



**(Sub)Urban Heat Islands: Analyzing the Relationship Between Air Temperature and
Impervious Surface and Distance to Coastline in Palo Alto, CA**
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Abstract

Record-breaking temperatures are being measured across the world, and California is no exception. Extreme heat is worsened by the Urban Heat Island (UHI) Effect – where urban areas experience significantly higher surface and air temperatures than surrounding rural areas. The UHI Effect is driven by multiple environmental factors: two of which are impervious surface concentration and distance to a body of water. This study analyzes the relationship between these two variables and air temperature across three time windows—morning (6-7 AM), afternoon (3-4 pm), and evening (7-8 pm)—on a hot day in Palo Alto. This analysis, although limited to Palo Alto, informs how higher impervious surface concentrations and longer distances to water can be associated with more extreme heat. The findings in this study provide insight into how future urban planning can reduce extreme heat risk.

Background

Termed the Urban Heat Island (UHI) effect, larger, more urbanized areas experience more extreme heat (Oke, 1982), greater pollution, and more negative health impacts during the summer months compared to less developed, rural areas. The UHI effect is "defined by a difference in temperature between the built environment and the natural (surrounding) environment" (Phelan et al., 2015).

The Urban Heat Island effect is impacted by numerous factors, two of which are impervious surface concentration and distance from the nearest body of water (Zou et al., 2021). Impervious surfaces are primary drivers of the Urban Heat Island (UHI) Effect. Because of their high heat capacity, impervious surfaces absorb heat throughout the day and gradually radiate heat in the evening and overnight, increasing surface temperature as the day progresses and preventing cities from cooling down after dark (Ziter et al., 2019). Additionally, impervious surfaces aren't permeable and thus block water from soaking into the ground and inhibit the cooling process of evaporation.

The location to the nearest water source is also known to impact air temperature. Water stabilizes temperature, reducing temperature range through its high specific heat capacity and process of evaporation. Water acts as a heat sink, absorbing heat during the hottest parts of the day and releasing heat during colder parts of the day. Both impervious surfaces and water have high specific heat capacities, but because impervious surfaces release heat directly to the air and water releases heat via evaporation, impervious surfaces have a majority heating effect while water has a majority cooling effect.

Our a-priori hypothesis was that hypothesized increased impervious surface percentage would positively predict air temperature, and a post-hoc analysis showed the strongest relationship during evening hours (likely due to delayed heat release). We also hypothesized that there is a direct relationship between air temperature and distance from coastline, which we found to be nonlinear.

This study addresses a current lack of literature that analyzes extreme heat in Palo Alto and the San Francisco Bay Area Peninsula. The findings outlined below inform how built (impervious surface) and environmental (distance to coastline) factors are correlated with air temperature.

This information can be used to inform urban planning decisions to minimize the urban heat island effect.

Literature Review

Urban areas experience exacerbated thermal stress through the Urban Heat Island (UHI) Effect, a phenomenon where built environments exhibit higher temperatures than surrounding rural or natural settings. Identifying the core environmental and spatial drivers of UHI intensity is essential for designing effective local climate mitigation strategies.

The theoretical foundations of urban climatology and surface energy balances were established by Oke (1982). Built materials—most notably asphalt and concrete—possess low albedo, high thermal capacity, and minimal moisture retention relative to vegetated landscapes. Consequently, urban structures absorb significant solar radiation during daytime hours and re-radiate sensible heat post-sunset, resulting in delayed nocturnal cooling and persistent diurnal temperature elevations.

Quantifying these dynamics via remote sensing, Yuan and Bauer (2007) demonstrated a strong positive correlation between impervious surface area (ISA) and land surface temperature (LST). They also measured the normalized difference vegetation index (NDVI) and found a more complex relationship, which included a strong negative relationship between NDVI and LST for areas and seasons with especially high vegetation. Their findings emphasized that replacing vegetation with impervious cover eliminates cooling from evapotranspiration, alters moisture dynamics, and increases thermal retention, establishing ISA percentage as a reliable indicator for urban heat modeling.

In addition to surface cover, proximate water bodies ("blue spaces") exert significant microclimatic influence. Völker & Kistemann (2011) demonstrated that urban hydrological features mitigate local heat through high specific heat capacity, localized evaporative cooling, and induced air currents. Their work highlighted a spatial gradient where cooling intensity diminishes with distance from the water source, proving most pronounced during peak afternoon heat windows.

Methods

The air temperature data was collected in collaboration with the National Oceanic and Atmospheric Administration as a part of the National Integrated Heat Health Information System. The temperatures were collected by 18 volunteers on August 27th, 2024 over three time windows: the morning from 6-7 AM, the afternoon from 3-4 pm, and the evening from 7-8 pm. The date was selected to be an accurate representation of a hot summer day while not being designated a heat advisory day.

Although data was collected across East Palo Alto, Menlo Park, and Palo Alto, the analysis of this study was limited to Palo Alto due to a lack of impervious surface data for East Palo Alto and Menlo Park.

Results

The analysis of the air temperature data was conducted in R. The raw data was expressed through traversal point graphs utilizing ggplot2 capabilities (Fig. 1). The morning traversal points ranged from 53.1° F - 62.3° F with an average of 57.3° F. The afternoon traversal points ranged from 83.6° F - 97.5° F with an average of 91.6° F. The evening traversal points ranged from 73.7° F - 88.9° F with an average of 82.0° F.

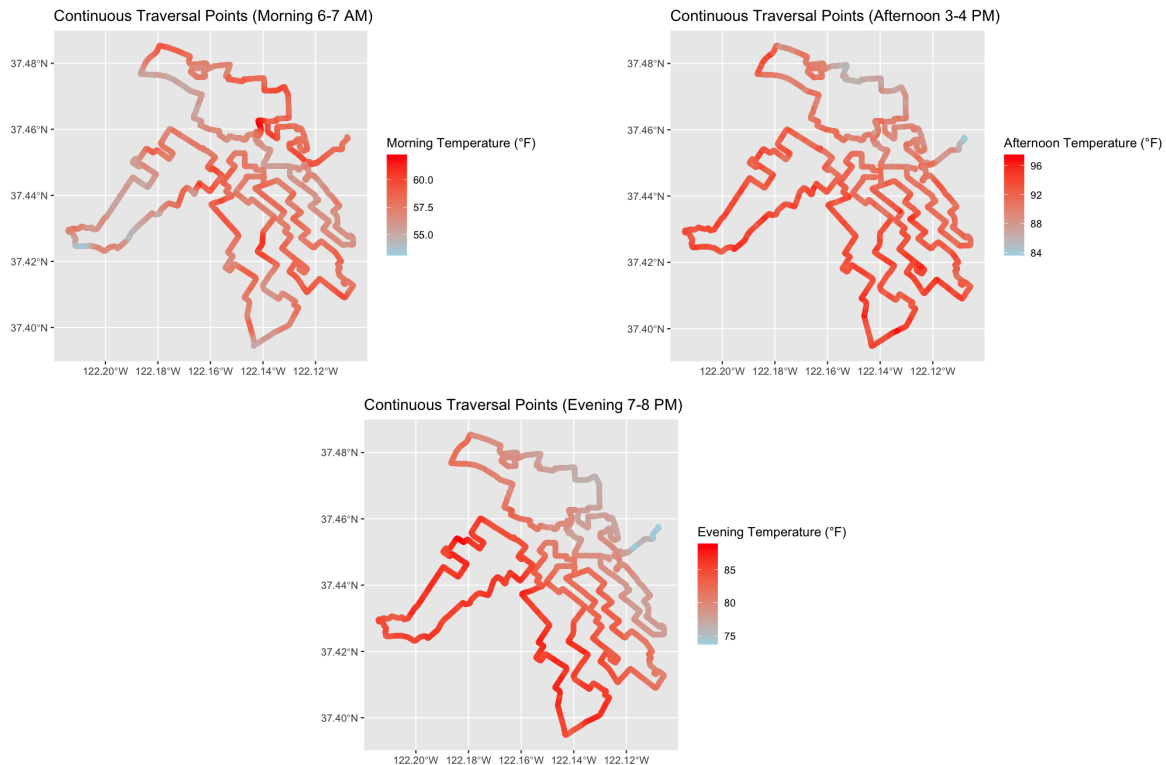
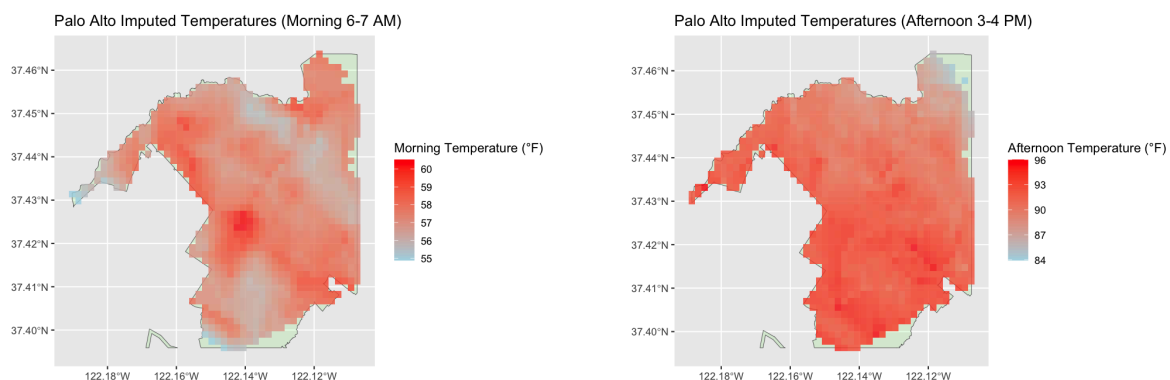


Figure 1: Continuous Traversal Points

To better analyze the data, imputed temperatures were calculated through the `akima::interp()` function, interpolating temperature for non-traversal point locations (Akima & Gebhardt, 1998). Using a granularity of 60, graphs with imputed temperatures for each time window were created (Fig. 2).



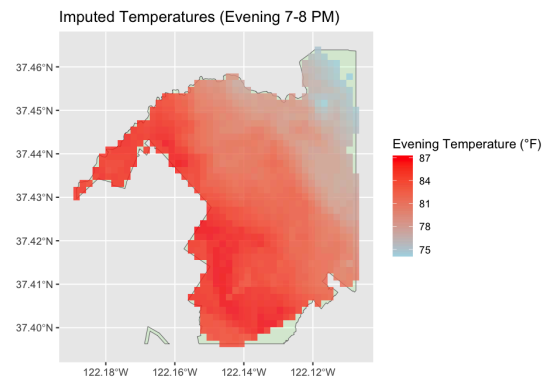


Figure 2: Imputed Temperatures Across Time Windows

We visualized the impervious surface concentration of Palo Alto, which we inferred from the discrete by land-use category (Fig. 3). Impervious surface concentration ranged from 0.00% to 96% with an average of 65.8% across the city.

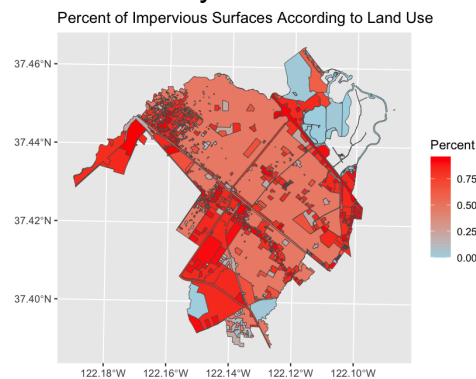


Figure 3: Percentage of Impervious Surface According to Land Use

Distance to coastline was visualized by calculating the difference in distance between imputed temperature squares and the nearest creek, canal, stream, pond, or the bay using Euclidean distance techniques. The water data was sourced from OpenStreetMap information on “coastline” under “natural” features. The calculated distance in meters was computed using Euclidean distance via the `geosphere::dist2Line()` function and was converted to miles for simplified analysis (Fig. 4).

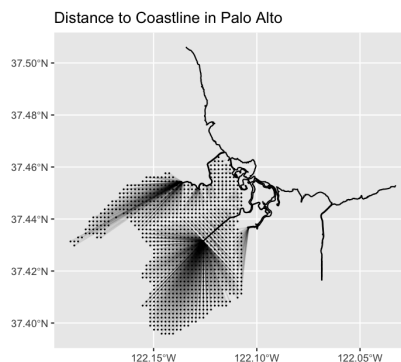


Figure 4: Quantified Distance to Coastline

Data Analysis

Impervious Surface

We found there to be a statistically significant direct correlation between impervious surface concentration and air temperature (Fig. 5, Fig. 6).

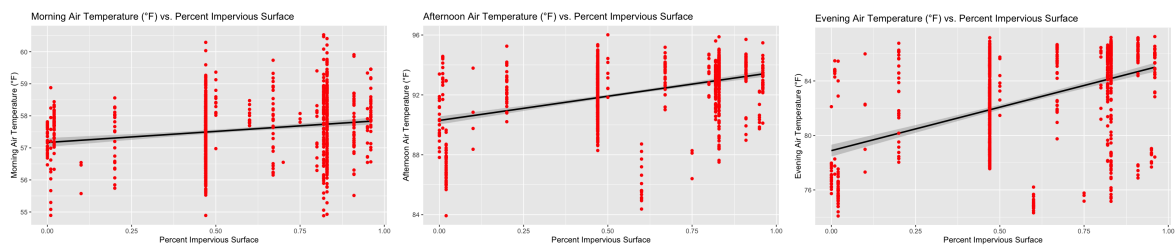


Figure 5: Linear Regression for Air Temperature Versus Percent Impervious Surface per Time Period

The slope of the linear regression model comparing air temperature and impervious suggests that as the day progresses, higher impervious surface concentrations were associated with higher temperatures. In other words, for every 1% increase of impervious surface, there was a 0.69° F increase in temperature in the morning, 3.23° F in the afternoon, and 6.38° F in the evening. Although correlation cannot give way to causation, existing knowledge on impervious surfaces corroborates these findings. Because of the impervious surfaces’ high heat capacity—trapping and radiating heat as time progresses—it is highly plausible that areas with higher concentrations of impervious surfaces experience the heating effect of impervious surfaces more extensively in the evening rather than the morning.

	Morning (6-7 AM)	Afternoon (3-4 PM)	Evening (7-8 PM)
Intercept Coefficient	57.169 ± 0.071	90.296 ± 0.137	78.885 ± 0.221
% Impervious Surface Coefficient	0.691 ± 0.115	3.232 ± 0.220	6.376 ± 0.356
R ²	0.034	0.173	0.237
Adjusted R ²	0.033	0.172	0.236
Residual Std. Error	0.918	1.765	2.870
F-statistic	35.79	216.3	320.8
p-value	3.072 x 10 ⁻⁹	<2.2 x 10 ⁻¹⁶	<2.2 x 10 ⁻¹⁶
N	1031	1036	1037
97.5% CI for Slope	[0.46, 0.92]	[2.80, 3.66]	[5.68, 7.07]

Figure 6: Statistical summary for air temperature versus percent impervious surface linear regression

Distance to Coastline

We found there to be a statistically significant quadratic relationship between distance to coastline and air temperature.

As analyzed by Takebayashi, et al. (2018), air temperature increases in accordance with distance from the coast, but reaches a maximum and slightly decreases at a certain point. Thus, we decided to analyze the relationship between air temperature and distance to coastline using a parabolic regression model. Through using Equation 1, we analyzed the relationship for each time window using a parabolic function.

$$\text{Temperature} = \beta_0 + \beta_1(\text{Miles}) + \beta_2(\text{Miles}^2) + \beta_3(\text{Impervious \%}) + \varepsilon$$

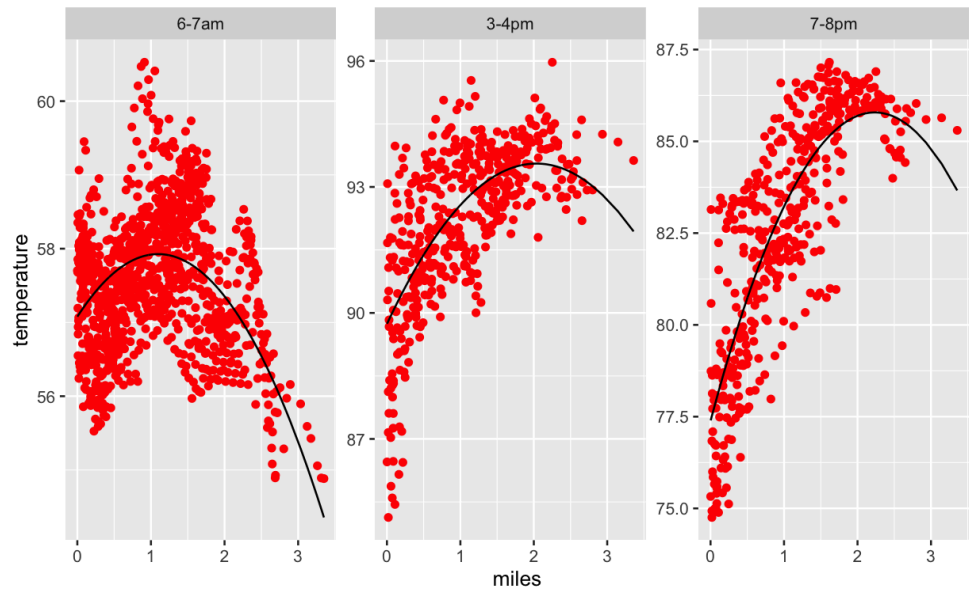


Figure 7: Parabolic relationship between distance to coastline and air temperature

Figure 7 demonstrates the parabolic relationship between distance and air temperature, showing that a farther distance results in higher temperatures up until a certain distance where the cooling effect of the water seems to be insignificant.

Time Period	x (Miles from Coastline)	y (Maximum Air Temperature Increase)
6-7 AM	1.098254	0.8489317
3-4 PM	2.025661	3.820046

7-8 PM	2.233802	8.40437
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Figure 8: Miles From Coastline versus Maximum Air Temperature

As shown in Figure 8, as the day progresses, the cooling effect of the water extends. Since the maximum air temperature found ranges from about one mile from the coastline in the morning to about two miles from the coastline in the afternoon/evening, we can infer that as the day gets hotter throughout the day, the water's high specific heat capacity causes the water to have a cooling effect that extends farther as the day progresses.

Discussion

Our findings suggest that there is a clear linear relationship between air temperature and impervious surface concentration which grows steeper as the day continues and a clear parabolic relationship between air temperature and distance from coastline.

The percent impervious surface was calculated by tracking land use, then finding the average impervious surface across the entire land use category. This analysis was completed by the City of Palo Alto, an outside organization, and thus limited the accuracy of impervious surface values for the entirety of the analysis.

Although this study is limited to Palo Alto, the overarching principles of a positive correlation between temperature and impervious surfaces can be applied to other municipalities. The relationship between air temperature and other variables such as impervious surface concentration and distance to bodies of water can inform future policy decisions on limitations of heat trapping materials. Not much can be done to move existing bodies of water, but this knowledge of the relationship between water and air temperature may be useful in future urban planning decisions to create ponds or bodies of water to combat extreme heat.

By utilizing the knowledge of the cooling properties of bodies of water, urban planners can better place facilities for demographics that are most prone to heat illness. Elderly individuals and young children are particularly prone to heat illness due to age-related physiological changes which limit thermoregulation (Núñez-Rodríguez et al., 2025, Faurie 2023). Paring the study's findings with public health knowledge suggests proximity to cooling features may be considered when evaluating locations for heat-vulnerable populations.

An additional solution to the heating effect of impervious surfaces while utilizing the cooling effect of water is the implementation of water-holding or permeable pavement which showed a decrease of multiple degrees centigrade (Nakayama & Hashimoto, 2010). Implementing permeable pavement allows for use of built pavement without the adverse effects of impervious surfaces on the urban heat island effect.

By utilizing the findings in this study, city planners in Palo Alto and beyond can understand the association of environmental factors with localized air temperature, and zone surrounding areas accordingly.

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