vulnerable populations within a reasonable distance of a cooling center and in turn see if cooling centers are reaching the targeted populations.

4. Results

4.1. PCA and HVI mapping results

The original composite HVI was not used since some of the variables correlated and were therefore accounted for multiple times in the final map. After running the PCA from the given 9 components, many of the variables were correlated. Using methodology from Nayak et al. (2018), components were retained based on the following criteria: 1) eigenvalues greater than 1.0; 2) any component that accounted for at least 10% of variance or cumulative percent of variance is at least 70%. All variables are shown in Table 2.

Table 2. Total Variance explained for each 9 Variables put through Principal Component Analysis

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.963	32.924	32.924	2.963	32.924	32.924
2	1.816	20.177	53.101	1.816	20.177	53.101
3	1.258	13.973	67.074	1.258	13.973	67.074
4	1.011	11.232	78.306	1.011	11.232	78.306
5	.687	7.628	85.934			
6	.503	5.593	91.527			
7	.395	4.388	95.916			
8	.227	2.518	98.434			
9	.141	1.566	100.000			

Source: Made by author

This process led to 4 components making up 78.306% of the total variance and eigenvalues ranging from 1.011 to 2.963. These 4 components are shown in Table 3 along with the variables that most closely correlated with them either positively or negatively. These components were then weighted equally and averaged for each census tract. The mean was 0, representing a standard deviation of 0, with a range from -1.34 to 2.48 standard deviations - with lower numbers representing lower vulnerability. Census tracts from each city were used in the same PCA so that the results could be compared against each other.

Table 3. Resulting 4 Components and Correlation to each Variable (bolded values carry heavy load)

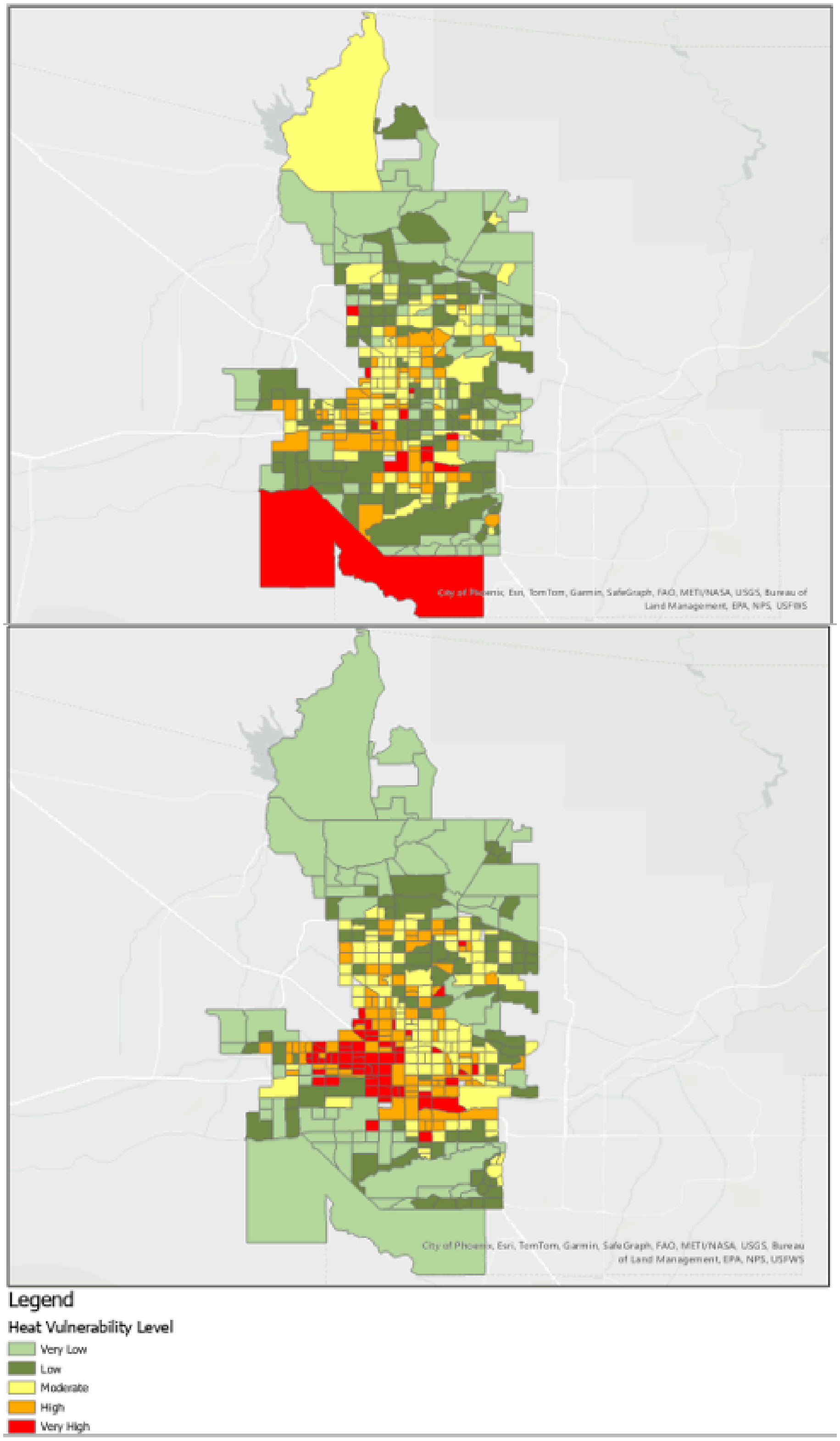
	1	2	3	4
65 and older	**-0.642**	0.240	**0.551**	0.301
Not green	0.019	**0.631**	0.061	**-0.633**
Living alone	-0.258	**0.726**	-0.412	-0.200
Over 65 and living alone	**-0.395**	**0.669**	**0.419**	0.292
Below poverty	**0.746**	0.371	-0.088	0.030
18-64 with disability	**0.514**	0.429	0.028	0.304
Not white, Asian, or Hispanic	0.241	0.249	**-0.587**	**0.546**
Poor English speaking	**0.831**	0.024	0.345	-0.052
No diploma	**0.871**	0.019	0.365	0.002

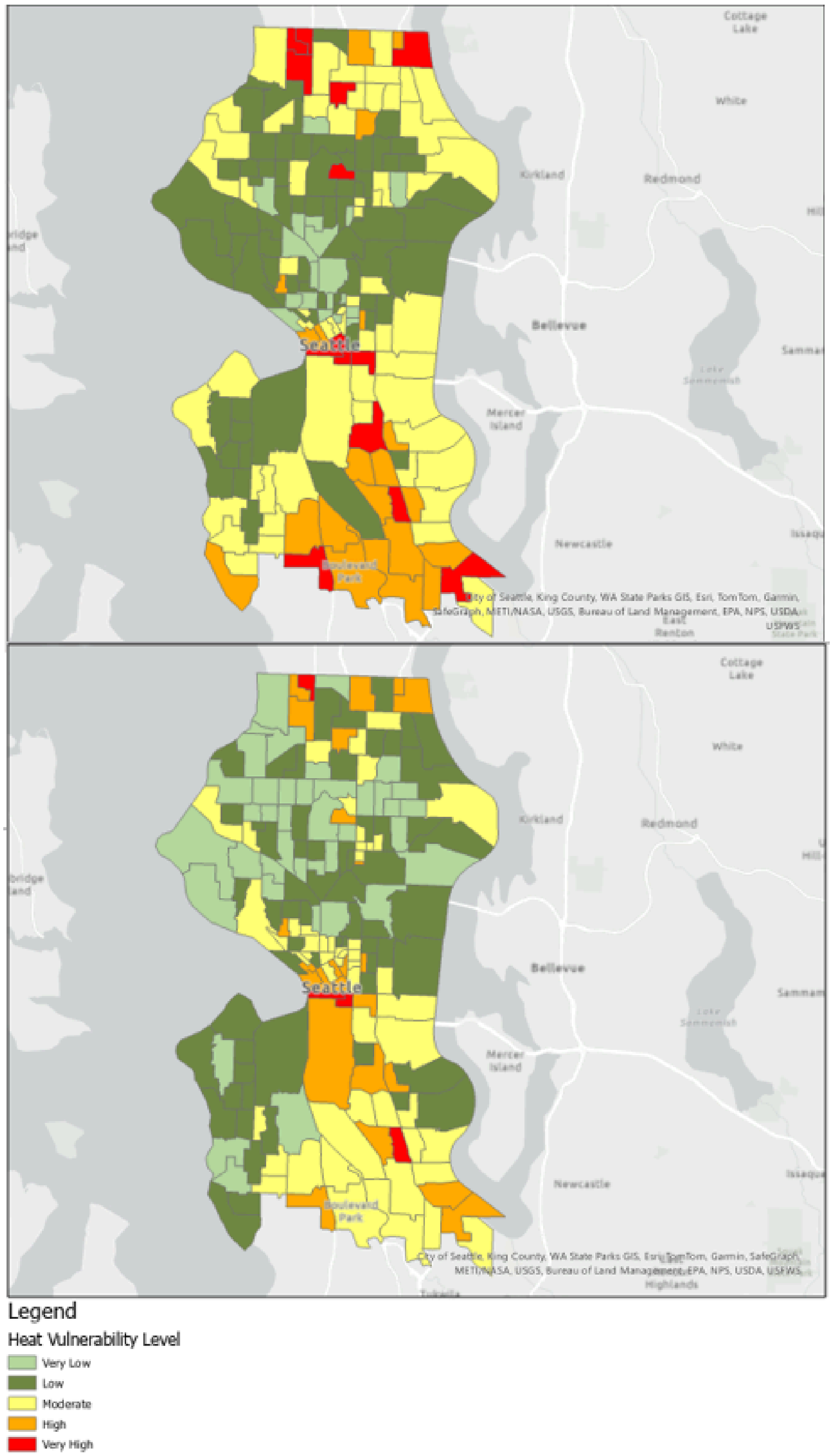
Source: Made by author

Between Seattle and Phoenix, 585 total census tracts made up the HVI. Some census tracts had missing data that contributed to the HVI and were therefore excluded from the analysis. These tracts show up as gray in the final mappings. The resulting maps were separated into 4 total maps - 2 for each city. This is to show the difference in outcomes when mapping using the PCA approach versus using the simpler composite index approach. Final HVI results are shown in Figure 1a-d, each census tract is on a scale from “Very Low” to “Very High” (in terms of levels of vulnerability). The values for each census tract come from the results of the PCA. Although each method for Seattle shows slightly different values in terms of heat vulnerability for any given census tract, both HVI maps for Seattle show a similar trend of unclustered vulnerability. Even though vulnerability seems to be dispersed in Figure 1a-b, both maps show that there is a slightly higher heat vulnerability in the southernmost region of Seattle. Overall, the mean vulnerability score for Phoenix is 0.10 and -0.22 for Seattle. Both of these averages fall into the “Moderate” vulnerability group. This indicates that Seattle is slightly less vulnerable in terms of socioeconomic factors than Phoenix, albeit by a very slight amount.

As for Phoenix, vulnerability seems to be most concentrated near the center of the city, with vulnerability generally decreasing towards the outskirts of the city. This pattern is more prevalent in Figure 1d where there are a minute amount of census tracts outside the city core that are above “Low” vulnerability. A similar trend is seen in Figure 1c, though not as prominent. The most likely reason is that many variables were overlapping and therefore overemphasized the vulnerability in these tracts in Figure 1c.

Figure 1a-d. HVIs using PCA and using Composite Index (top is PCA, bottom is Composite)





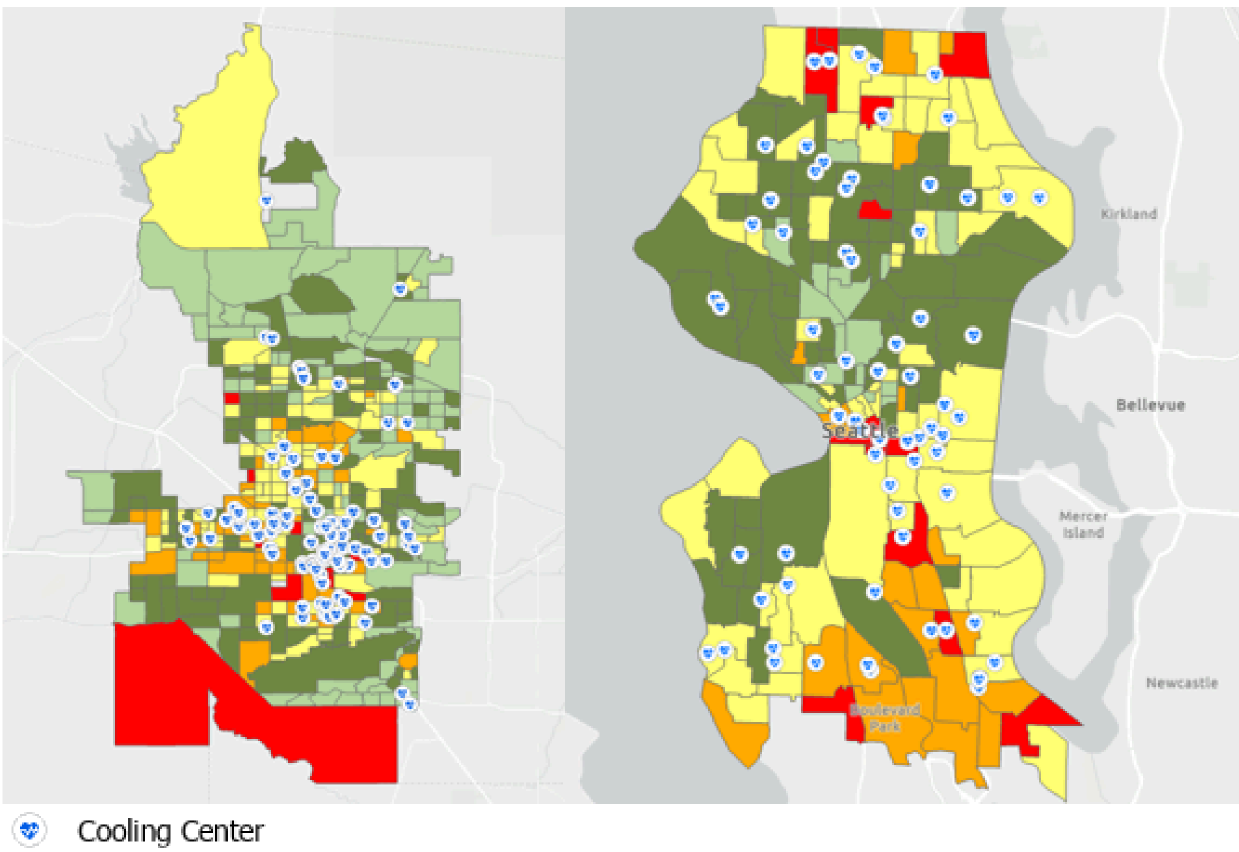
Source: Map made by the author

4.1.1. Cooling center analysis

A primary avenue to adapting to heatwaves is the accessibility of cooling centers. Cooling centers can vary in appearance, however, pertinent literature describes cooling centers generally as public buildings or similar facilities that are open to the public and have AC (New York State Department of Health, n.d.). This allows the body to cool down its temperature thus becoming less susceptible to extreme heat.

Cooling center locations were geocoded based on data from each city's government website and placed onto the same maps seen in Figure 1a-d. The most recent data shows that Seattle has 72 cooling centers (City of Seattle, 2022), while Phoenix has 108 (Arizona Department of Health Services, 2023). It should be noted that these cooling centers are not fully representative of what may be happening during a heatwave. The reason for this is that Phoenix, in addition to the permanent cooling centers, sets up temporary cooling centers during heatwaves to produce additional support (City of Phoenix, 2023). The number for temporary cooling centers was unavailable. A selection of 1 mile centered around the cooling centers was used to determine census tracts that did not have easily accessible cooling centers. This distance of 1 mile was based on each census tract's centroid. By using the centroid as the measurement, I can guarantee that at least half of the area of the census tract is within the 1-mile distance. 1 mile is used since this is approximately a 15-minute walk for the average person, which is also the same time heat-related side effects can begin to occur (CDC, 2012). This metric is also the most conservative, as it presents the worst-case scenario of someone not having a car or immediate access to public transportation. In actuality, 16.6% of households in Seattle do not own a car, and 9.1% in Phoenix. A map of all cooling centers in each city is seen in Figure 2a-b. This selection showed the opposite of what would be expected. The selection showed that 161 of the 182 census tracts in Seattle were within 1 mile of a cooling center. These 161 census tracts translate to 88.18% of the population of the city. Conversely, the same selection for Phoenix showed only 172 of the 405 census tracts to match the criteria for selection. This is 40.30% of the population. This is likely due to the clumping of Phoenix's cooling centers in the downtown area, while Seattle has their cooling centers more dispersed throughout the entirety of the city. However, the clustering of Phoenix's cooling centers may be a benefit for them, as they seem to be surrounding the more vulnerable census tracts, while many of Seattle's cooling centers are around low-vulnerability census tracts.

Figure 2a-b. Cooling Centers (blue symbol) in Phoenix (left) and Seattle (right)



Source: Map made by the author

4.2. Heat response and planning programs

The last aspect of vulnerability is to understand the adaptive capacity of each city. To compare this, I observed all available heat response plans that each city had publicly available on their respective website for the most recent year. This portion of the analysis looked at the total number of heat response plans each city had in case of an extreme heat event, as well as the comprehensiveness of the plans. This analysis was also the most telling in understanding why Seattle has such a low heat mortality threshold. Heat response plans contain a wide variety of different strategies, measures, protocols, and guidelines aimed at mitigating the impacts of high temperatures on individuals, communities, and infrastructure. Both cities have clear outlines of actions that each respective government should take during a heatwave. Each city also broadly has the same strategies and objectives for heat response plans. Phoenix writes out each of its 6 different focus areas during a heat event, as seen in Figure 3. Seattle shares similar objectives. These objectives focus primarily on situational awareness, public outreach, and supporting cool areas.

Figure 3. Phoenix's objectives for responses during a heat event

The Heat Response programs and services reflect attention to six priority focus areas:

1. Situational awareness at City Hall and real-time response
2. Public engagement, communications, and outreach
3. Publicly accessible cool space and drinking water
4. Supporting cool and safe home environments
5. Supporting cool and safe mobility and recreation
6. Supporting cool and safe workplaces and schools

Source: City of Phoenix 2023: 14

Phoenix's approach is very comprehensive, offering detailed descriptions of each of its 31 dedicated programs tailored specifically for heat response services and initiatives, beginning in 2022 (City of Phoenix, 2023). Similarly, Seattle's approach is comparably as comprehensive as Phoenix's, describing 28 targeted heat response plans. Figure 4 shows an example of one of Seattle's heat response plans. Despite similarities in the level of detail and comprehensiveness between Seattle and Phoenix's heat response plans, with both cities outlining clear objectives and strategies, Seattle's initiation of its heat response plan in 2023 (King County, 2023) may have impacted its historical preparedness. This aspect could have played a role in Seattle's lower heat mortality threshold and the significant number of excess deaths observed during the 2021 heatwave and in the Saha et al (2014) study.

Figure 4. Seattle's Objective and Strategy for Reaching Out to At-Risk Populations during a Heat Event

AT-RISK POPULATIONS and KEY SETTINGS GUIDANCE

- **Objective**: Develop relevant, specific, and actionable messaging for key at-risk populations to stay safe in high temperatures: those experiencing homelessness, elderly, infants, those on certain medications, pets, outdoor workers, those without cooling systems in their homes, etc.
    - *Strategy*: Promote heat safety messages on platforms in addition to Public Health's regular channels, considering alternative outlets to target the specific at-risk populations [radio spots; community blogs and newspapers; schools; libraries; etc.]
        - Lead: Communications
    - *Strategy*: Provide heat messaging and recommended actions in multiple languages.
        - Lead: Communications
            - **Attachment**: *Heat Risk Communications Resources*
            - **Attachment:** *Heat Messages in Translation*

Source: Public Health - Seattle and King County 2023: 13

5. Discussion and next steps

Numerous studies have analyzed mortality displacement across different cities (e.g. Saha et al., 2014; Hondula & Davis, 2014; Curriero et al., 2002) and others have constructed and validated Heat Vulnerability Indices (HVIs) for a given geographic area (Fard et al., 2021; Nayak et al., 2018; Reid et al., 2009). A niche area of scholars has also analyzed cities' heat response plans and potential strategies to put in place (Keith et al., 2021; Hondula et al., 2019; Bernard & McGeehin, 2004). To my knowledge, however, there has yet to be a thorough comparative analysis to identify why one city suffers mortality at a lower temperature threshold than another.

The result of each city's respective HVI shows no large difference. One important result from the HVI was that Seattle did have the lowest overall value for a given census tract. Lower values signify less vulnerability. This signifies that between both cities, surprisingly, Seattle had one of the least vulnerable tracts. This tract has a value of -0.73. However, Seattle also has many more moderately vulnerable tracts, which brings the average up, closer to Phoenix’s. In addition to the range of vulnerability for each city, the average for Phoenix is 0.10 and Seattle has an average of -0.22, with 0 being moderately vulnerable. Both averages fell into the same category of “Moderate” vulnerability. These two averages are very similar and therefore suggest that both Phoenix and Seattle face comparable levels of vulnerability, at least in the realm of socioeconomic vulnerability. This goes against my former hypothesis, and that of Klinenberg which would assume that socioeconomic factors play a large role in determining heat vulnerability. If this were to be the case, then the HVI scores for Seattle would likely have had an average in the “High” or “Very High” vulnerability categories. One possibility for the discrepancy could be attributed to the focus of Klinenberg's theory on intracity (occurring within one city) differences rather than intercity (occurring between two cities) variations. Klinenberg's theory may highlight socioeconomic factors that influence vulnerability within a city's boundaries. Still, it does not fully account for the broader regional or climatic differences that could affect vulnerability between different cities. Therefore, while socioeconomic factors could play a significant role in determining vulnerability within cities, other factors such as climate, government response, heat acclimatization, and infrastructure may contribute to the varying vulnerability levels observed between different cities like Phoenix and Seattle.

One possible reason for the lack of disparity could be because of the number of variables used. Although other studies use a similar number of variables (Fard et al., 2021; Buscail et al., 2012; Reid et al., 2009), an increase in variables that are often associated with vulnerability during heatwaves could add nuance and make the maps less similar. Klinenberg discusses a few factors that may increase vulnerability during heatwaves, despite not being used in any HVI studies. Klinenberg (2003) discusses how crime may play a role in heat vulnerability during heatwaves since this may heat residents' homes since they do not open their windows due to the risk of being robbed. Expanding on Klinenberg's insights and incorporating physiological studies, it is evident that children represent a vulnerable demographic during heatwaves (Huettman, 2022). Physiological studies have highlighted that children have a reduced capacity to regulate body temperature compared to adults, making them more susceptible to heat-related illnesses such as heat exhaustion and heatstroke (Huettman, 2022). Additionally, AC prevalence is an important variable that should be accounted for. As mentioned above, a study by Romitti (2022) derived AC prevalence in census tracts in chosen cities across the US, however, much of the data is incomplete. If this data were to be completed in the future, or if the American Community Survey had finer-grained data, this is another variable that should be included in the PCA. Lastly, given the potential for diabetes prevalence data to introduce inaccuracies into the

PCA, I opted not to include it initially. However, considering its potential relevance to heat vulnerability, future analyses may warrant its inclusion to evaluate its impact on PCA outcomes and assess its validity in capturing socioeconomic and health disparities related to heat susceptibility. In future studies, it may be valuable to adjust the PCA and in turn the HVI with such variables to determine potential changes in city overall scores, thereby enriching the understanding of heat vulnerability dynamics within communities.

Since the values of the HVI do not vary notably between Phoenix and Seattle, it suggests that other factors beyond socioeconomic status may be influential in determining heat vulnerability at the city level. This leaves the other two candidates reasons this paper presented: cooling centers and government heat response plans. The cooling center analysis which plotted all cooling centers for each city shows that Seattle may actually be more well equipped in this regard. Based on the publicly and most recently available data, as mentioned above, Seattle has 161 of their 182, or 88.18% of their population within a 1-mile walking distance of a cooling center. While Phoenix only has 172 out of its 405 census tracts within this same distance, or 40.30% of its population. Despite Seattle having more total cooling centers and populations within close proximity, there are still possible concerns to be addressed about this matter. Although Seattle has more cooling centers proportional to their population and more widespread, I was unable to find the average capacity of each cooling center. This could play a significant role in assessing the effectiveness of cooling centers in mitigating heat vulnerability. Capacity considerations are crucial since they determine the number of individuals a cooling center can physically accommodate during heatwaves. Another concern with cooling centers previously mentioned is that the City of Phoenix (2023) mentions the use of temporary cooling structures. These are fully enclosed tents that have AC inside and provide free water to those using them.

The cooling tent mentioned in their summer 2023 heat response plan described that it was used daily by approximately 40 people as it ran from mid-June until September (City of Phoenix, 2023). However, despite acknowledging the utilization of temporary cooling structures in Phoenix, the City's documentation does not explicitly outline the quantity or distribution of these facilities. While the concept of temporary cooling tents with enclosed AC units and free water provision addresses the need for immediate relief during extreme heat events, the lack of specific information regarding their deployment makes it challenging to assess their effectiveness and coverage in mitigating heat vulnerability across the city. Future studies may explore the possibility of doing more in-depth research on these cooling centers. This research could answer questions not only about the proximity of cooling centers but also about capacity and overall efficacy. For temporary cooling tents, if this data were made available, it would be easier to assess their contribution to heat resilience strategies and their effectiveness in providing immediate relief during heatwaves. While the initial expectation was that the availability and coverage of cooling centers might contribute significantly to differences in heat vulnerability between Seattle and Phoenix, the observed data presents a contrary finding.

Opposite to the initial expectation, Seattle, not Phoenix, actually demonstrated a higher proportion of its population covered by cooling centers within proximity. This unexpected finding challenges the hypothesis that the availability and coverage of cooling centers could be a determining factor for Seattle's lower heat mortality threshold. Therefore, it is evident that the discrepancy in heat vulnerability between Seattle and Phoenix cannot be attributed to the presence or accessibility of cooling centers in either city.

This leaves my final hypothesis which is differing heat response plans. The results show that Phoenix and Seattle had similar levels of detail in their heat response plans. Phoenix had 31 clearly written out response plans with objectives and strategies to achieve such objectives and Seattle had 28. This resemblance of heat response plans was rather surprising. This does not necessarily go against my original hypothesis that heat response plans played a large role in the low heat mortality threshold. This is because, despite the similarity in extensiveness in each city's heat response plans, Seattle's has only been ongoing since 2023, which was likely implemented in response to the 2021 heatwave. With the study by Saha et al. (2014) being written long before the implementation of this heat response plan, it is possible that the lack of preparedness at the time played a large role in the heat mortality threshold. The same may be true for the heatwave in 2021 which resulted in 100 heat-related mortalities (Washington State Department of Health, n.d.). If a similar study to Saha et al. (2014) were to be recreated today, it may be the case that Seattle would have a higher heat mortality threshold due to these recent innovations in their heat response plans. Phoenix began thorough heat response and planning strategies one year prior, in 2022 (City of Phoenix, 2023). Seeing that neither city had definitive heat response plans at the time that the study by Saha et al. (2014) was conducted, it cannot be attributed to the differing heat mortality thresholds observed. The absence of such plans during that period suggests that other factors may have influenced the outcomes of extreme heat events at that time.

With the three primary candidate reasons for heat mortality not aligning as expected—namely the HVI, availability of cooling centers (where Seattle exhibited greater coverage and capacity), and similarity in heat response plans—it's apparent that a straightforward explanation for the observed differences in heat mortality thresholds between Phoenix and Seattle may not suffice. This suggests that the likely reason for the differing heat mortality threshold is related to physiological heat acclimatization or AC prevalence.

As discussed previously, AC plays a large role in reducing vulnerability to extreme heat (Klinenberg, 2003). The American Housing Survey (2021) provides city-level data indicating that Seattle has 76.3% of its households without central AC, while Phoenix only has 3.2% of its households without central AC. Given the large disparity in AC prevalence, it is likely that if there was census tract-level data, this variable would increase vulnerability in Seattle.

Assessing the role of heat acclimatization in this study proves challenging, given the limited ability to gauge its extent across different regions. However, there is a clear consensus that heat acclimatization does occur and can make our body less susceptible physiologically to extreme temperatures (Cole et al., 2023; Wang et al., 2016; Martens, 1998). Similarly, studies have shown there is likely a reduction in heat-related mortalities in areas where there is a regional acclimatization to heat (Diem et al., 2017; Kalkstein & Davis, 1990). Kalkstein and Davis (1990) also found that there is likely interseason heat acclimatization that occurs. This means that if a heatwave occurs in August, it is likely to be less devastating than one that occurs in the earlier summer months, such as early June (Davis, 1990). In addition to regional acclimatization to heat, future projections anticipate that as many climates become warmer, heat-related mortalities may decrease, while cold-related ones may increase (Ballester, 2011). While it is clear that heat acclimatization plays a significant role in the body's physiological response to heat, it is challenging to determine the extent to which it alters our physiological reactions. Numerous studies confirm the existence and beneficial effects of heat acclimatization, particularly in adapting to the increasing temperatures worldwide. While these studies emphasize its importance and confirm its impacts, accurately quantifying the extent of change remains a challenge. Nevertheless, it is clear that heat acclimatization significantly enhances our ability to tolerate high temperatures.

6. Conclusion

This comparative analysis sheds light on the complex dynamics underlying heat vulnerability and mortality thresholds in urban environments, focusing on Phoenix, Arizona, and Seattle, Washington. Through an examination of various factors such as socioeconomic status, cooling center availability, and heat response plans, this study aimed to identify why one city may experience higher heat-related mortality at lower temperatures than another. The results indicate that the differences in heat vulnerability between Phoenix and Seattle cannot be solely attributed to socioeconomic factors, cooling center accessibility, or the extent of heat response plans. While socioeconomic vulnerability, as measured by the HVI showed comparable levels between the two cities, Seattle exhibited greater coverage and capacity of cooling centers within close proximity to its population. Additionally, both cities had similar levels of detail in their heat response plans, despite Seattle's initiatives being implemented slightly more recently. This suggests that other factors, such as physiological heat acclimatization and AC prevalence, may play significant roles in determining heat vulnerability and mortality thresholds.

The stark contrast in central AC prevalence between Seattle and Phoenix underscores the importance of considering regional climatic differences and adaptation strategies in assessing heat vulnerability. Furthermore, the potential impact of heat acclimatization on physiological responses to extreme temperatures highlights the need for further research to understand how individuals and communities adapt to heat over time. While studies confirm the existence and beneficial effects of heat acclimatization, the extent of its influence remains challenging to quantify precisely.

This study underscores the multifaceted nature of heat vulnerability and the importance of considering a diverse range of factors in developing effective heat mitigation strategies. By recognizing the interplay between socioeconomic, environmental, and physiological factors, policymakers and urban planners can better address the growing threat of heat-related mortality in cities and enhance resilience to climate change impacts.

Bibliography

2018. (n.d.). National Institutes of Health (NIH). Retrieved May 6, 2024, from https://www.nih.gov/taxonomy/term/1341

American Housing Survey (AHS)—Ahs table creator. (n.d.). Retrieved October 27, 2023, from https://www.census.gov/programs-surveys/ahs/data/interactive/ahstablecreator.html?s_areas=38060&s_year=2021&s_tablename=TABLE3&s_bygroup1=1&s_bygroup2=1&s_filtergroup1=1&s_filtergroup2=1

Arizona department of health services. (n.d.). Retrieved May 6, 2024, from https://www.azdhs.gov/

Arsad, F. S., Hod, R., Ahmad, N., Ismail, R., Mohamed, N., Baharom, M., Osman, Y., Radi, M. F. M., & Tangang, F. (2022). The impact of heatwaves on mortality and morbidity and the associated vulnerability factors: A systematic review. *International Journal of Environmental Research and Public Health*, *19*(23), 16356. https://doi.org/10.3390/ijerph192316356

Ballester, J., Robine, J.-M., Herrmann, F. R., & Rodó, X. (2011). Long-term projections and acclimatization scenarios of temperature-related mortality in Europe. *Nature Communications*, *2*(1), 358. https://doi.org/10.1038/ncomms1360

Bao, J., Li, X., & Yu, C. (2015). The construction and validation of the heat vulnerability index, a review. *International Journal of Environmental Research and Public Health*, *12*(7), 7220–7234. https://doi.org/10.3390/ijerph120707220

Basu, R., & Samet, J. M. (2002). Relation between elevated ambient temperature and mortality: A review of the epidemiologic evidence. *Epidemiologic Reviews*, *24*(2), 190–202. https://doi.org/10.1093/epirev/mxf007

Bernard, S. M., & McGeehin, M. A. (2004). Municipal heat wave response plans. *American Journal of Public Health*, *94*(9), 1520–1522. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1448486/

Best, K., & Jouzi, Z. (2022). Climate gentrification: Methods, gaps, and framework for future research. *Frontiers in Climate*, *4*. https://doi.org/10.3389/fclim.2022.828067

Boni, Z., Bieńkowska, Z., Chwałczyk, F., Jancewicz, B., Marginean, I., & Serrano, P. Y. (2023). What is a heat(Wave)? An interdisciplinary perspective. *Climatic Change*, *176*(9), 129. https://doi.org/10.1007/s10584-023-03592-3

Browning, C. R., Wallace, D., Feinberg, S. L., & Cagney, K. A. (2006). Neighborhood social processes, physical conditions, and disaster-related mortality: The case of the 1995 chicago heat wave. *American Sociological Review*, *71*(4), 661–678. https://doi.org/10.1177/000312240607100407

Buscail, C., Upegui, E., & Viel, J.-F. (2012). Mapping heatwave health risk at the community level for public health action. *International Journal of Health Geographics*, *11*(1), 38. https://doi.org/10.1186/1476-072X-11-38

CDC. (2024, May 6). *CDC*. Centers for Disease Control and Prevention. https://www.cdc.gov/index.htm

City of Phoenix. (n.d.). *Phoenix, Arizona ~ Tree Canopy Cover*. https://www.phoenix.gov/parkssite/Documents/PKS_Forestry/PKS_Forestry_Map_Tree_Canopy.pdf

City of Phoenix. (2023). *Summer 2023 Heat Response Plan*. https://www.phoenix.gov/heatsite/Documents/Heat%20Response%20Plan%202023%20-%20For%20Gen%20Info%20Packet%20Apr19.pdf

Cole, E., Donnan, K. J., Simpson, A. J., & Garrett, A. T. (2023). Short-term heat acclimation protocols for an aging population: Systematic review. *PLOS ONE*, *18*(3), e0282038. https://doi.org/10.1371/journal.pone.0282038

Communications--OS-C4PA--1620. (n.d.). *Heat Wave 2021*. Washington State Department of Health. Retrieved October 27, 2023, from https://doh.wa.gov/emergencies/be-prepared-be-safe/severe-weather-and-natural-disasters/hot-weather-safety/heat-wave-2021

Coseo, P., & Larsen, L. (2014). How factors of land use/land cover, building configuration, and adjacent heat sources and sinks explain Urban Heat Islands in Chicago. *Landscape and Urban Planning*, *125*, 117–129. https://doi.org/10.1016/j.landurbplan.2014.02.019

Davis, R. E., & Kalkstein, L. S. (1990). Development of an automated spatial synoptic climatological classification. *International Journal of Climatology*, *10*(8), 769–794. https://doi.org/10.1002/joc.3370100802

Davis, R. E., Knappenberger, P. C., Michaels, P. J., & Novicoff, W. M. (2003). Changing heat-related mortality in the United States. *Environmental Health Perspectives*, *111*(14), 1712–1718. https://doi.org/10.1289/ehp.6336

Deploy heat officers, policies and metrics—ProQuest. (n.d.). Retrieved October 26, 2023, from https://www.proquest.com/docview/2581070848?parentSessionId=AOzcv6%2BAvKk2

Zv5FiokehCfYanJH1y3RFaS2ff%2FdAlY%3D&parentSessionId=UsYgvNBPpE%2FaWCOwYCxSW12wCtg5jENYM200utDZhdE%3D&pq-origsite=summon

Diem, J. E., Stauber, C. E., & Rothenberg, R. (2017). Heat in the southeastern United States: Characteristics, trends, and potential health impact. *PLoS ONE*, *12*(5), e0177937. https://doi.org/10.1371/journal.pone.0177937

Errett, N. A., Hartwell, C., Randazza, J. M., Nori-Sarma, A., Weinberger, K. R., Spangler, K. R., Sun, Y., Adams, Q. H., Wellenius, G. A., & Hess, J. J. (2023). Survey of extreme heat public health preparedness plans and response activities in the most populous jurisdictions in the United States. *BMC Public Health*, *23*(1), 811. https://doi.org/10.1186/s12889-023-15757-x

Explore census data. (n.d.). Retrieved October 27, 2023, from https://data.census.gov/

Geographic Information. (2023, October 27). U.S. Bureau of Labor Statistics. https://www.bls.gov/regions/home.html

Extreme heat response plan. (2023). Public Health Seattle & King County. https://cdn.kingcounty.gov/-/media/king-county/depts/dph/documents/safety-injury-prevention/emergency-preparedness/phskc-extreme-heat-response-plan-2023.pdf?rev=1585a686bac144c9aa2d7d4fe6e498ed&hash=A97B9518E169E95C9D987E0E2490A35E

Huetteman, E. (2022, August 4). ‘Children are not little adults’ and need special protection during heat waves. *KFF Health News*. https://kffhealthnews.org/news/article/children-heat-wave-risk-heatstroke/

Jalalzadeh Fard, B., Mahmood, R., Hayes, M., Rowe, C., Abadi, A. M., Shulski, M., Medcalf, S., Lookadoo, R., & Bell, J. E. (2021). Mapping heat vulnerability index based on different urbanization levels in Nebraska, usa. *GeoHealth*, *5*(10), e2021GH000478. https://doi.org/10.1029/2021GH000478

Kearl, Z., & Vogel, J. (2023). Urban extreme heat, climate change, and saving lives: Lessons from Washington state. *Urban Climate*, *47*, 101392. https://doi.org/10.1016/j.uclim.2022.101392

Keith, L., Meerow, S., Hondula, D. M., Turner, V. K., & Arnott, J. C. (2021). Deploy heat officers, policies and metrics. *Nature*, *598*(7879), 29–31. https://doi.org/10.1038/d41586-021-02677-2

Kenny, G. P., Sigal, R. J., & McGinn, R. (2016). Body temperature regulation in diabetes. *Temperature: Multidisciplinary Biomedical Journal*, *3*(1), 119–145. https://doi.org/10.1080/23328940.2015.1131506

Kenny, G. P., Yardley, J., Brown, C., Sigal, R. J., & Jay, O. (2010). Heat stress in older individuals and patients with common chronic diseases. *CMAJ : Canadian Medical Association Journal*, *182*(10), 1053–1060. https://doi.org/10.1503/cmaj.081050

King County. (2023). *Public Health extreme heat response*. https://kingcounty.gov/en/dept/dph/health-safety/safety-injury-prevention/emergency-preparedness/personal-preparedness/hot-weather/extreme-heat

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

Lay, C. R., Sarofim, M. C., Vodonos Zilberg, A., Mills, D. M., Jones, R. W., Schwartz, J., & Kinney, P. L. (2021). City-level vulnerability to temperature-related mortality in the USA and future projections: A geographically clustered meta-regression. *The Lancet Planetary Health*, *5*(6), e338–e346. https://doi.org/10.1016/S2542-5196(21)00058-9

Martens, W. J. M. (1998). Climate change, thermal stress and mortality changes. *Social Science & Medicine*, *46*(3), 331–344. https://doi.org/10.1016/S0277-9536(97)00162-7

Nayak, S. G., Shrestha, S., Kinney, P. L., Ross, Z., Sheridan, S. C., Pantea, C. I., Hsu, W. H., Muscatiello, N., & Hwang, S. A. (2018). Development of a heat vulnerability index for New York State. *Public Health*, *161*, 127–137. https://doi.org/10.1016/j.puhe.2017.09.006

News, E. H., KFF Health. (n.d.). *Heat waves affect children more severely*. Scientific American. Retrieved April 10, 2024, from https://www.scientificamerican.com/article/heat-waves-affect-children-more-severely/

Petkova, E. P., Morita, H., & Kinney, P. L. (2014). Health impacts of heat in a changing climate: How can emerging science inform urban adaptation planning? *Current Epidemiology Reports*, *1*(2), 67–74. https://doi.org/10.1007/s40471-014-0009-1

Popovich, N., & Choi-Schagrin, W. (2021, August 11). Hidden toll of the northwest heat wave: Hundreds of extra deaths. *The New York Times*. https://www.nytimes.com/interactive/2021/08/11/climate/deaths-pacific-northwest-heat-wave.html

Pörtner, H.-O., Roberts, D. C., Tignor, M. M. B., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., & Rama, B. (Eds.). (2022). *Climate change 2022: Impacts, adaptation and vulnerability. Contribution of working group ii to the sixth assessment report of the intergovernmental panel on climate change.*

Reid, C. E., O’Neill, M. S., Gronlund, C. J., Brines, S. J., Brown, D. G., Diez-Roux, A. V., & Schwartz, J. (2009). Mapping community determinants of heat vulnerability.

Environmental Health Perspectives, *117*(11), 1730–1736. https://doi.org/10.1289/ehp.0900683

Romitti, Y., Sue Wing, I., Spangler, K. R., & Wellenius, G. A. (2022). Inequality in the availability of residential air conditioning across 115 US metropolitan areas. *PNAS Nexus*, *1*(4), pgac210. https://doi.org/10.1093/pnasnexus/pgac210

Saha, M. V., Davis, R. E., & Hondula, D. M. (2014). Mortality displacement as a function of heat event strength in 7 US cities. *American Journal of Epidemiology*, *179*(4), 467–474. https://doi.org/10.1093/aje/kwt264

Seattle's Canopy Cover—Trees | seattle.gov. (n.d.). Retrieved October 27, 2023, from https://www.seattle.gov/trees/management/canopy-cover

Sharma, A., Woodruff, S., Budhathoki, M., Hamlet, A. F., Chen, F., & Fernando, H. J. S. (2018). Role of green roofs in reducing heat stress in vulnerable urban communities—A multidisciplinary approach. *Environmental Research Letters*, *13*(9), 094011. https://doi.org/10.1088/1748-9326/aad93c

Surveillance—United States diabetes surveillance system. (n.d.). Retrieved October 27, 2023, from https://gis.cdc.gov/grasp/diabetes/diabetesatlas-surveillance.html

Szagri, D., Nagy, B., & Szalay, Z. (2023). How can we predict where heatwaves will have an impact? – A literature review on heat vulnerability indexes. *Urban Climate*, *52*, 101711. https://doi.org/10.1016/j.uclim.2023.101711

Team, N. W. S. C. I. W. (n.d.). *National weather service—Nws seattle*. Retrieved April 23, 2024, from https://w1.weather.gov/climate/xmacis.php?wfo=sew

Wang, Y., Bobb, J. F., Papi, B., Wang, Y., Kosheleva, A., Di, Q., Schwartz, J. D., & Dominici, F. (2016). Heat stroke admissions during heat waves in 1,916 US counties for the period from 1999 to 2010 and their effect modifiers. *Environmental Health*, *15*(1), 83. https://doi.org/10.1186/s12940-016-0167-3

Whipple, H., Garver, J., & Ahearn, H. (2016). *Promoting Equitable Climate Resilience in King County: Mapping Communities Vulnerable to Extreme Heat*. University of Washington.