Energy Research and Development Division

FINAL PROJECT REPORT

Monitoring the Urban Heat Island Effect and the Efficacy of Future Countermeasures

California Energy Commission

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution, and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities – Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company – were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that benefit their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and, finally, with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Monitoring the Urban Heat Island Effect and the Efficacy of Future Countermeasures is the final report for the Monitoring the Urban Heat Island Effect and the Efficacy of Future Countermeasures project (Contract Number EPC-14-073) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

To relate fine-scale spatial air-temperature variations in local urban heat islands and urban cool islands—increases and decreases in outside air temperature—within a large urban-climate archipelago to variations in land-use and land-cover properties in the Los Angeles Basin, the research team sought to (a) use fine-resolution meso-urban climate models to identify areas of urban heat and cool islands, select sites for fixed weather monitoring, and choose routes for mobile observations; (b) relate observed intraurban temperature variations to land use and land cover and surface physical properties; and (c) calibrate/validate the climate models. The research team assessed urban temperature variations via simulations and observations, including mobile transects, mesonet, dense networks of personal weather stations, and sparse but more accurate research-grade monitors. To identify the causative factors of the urban heat and cool islands at the neighborhood scale, the research team collected detailed urban morphometric and land use and land cover datasets, such as 1-meter (3.3 foot) resolution roof albedo (solar reflectance) and tree canopy cover. The research team used the observation-validated model to finalize the transect routes and site the stationary monitors.

This study provides the first observational evidence from analysis of high-spatial-density weather stations that increases in roof albedo at neighborhood scale are associated with reductions in near-surface air temperature. This finding was corroborated with the analysis from mobile transect measurements and correlation of observed air temperature with neighborhood-scale albedo and vegetation. This correlation revealed a cooling effect from area-wide increase in albedo or canopy cover or both.

The calibrated meteorological model accurately identified the localized urban heat and cool islands observed in this study. Interested stakeholders/researchers can use the same models and calibration/validation methodology to characterize within-city microclimate variations elsewhere in California, and can apply them to analyze the benefits from using urban heat island countermeasures.

This project report is an extended and more detailed version of a related report prepared for California's Fourth Climate Change Assessment.

Keywords: Urban heat islands, urban cool islands, land-use and land-cover, intra-urban temperature variability, mobile transects, personal weather stations, stationary weather monitor, fine-scale meteorological model

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EXECUTIVE SUMMARY

Introduction

The urban heat island effect is the increase of air temperature in cities from surrounding rural areas. Urban heat islands are either skin-surface urban heat islands or air-temperature urban heat islands. Air-temperature urban heat islands are relevant to building energy use, thermal comfort, public health, precursor air emissions, air pollutant formation, and climate and, as such, are the focus of this study. Urban heat islands result in part from the transformation of urban land cover from trees and vegetation to buildings and other heat-absorbing urban infrastructure.

Future climate change scenarios project that the annual number of extreme heat days in California's urban areas will increase. In the San Fernando Valley in the Los Angeles Basin, the number of extreme heat days—those with maximum air temperatures exceeding 39.7 ˚C (103.4 ˚F), based on the ninety-eighth percentile of daily maximum temperatures recorded April–October 1961–1990—are estimated to increase on average to 12 days per year from 4 by midcentury. Temperature increases induced by climate change would exacerbate existing heat islands, threatening human and nonhuman health and straining energy resources. While warming from climate change requires global action to mitigate, urban heat islands are city-specific phenomena with solutions a city can implement locally. Modeling studies have found that urban heat island countermeasures, such as "cool roofs" and tree canopies, reduce urban temperatures when implemented at scale in cities.

Project Purpose

Understanding the variations in local heat and cool islands and the related interaction with land use land-use and land-cover properties can help cities implement policies to address urban heat islands now and build resiliency to future urban warming from climate change. To design and implement appropriate countermeasures, cities need to characterize urban heat and related causes. This project sought to understand spatial variations in local heat and cool islands and the relationship to land-use and land-cover properties, providing guidance for future mitigation via control measures such as higher albedo (solar reflectance) and more vegetation. The objective was to establish the causative factors of the local heat and cool islands at the neighborhood scale in the study areas, based on site-specific and upwind micrometeorological dynamics (for example, local generation of heat and transport of heat from upwind sources); land-use and land-cover properties; and surface physical properties. The research team sought to use fine-resolution climate models to identify urban heat and cool island areas, relate observed intra-urban temperature variations (from mobile transects and fixed weather stations) to land-use and land-cover and surface physical properties, and (c) calibrate/validate the fine-resolution meso-urban climate models used in identifying the urban heat islands and urban cool islands.

Project Approach

To characterize the meteorological variables in the study areas, the research team collected data from existing weather networks; conducted detailed, fine resolution meteorological modeling; installed research-grade stationary weather monitors; and performed mobile transects (measurement of temperature along a path). The research team partnered with the City of Los Angeles, County of Los Angeles, and Los Angeles Unified School District to help identify and host stationary monitors in two study areas that the research team identified: "SFV5", an area that is part of the San Fernando Valley; and "LA1", a region that includes and extends to the southeast of downtown Los Angeles. The research team installed three research-grade stationary monitors in the SFV5 study area. The research team also installed a research-grade monitor at the University of Southern California campus west of downtown Los Angeles. To supplement the data collected from these stationary monitors, the research team designed and executed multiple mobile transects. To identify the causes of the local heat and cool islands at the neighborhood scale, the research team collected detailed land-use and land-cover datasets for the Los Angeles Basin, such as 1-meter (3.3 foot) resolution roof albedo and tree canopy cover, as inputs for the meteorological modeling and analysis. The fine-scale meteorological model was used to design mobile-transect routes and site the stationary weather monitors based on the definition of urban heat island/urban cool island areas.

Project Results

The research team found the first observational evidence from analysis of high-spatial-density weather stations that increases in roof albedo at neighborhood scale are associated with reductions in near-surface air temperature. The research team corroborated this finding with analysis from mobile transect measurements, which revealed a cooling effect from areawide increase in albedo or canopy cover or both. The albedo and canopy cover values in the analysis are existing conditions in Los Angeles neighborhoods where there has not been a concerted effort to address urban heat islands. This situation suggests there are opportunities for community cooling using existing technologies and practices to increase urban albedo and canopy cover. Knowing that these are effective cooling measures, cities can also accelerate implementation of these urban heat island countermeasures in heat-vulnerable neighborhoods.

In addition, the calibrated meteorological model accurately identified the localized urban heat islands and urban cool islands observed in this study. Therefore, it can be applied by stakeholders, including city and state government, to characterize the intraurban microclimate variations elsewhere in California. Stakeholders can also apply the model to analyze the benefits from using urban heat island countermeasures.

Knowledge Transfer

The research team installed four research-grade stationary monitors: a reference monitor at University of Southern California (Monitor 0) and three at carefully selected sites in Los Angeles (Monitors 1–3). The data from Monitors 1–3 can be accessed for free via Weather Underground. The monitors will remain in place after the project concludes, providing valuable new weather stations in the urban core of the Los Angeles region. These monitors will help urban and

environmental professionals, planners, and researchers conduct future analysis of urban heat island mitigation strategies, building energy modeling, urban planning, local weather forecasts, and other modeling activities (for example, air quality analysis).

Los Angeles Unified School District staff in the Magnet Schools Assistance Program will share the data in the Global Learning and Observations to Benefit the Environment program, a worldwide hands-on science and education program focusing on the environment. This project information and experiences will help enable students to carry out their own research projects about their urban environments.

Research Recommendations

To further validate the research team's findings and to build upon these findings to help cities implement effective local urban heat island countermeasures, the team recommends the following future research:

- Guide the implementation of cool-community measures by determining the minimum changes in albedo and vegetation cover (in heat-vulnerable communities) that are required to achieve cooling benefit.
- Identify a neighborhood in which UHI countermeasures can be adopted and their air cooling effects can be monitored.
- Repeat the personal weather station analysis over the next few years as land cover properties evolve (for example, increasing prevalence of cool roofs) and more personal weather stations are added to networks.
- Repeat the personal weather station analysis using WeatherBug network data and measurements from the newly installed stationary monitors of the project.
- Carry out additional transects, modeling, and analysis of personal weather stations in other parts of the Los Angeles Basin.
- Design a specialized air temperature sensor that piggybacks on ride-share vehicles to provide detailed time-and-space maps of urban air temperature.
- Repeat the study for other areas in California.
- Complete related modeling and analysis for future-climate scenarios.
- Enhance analysis (observations, modeling, and so forth) by including year-round conditions.

Benefits to California

The research team found the first observational evidence that increases in roof albedo and vegetation at neighborhood scale are associated with reductions in near-surface air temperature. This lends credibility to many cool-cities studies done to date and suggests that measurable and significant community-scale cooling can be attained by using existing technologies and practices to increase urban albedo and canopy cover. Cities can also accelerate implementation of these heat island countermeasures, especially in heat-vulnerable neighborhoods.

The ability to cool neighborhoods with these simple technologies means that cities and ratepayers can save energy; reduce emissions of greenhouse gases, particulate matter, and ozone precursors, thereby attaining better air quality; improve thermal environmental conditions inside buildings and at street-level; and locally offset some of the potential impacts of heat events or climate change.

The carefully sited research-grade weather stations installed by the team will help researchers track how implementation of these heat island countermeasures cools neighborhoods in Los Angeles and, thus, realizes the benefits listed above.

In addition, the calibrated meteorological model accurately identified the localized urban heat islands and urban cool islands observed in this study. Therefore, the methodologies developed in this project can be applied by stakeholders, including city and state government, to characterize the intraurban microclimate variations elsewhere in California, and stakeholders can apply the model to analyze the benefits from launching urban heat island countermeasures.

CHAPTER 1: Introduction

1.1 About Urban Heat Islands

The urban heat island effect (UHIE) is the elevation of air temperature in urban areas above that in surrounding rural areas. Urban heat islands (UHI)—that is, regions of elevated urban temperature—are categorized as either skin-surface UHIs or air-temperature UHIs. Air-temperature UHIs are relevant to building energy use, thermal comfort, public health, precursor emissions, air-pollutant formation, and climate and, as such, are the focus of this study. UHIs result in part from the transformation of urban land cover from trees and vegetation to buildings and other heat-absorbing urban infrastructure.

Future climate change scenarios project that the annual number of extreme heat days in California's urban areas will increase. In the San Fernando Valley in the Los Angeles Basin, the number of extreme heat days—those with maximum air temperatures exceeding 39.7 °C (103.4 °F), based on the ninety-eighth percentile of daily maximum temperatures recorded April–October 1961–1990—are estimated to increase on average to 12 days per year from 4 by midcentury. Temperature increases induced by climate change would exacerbate existing heat islands, threatening human and nonhuman health and straining energy resources. While warming from climate change requires global action to address, UHIs are city-specific phenomena with solutions a city can implement locally. UHI countermeasures, such as cool roofs and tree canopy cover, have been found in modeling studies to reduce urban temperatures when implemented at scale in cities.

1.2 Objective and Scope

To design and implement appropriate countermeasures, cities need to characterize urban heat and related causes. This project seeks to understand spatial variations in local heat and cool islands and the relationship to land-use and land-cover (LULC) properties, providing guidance for future mitigation via control measures such as higher albedo (solar reflectance) and more vegetation. The objective was to establish the causative factors of the local heat and cool islands at the neighborhood scale in the study areas, based on site-specific and upwind micrometeorological dynamics (for example, local generation of heat and transport of heat from upwind sources), LULC properties, and surface physical properties. The research team sought to use fine-resolution climate models to identify UHI/urban cool island (UCI) areas, relate observed intra-urban temperature variations (from mobile transects and fixed weather stations) to LULC and surface physical properties, and calibrate/validate the fine-resolution meso-urban climate models that were used in identifying the UHI/UCI. By understanding the variations in local heat and cool islands and the associated interaction with LULC properties, cities can implement policies to address UHIs now and build resiliency to future urban warming from climate change.

To characterize the meteorological variables in the study areas, the research team collected data from existing weather networks; conducted detailed, fine resolution meteorological modeling; installed research-grade stationary weather monitors; and performed mobile transects. The research team partnered with the City of Los Angeles, County of Los Angeles, and Los Angeles Unified School District (LAUSD) to help identify and host stationary monitors in two study areas that the research team identified: "SFV5," an area that is part of the San Fernando Valley; and "LA1," a region that includes and extends to the southeast of downtown Los Angeles. The research team installed three research-grade stationary monitors in the SFV5 study area. The research team also installed a research-grade monitor at the University of Southern California campus west of downtown Los Angeles. To supplement the data collected from these stationary monitors, the research team designed and executed multiple mobile transects. To identify the causative factors of the local heat and cool islands at the neighborhood scale, the research team collected detailed LULC datasets for the Los Angeles Basin, such as 1-m. (3.3-ft.) resolution roof albedo and tree canopy cover, as inputs for the meteorological modeling and analysis. The fine-scale meteorological model was used to design mobile-transect routes and site the stationary weather monitors based on the definition of UHI/UCI areas.

1.3 Brief Overview of Project Technical Tasks

This project has three technical tasks, numbered 2 through 4:

- Task 2: Identify and characterize study regions in the Los Angeles Basin.
- Task 3: Develop a monitoring plan, design instrumentation, and deploy a sensor network to measure the UHIE in the selected study region.
- Task 4: Collect and analyze weather data from fixed and mobile monitors.

Task activities and outcomes are summarized in Chapters 2–4 and detailed in a series of task reports (Appendices A – F).

1.4 Relationship to Report Prepared for California's Fourth Climate Change Assessment

A briefer report prepared for California's Fourth Climate Change Assessment—*Modeling and Observations to Detect Neighborhood-Scale Heat Islands and Inform Effective Countermeasures in Los Angeles* (Taha et al. 2018a)—summarizes most of the work performed in this study but omits many details presented in the current report.

CHAPTER 2: Identifying and Characterizing Study Regions in the Los Angeles Basin (Task 2)

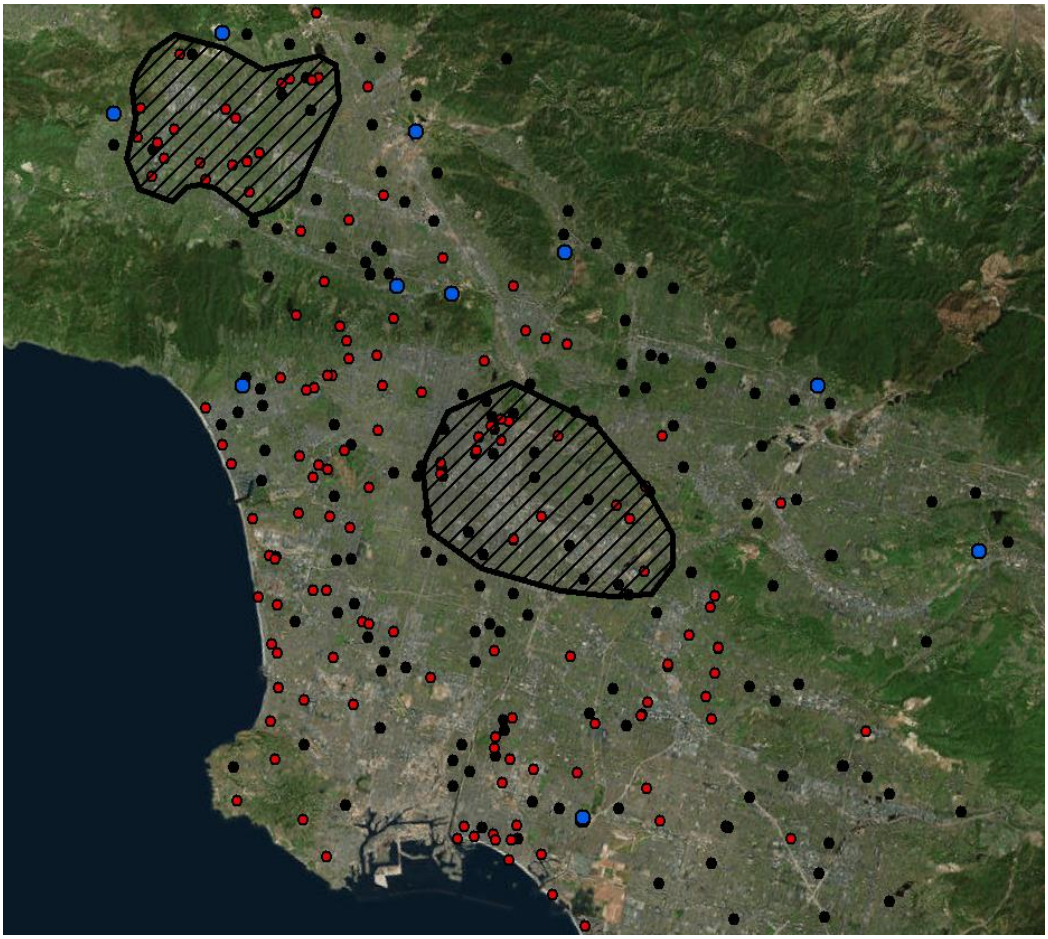
Task 2 identified and characterized study regions in the Los Angeles Basin suitable for UHI assessment. Task elements included:

- Assessing and acquiring data from existing monitors by reviewing the locations, sensors, outputs, availabilities, and data-access costs of several existing networks of weather monitors in the study region.
- Evaluating the quantity, quality, and spatial density of air temperature, relative humidity (RH), wind speed, and wind direction measurements obtainable from existing monitors.
- Statistically analyzing and correlating observational data from all sources.
- Characterizing, compiling, and upscaling LULC data and supplementing these data with characterizations from remote sensing.
- Applying a fine-resolution meso-urban meteorological model to the LULC information to simulate annual or seasonal hourly values of air temperature, humidity, wind speed, and wind direction in the study region.
- Comparing simulation results to any relevant weather data from existing monitors nearby.
- Assessing wind patterns and the variations of air temperatures with LULC, as well as variations with respect to height above ground in various areas of the study.
- Identifying the likely areas where an urban heat island might be detected with the monitors, as well as an initial, first-order guess of expected UHI intensity in different regions.

2.1 Acquisition of External Weather Measurements

To inform placement of new stationary monitors and provide observations to compare to modeled temperatures, the research team created a database of accessible historical weather data from all sources that had at least 10 stations available for the Los Angeles Basin. These sources included the California Irrigation Management Information System (CIMIS), WeatherBug, and Weather Underground (Figure 1). However, for simplicity and to avoid temperature differences that might result from variations in measurement techniques between networks, the research team's analysis of PWS data included only monitors from the Weather Underground network and focused on a single season (summer 2015). Data downloaded from the existing weather station sources were postprocessed to remove outliers. Acquisition and refinement of external weather measurement data are detailed in the Task 4 Report, Part III: *Observational Evidence of Neighborhood Scale Reductions in Air Temperature Associated With Increases in Roof Albedo* (Appendix G; also published as Mohegh et al. 2018).

Figure 1: Locations of Existing Weather Stations Used in the Study



The cross-hatched black polygons outline the team's initial areas of interest for study of existing weather data. The red, blue, and black points identify Weather Underground, WeatherBug, and CIMIS weather stations, respectively.

Source: Research Team

2.2 Study Area Characterization

LULC analysis was the first step in identifying urban areas with delineations or transitions of interest—that is, changes in physical properties. The research team performed this analysis to derive surface inputs to the meteorological model and provide a basis for relating observed air temperature to LULC properties at stationary monitor sites or along mobile-transect routes. Figure 2 shows an example of LULC characterization in one study area selected in this project. LULC analysis is detailed in the Task 2 Report, Part I: *Land-Use/Land-Cover Analysis and Atmospheric Modeling to Support Site Identification and Selection for Fixed Meteorological Monitors and Mobile-Observation Routes* (Appendix A).

Figure 2: Sample Detail From Land-use and Land-cover Analysis

Image shows an area including downtown Los Angeles (area LA1). There are about 50 LULC classes represented in this figure; the USGS Level-IV system includes more than 100 classifications. The darker areas are residential land uses, and the areas color-coded blue, dark green, and red in the middle are industrial and commercial land functions. Bright green represents open or vegetated areas or both.

Source: Research Team

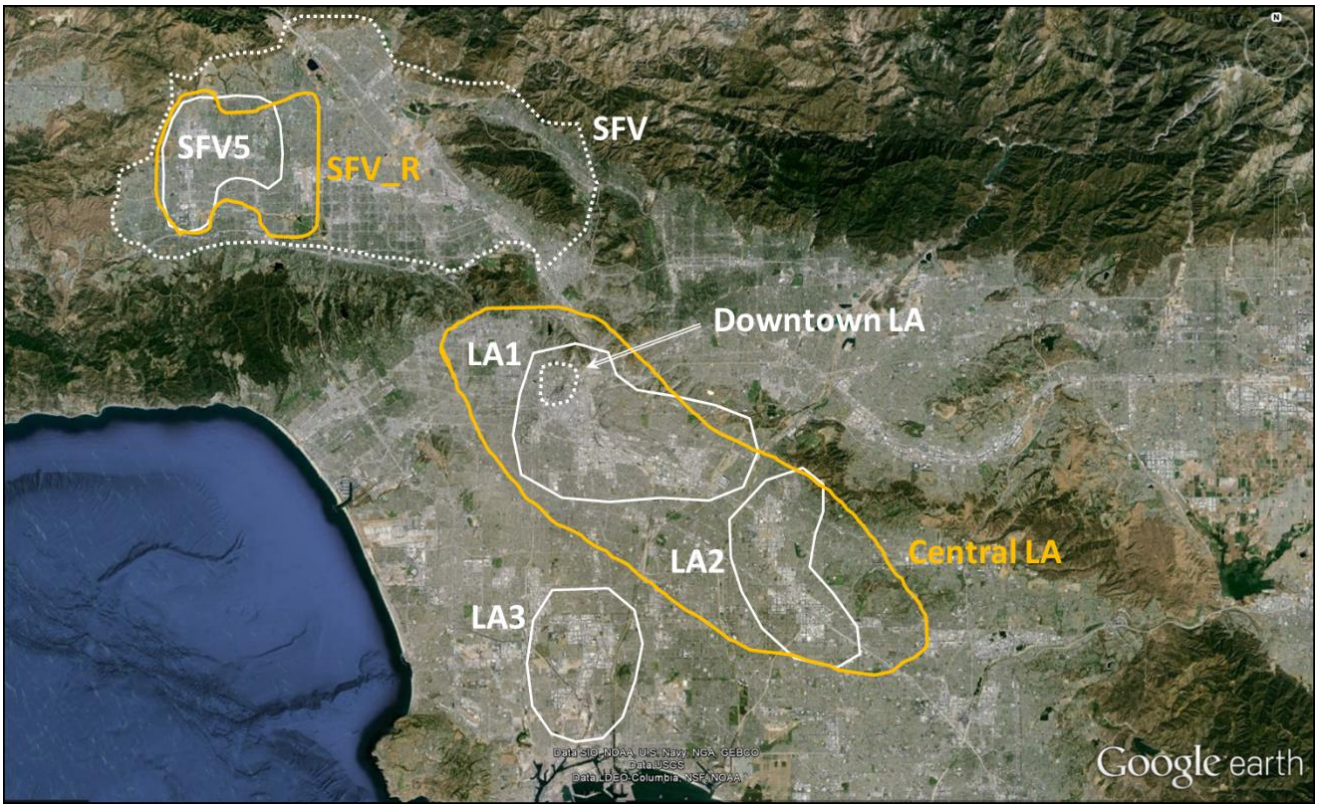
2.3 Study Area Selection

Figure 3 shows four study areas initially considered for meteorological modeling (LA1, LA2, LA3, and SFV5), along with the two areas used in analysis of personal weather station data (Central Los Angeles and SFV_R). The two most promising study areas identified—LA1, containing downtown Los Angeles in its northwestern tip, and SFV5, a portion of the San Fernando Valley—were modeled to assess the potential UHI or UCI signals or both that stationary monitors and mobile transects in this area would capture. This preparatory modeling is detailed in the Task 2 Report, Part I: *Land-Use/Land-Cover Analysis and Atmospheric Modeling to Support Site Identification and Selection for Fixed Meteorological Monitors and Mobile-Observation Routes* (Appendix A).

To quantitatively evaluate the model prediction of temperature tendency and spatial gradients in temperature in the modeled areas, the research team devised preliminary mobile-transect measurements of temperature for initial feedback and preparation for more rigorous model performance evaluation. The transect was conducted in Area LA1 during April 2016. Execution of the preliminary transect is detailed in the Task 2 Report, Part II: *Preliminary Mobile Measurements of Air Temperature via Transect* (Appendix B). Design of the mobile monitor is summarized in Chapter 3 and detailed in the Task 3 Report, Part I: *Monitoring Plan, Instrumentation Design, and Sensor Deployment* (Appendix C).

The transect observations confirmed the findings from the model, allowing the team to use the modeled results to select the study areas of interest. Therefore, the research team chose to install stationary monitors in areas SFV5 and LA1 to capture the interactions between LULC and microclimates in inland regions (the San Fernando Valley) and areas influenced by the sea breeze flow and climate archipelago[1] effects (the semi-coastal region that includes Area LA1). Monitoring two unlike areas helps the team understand the role of local surface properties and impacts on temperature in different climate regimes—here, inland valleys, and quasi-coastal areas.

Figure 3: Boundaries of Initial and Selected Study Areas



Boundaries of initial study areas LA1, LA2, LA3, and SFV5 (solid white lines) considered for meteorological modeling, installation of new stationary monitors, and mobile transects; LA1 and SFV5 were selected. Also shown are the boundaries of study areas Central Los Angeles and SFV_R (solid gold lines) used in analysis of personal weather station data, and the boundaries of the San Fernando Valley (SFV) and downtown Los Angeles (dotted white lines).

Source: Research Team

1 An archipelago is group of islands or a body of water containing a group of islands. The research team uses the term "climate archipelago" to refer to the complex climate effects of a very large, continuous urban area in which upwind portions can affect downwind portions.

CHAPTER 3: Developing a Monitoring Plan, Designing Instrumentation, and Deploying a Sensor Network to Measure the Urban Heat Island Effect in the Selected Study Regions (Task 3)

In Task 3 the research team developed a monitoring plan, designed instrumentation, and used a sensor network to measure the UHIE in the selected study regions. Task elements included:

- Designing a mobile monitor for transects.
- Designing stationary monitors to install on buildings.
- Deciding where to install new stationary monitors in the selected study regions.
- Acquiring suitable sites for installation of the stationary monitors.
- Calibrating, installing, and verifying operation of the new monitors.

All Task 3 activities are detailed in the Task 3 Report, Part I: *Monitoring Plan, Instrumentation Design, and Sensor Deployment* (Appendix B).

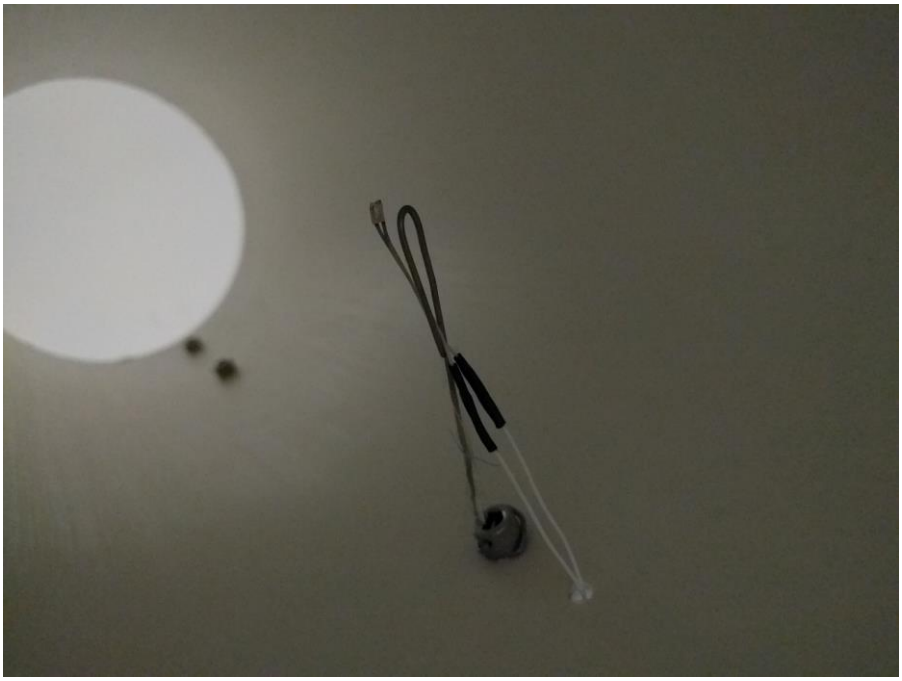
3.1 Mobile Monitor Design

Horizontal variations in air temperature near the ground—say, 2 meters above ground level—can be mapped by attaching a thermometer to roof of a vehicle, such as a car, then logging temperature, position, and time during a transect. To ensure that the thermometer accurately measures air temperature, the sensor should be aspirated by the motion of the vehicle, shielded from the sun, and radiatively isolated (decoupled) from the shield. The sensor should also respond quickly to air temperature changes to minimize spatial inaccuracies, or blurring, in the air temperature map induced by the motion of the vehicle.

The research team's mobile monitor contains five elements:

1. A shielded temperature sensor aspirated by vehicle motion (Figure 4).
2. A quick-install mount to attach the shielded sensor to the roof of a vehicle (Figure 5).
3. A portable data logger to record the temperature time series (Figure 6).
4. A global positioning system (GPS) to record the position time series.
5. A dash camera (dash cam) to record time-stamped video of the transect from the perspective of the driver.

Figure 4: Mobile Monitor Temperature Sensor



A clip secures a foil-wrapped bead thermistor in the center of the shield.

Source: Research Team

Figure 5: Mobile Monitor on Quick-Install Car-Roof Mount

System includes white PVC-pipe shield, gray PVC-pipe vertical risers, aluminum tube roof mounting on plastic and rubber feet, and white PVC-pipe crossbeams. Straps with hooks (not shown) secure the bars to the vehicle frame.

Source: Research Team

Figure 6: Mobile Monitor Temperature Logger

Logger shown with stock thermistor probe. The detachable probe was replaced by a 4 meter extension cable leading to the foil-wrapped bead thermistor shown in Figure 4.

Source: Lascar Electronics

3.2 Stationary Monitor Design

The research team sought the following performance characteristics for each stationary monitor:

- The monitor should accurately and continuously measure the primary signal, dry-bulb air temperature; secondary signals, including wind speed, wind direction, solar irradiance, and relative humidity, useful for interpreting variations in air temperature; and monitor diagnostics, such as radiation-shield fan speed, needed to verify that the sensors are operating as designed.
- To ease installation and subsequent maintenance, the monitor should be easy to assemble and program.
- The monitor should be readily installed on an elevated surface, such as that of a low-slope roof, to measure air temperature at some fixed height above ground.
- The monitor should communicate over the internet or by cellular modem for convenient data collection and (if necessary) reprogramming.
- The monitor should be durable, ideally with a service life approaching a decade.

The research team reviewed the specifications and prices of two loggers, six wind speed/direction sensor kits, two silicon pyranometers, two temperature sensors, one RH sensor, and four aspirated radiation shields. The research team also factored in positive and negative experiences with some of these instruments in past projects. After considering all these inputs, the research team specified and purchased a system from Onset Corporation that connects to a logger (RX3000) plug-and-play digital-output sensors that measure wind speed (S-

WSB-M003 three-cup anemometer), wind direction (S-WDA-M003 wind vane), solar irradiance (LIB-M003 silicon pyranometer), and temperature/RH (S-THB-M002 temperature/RH). The logger also has a four-channel analog module (RXMOD-A1) that can excite and measure analog signals, such as the output of a thermistor circuit (air temperature) and a pulse-counting circuit (fan speed). The logger can upload its measurements to a cloud data server via cellular modem. All components can be mounted on a tripod structure, which in turn can be installed on a roof. (They can also be connected to an existing pole if desired.)

The research team acquired evaluation units of two aspirated radiation shields. After extensive testing, the research team determined that both were suitable but selected the Apogee Instruments TS-100 shield with ST-110 precision thermistor because the fan drew less power than that of the other unit. (This is helpful for monitors powered by solar-charged batteries.)

3.3 Selecting Stationary Monitor Sites

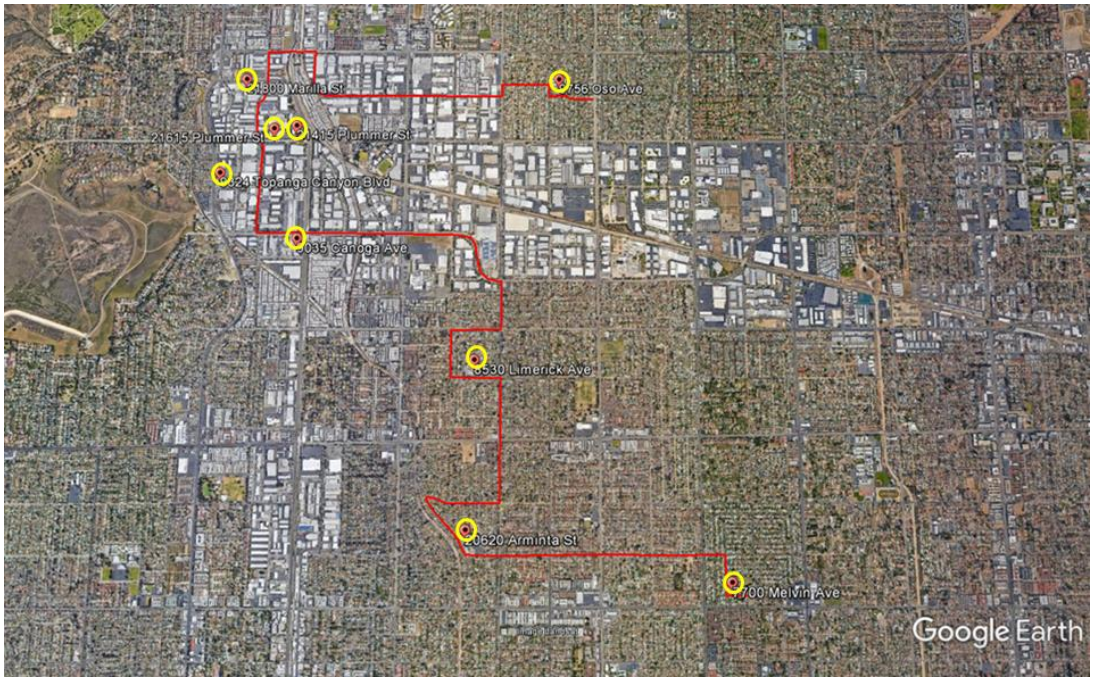
Several points in the LA1 and SFV5 study areas were identified as localized UHI or UCI areas based on model and initial mobile-transect results. The research team shared these points and study areas with project partners—including the City of Los Angeles, County of Los Angeles, and LAUSD—and collectively developed a list of their facilities that could serve as potential sites for the stationary monitors. Upon further evaluation of these sites via examination of three-dimensional imagery (for example, Google Earth Pro) and location visits, certain sites were assigned a lower priority because of such factors as unavailability of flat roofs (sloped roofs can be an issue for installing weather stations), lack of secure sites in open areas (at ground level), and physical characteristics of the site. These factors resulted in a top tier of 10 potential sites, some of which are shown in Figure 7.

3.4 Acquiring Monitor Installation Sites

The research team struggled to get local approval and find suitable locations for monitor installation at each of the potential sites. While the research team had high-level support from our partners, many layers of approval were required. For example, the research team had support from City of Los Angeles Fire Department management to install monitors but ran into a barrier with the labor union representing the firefighters, which did not want a rooftop monitor on their fire station transmitting data via a cellular modem. Partners also expressed concerns about the ability of old roofs to support the (lightweight) monitors.[2]

[2] Each roof-mounted monitor (sensors on a tripod) weighs 43 lb. (19.5 kg) and is secured to three 5’ by 5’ by 0.75” (1.5 m by 1.5 m by 1.9 cm), 44 lb. (20 kg) plywood plates. Each plate is further ballasted with 44 lb. of bricks. Hence, a secured station weighs about 255 lb. (116 kg) and exerts 3.4 lb.-force/square ft (163 Pa) pressure on the roof. That’s about 0.3% of the ground pressure exerted by a standing human male (1,150 lb-force/ft² [55 kPa]) (https://en.wikipedia.org/wiki/Ground_pressure).

Figure 7: Prospective Installation Sites for Stationary Monitors



(a) Potential sites in SFV5 (red markers circled in yellow) along a sample mobile-transect route.

Source: Research Team

(b) Potential sites in SFV5 (red markers circled in yellow) along a sample mobile-transect route.

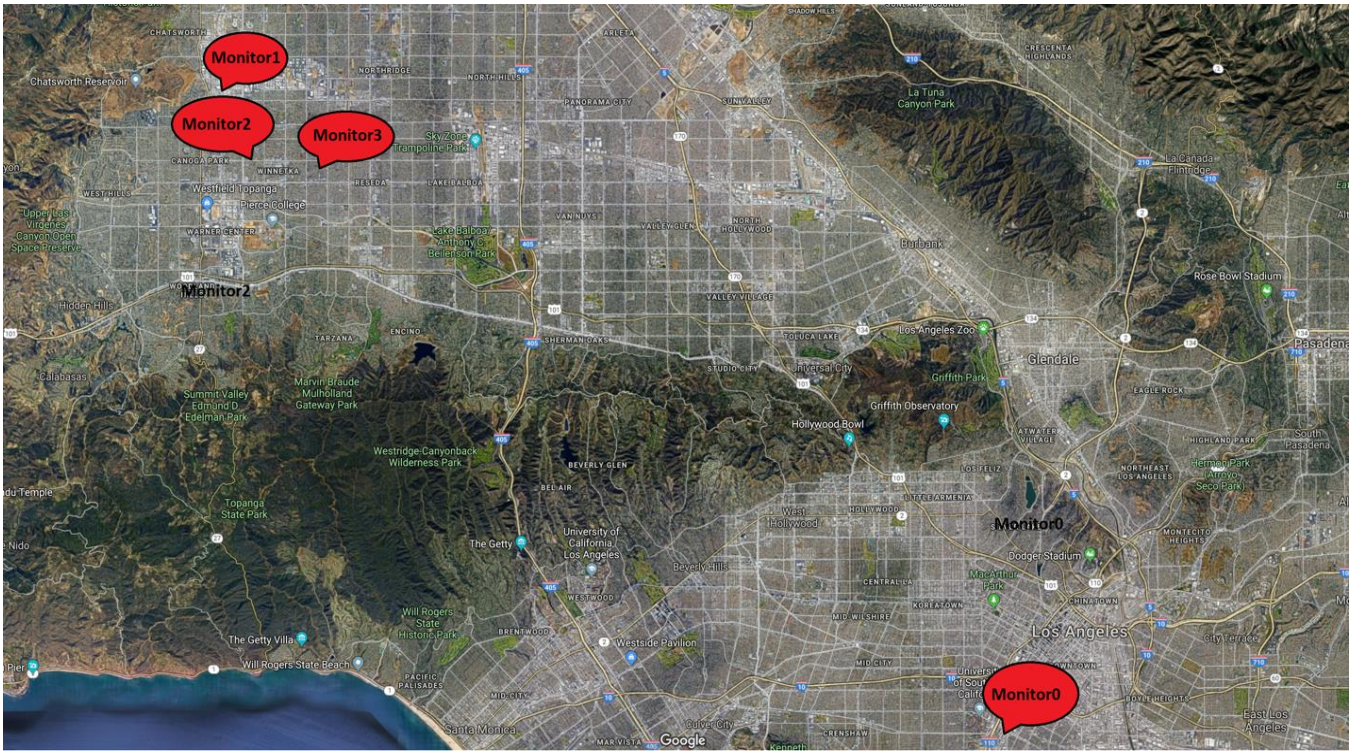
Source: Research Team

3.5 Installing and Calibrating Monitors

After extensive negotiation, the research team received partner approvals to install four monitors (Figure 8). The first monitor (Monitor 0, the reference monitor) was installed October 26, 2016, on the campus of the University of Southern California (USC) inside a gated area in a parking lot, 2 m above ground level (AGL). Monitor 1 was installed July 25, 2017, at the City of Los Angeles' Bureau of Street Services Facility Yard in Topanga Canyon, 2 m above the roof of a structure that shades a parking lot. Monitor 2 was installed January 11, 2018, at LAUSD's Sunny Brae Elementary School, 2 m above the roof of a school building. Monitor 3 was installed April 13, 2018, at LAUSD's Melvin Elementary School, also 2 m above the roof surface of a school building.

The temperature sensors in all four monitors were cross-calibrated at the USC (Monitor 0) site before Monitors 1, 2, and 3 were deployed.

Figure 8: Locations of the Four Stationary Monitors Installed in Los Angeles



Monitor 0 was installed on the campus of the University of Southern California, while Monitors 1 – 3 were installed in the San Fernando Valley.

Source: Research Team

CHAPTER 4: Collecting and Analyzing Weather Data From Fixed and Mobile Monitors (Task 4)

Task 4 sought to observationally quantify the UHIE and the relationship to LULC, establish a baseline for future UHI mitigation, and calibrate/validate a fine-resolution mesoscale climate model. Task elements included:

- Collecting data from the new stationary monitors.
- Designing and conducting mobile measurements of near-ground air temperature.
- Using stationary and mobile measurements to update fine-resolution model simulations and parameterizations, such as those supported by the California Environmental Protection Agency for UHI Index development, and to calibrate/validate these models.
- Using hourly air temperature measurements and other meteorological variables from the existing weather stations to evaluate the UHIE, and to correlate spatial variations in air temperature and UHIE intensity with LULC and urban morphological characteristics.

For full details of mobile measurements and the related application to model calibration/validation, please see the Task 4 Report, Part I: *Model Validation and Development of Correlations Between Observed Air Temperature and Surface Physical Properties* (Appendix E), and Task 4 Report, Part II: *Air-Temperature Response to Neighborhood-Scale Variations in Albedo and Canopy Cover in the Real World: Fine-Resolution Meteorological Modeling and Mobile Temperature Observations in the Los Angeles Climate Archipelago* (Appendix F; also published as Taha et al. 2018b). For full details of using measurement from existing weather stations to relate urban air temperature to LULC, please see Task 4 Report, Part III: *Observational Evidence of Neighborhood-Scale Reductions in Air Temperature Associated With Increases in Roof Albedo* (Appendix G).

4.1 Stationary Monitor Measurements

The research team has continuously collected data from Monitors 0–3 since installation. However, because of logistical delays in the installations of Monitors 2 and 3, the analysis in the current study is based instead on the team's mobile transect measurements. Data from the stationary monitors can be used in subsequent research. The research team also presents here analysis of data drawn from many personal weather stations.

4.2 Mobile Transect Measurements

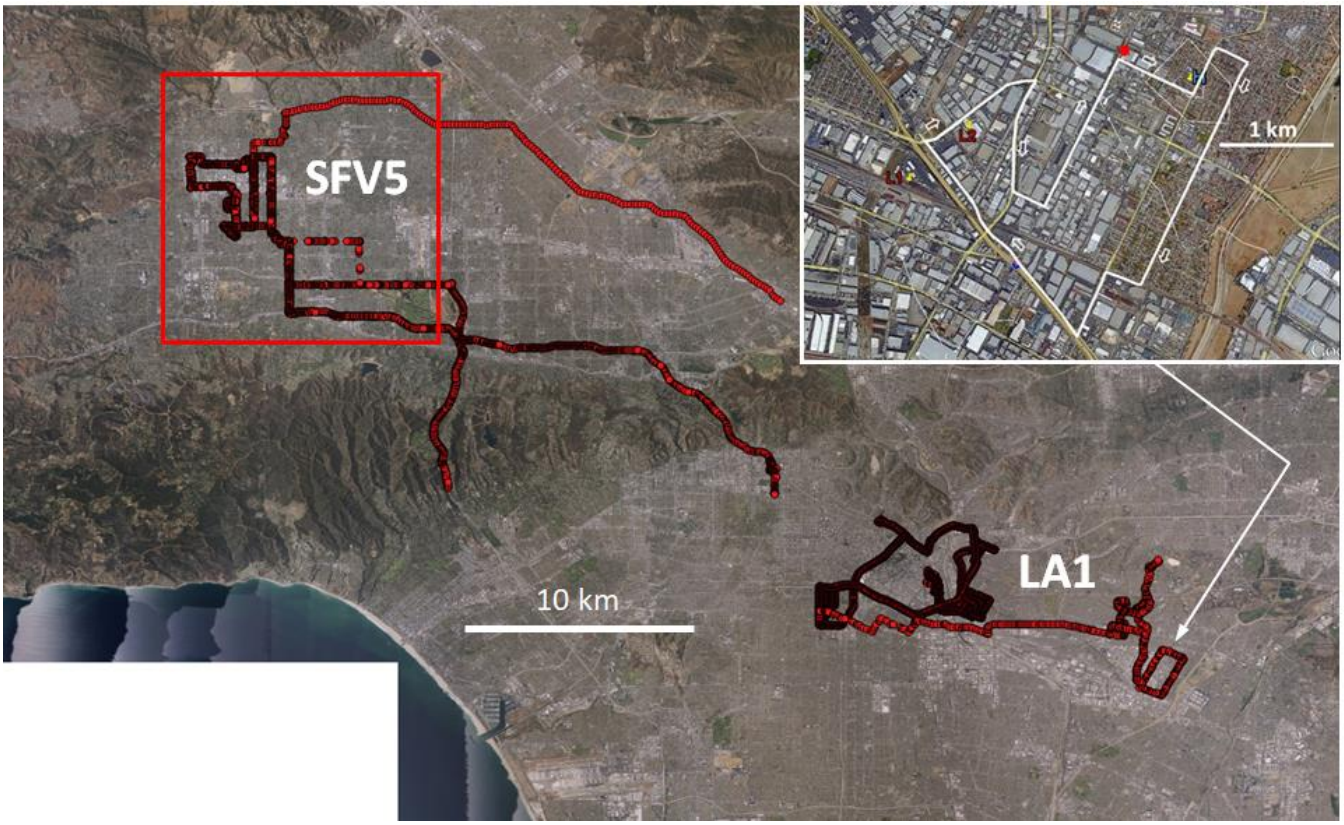
Mobile-observation transects were carried out to measure microclimate variations along the routes. Of particular interest was air temperature variation as the LULC and surface properties change along each route segment. The goal was to develop correlations that quantify the responses in temperature to changes in albedo and vegetation canopy.

The research team identified points of interest (for example, UHI and UCI) in the SFV5 and LA1 domains based on the modeled temperature-field characteristics.

The selected mobile-observation routes were designed to cut across the LULC boundaries and transitions and capture the possible effects of changes in LULC from one neighborhood to another. The routes also were designed to yield small changes in elevation and keep the duration of each transect subsegment under 20 minutes (minimizing variations in air temperature that result from change in time of day).

In all, 15 transects were carried out in the summers of 2016 and 2017 in SFV5 and LA1. Figure 9 shows a composite of all transects that were carried out, as well as a random example detail of one transect subsegment. Some transect routes are duplicates (superimposed on each other) and, hence, appear as one. While the research team considered all transects shown in LA1 in the analysis, only the parts of the transects within the red box were considered in the analysis for SFV5.

Figure 9: Superimposed Routes of 15 Transects



While all transects shown in area "LA1" were considered in the analysis, only the parts of the transects within the red box were considered in the analysis for SFV5. Inset: example detail.

Source: Research Team

The first transects were conducted in personal vehicles, with two researchers in each vehicle—one to drive and the other to make measurements. The research team soon switched to ride-share services, hiring Uber drivers to install the apparatus on their cars and drive along the transect paths with a researcher in the car to manage the equipment. This proved to be a time- and cost-saving improvement because (1) it was cheaper to hire Uber than to reimburse researchers for personal vehicle use and (2) only one researcher was needed in the car.

The design of the apparatus also withstood the wear and tear from being installed, uninstalled, and stored over the project duration. Hurdles to carrying out the mobile transects included time wasted being stuck in traffic traveling to and from study areas, the need to modify initial transect routes on the fly because of unexpected road construction and closures, and crime safety concerns (that went unmerited) of driving through certain locations at night (20:00 - 22:00 local daylight time).[3]

4.3 Calibration of Climate Model to Mobile Observations

The research team evaluated the model performance against fine-scale observations from mobile transects. For transect-specific modeling (500-m resolution), modeled air temperature was compared to observations from transects at the coincident time (subhourly intervals). The goal was to ascertain that the model correctly captures the micrometeorological variations in the urban areas and to validate the modified WRF model against the mobile observations. The modeled and observed air temperatures from mobile transects were assessed at 2 m AGL.

While the transect-specific WRF model (TSM) runs were initiated a week ahead of the actual transect time and were continued for two days past that, the team evaluated the performance of TSM runs only and specifically at the transect time. The research team found good agreement between along-transect roadway observations and area-averaged model results. Mean absolute error (MAE) and root mean square error (RSME) in temperatures ranged 0.55–1.73 ˚C and 0.60–2.00 ˚C, respectively, and were often significantly better than the recommended performance benchmarks of MAE ≤ 2˚C (3.6 ˚F) and RMSE ≤ 2˚C (3.6 ˚F).

4.4 Relating Mobile Air Temperature Observations to LULC

Following model performance evaluation, the research team evaluated correlations between observed temperature and surface physical properties. In this case, two surface properties of interest were examined: neighborhood-scale albedo and vegetation canopy cover (500-m scale). The research team examined these two properties because they have been shown in many studies to influence significantly the urban air temperature and they are easy to control and use as mitigation measures. The relationships between observed air temperature (predictand) and either albedo or canopy cover (predictors) or both were examined in three manners: (1) simple linear regression, (2) multiple regression, and (3) CART analysis for further detail. Examples of each analysis are given in this discussion.

3 Los Angeles is in the Pacific time zone, where local daylight time (LDT) is UTC/GMT -7 hours.

4.4.1 Simple Linear Regression

In the downtown Los Angeles (LA1) domain, observed air temperature from mobile transects was correlated to grid-level albedo and canopy cover. For the San Fernando Valley study area, the observed temperature was correlated only with canopy cover (as predictor) since albedo has a smaller variability in this domain (Figure 10).

Figure 10: Detail From the San Fernando Valley Study Domain

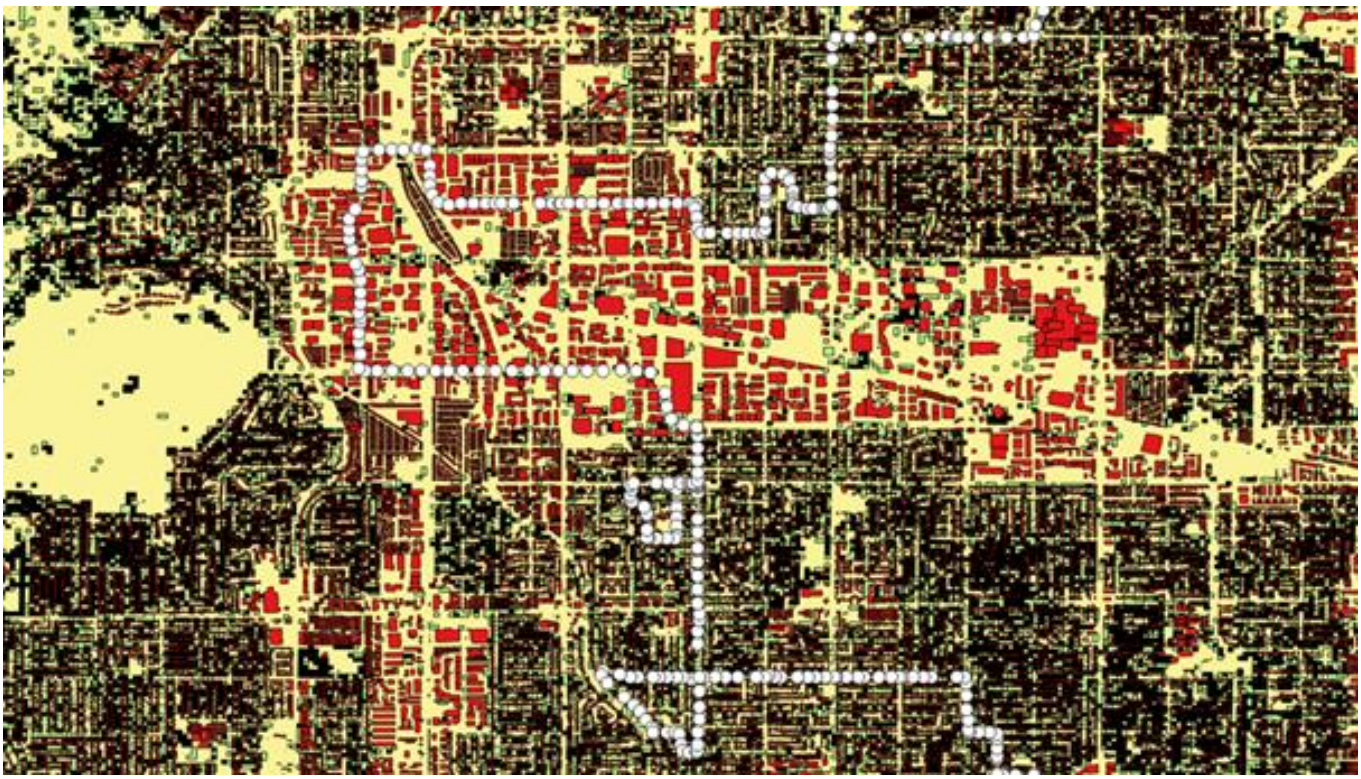


Image shows 30-m tree cover (yellow: < 10%, light green: 10 – 20%, black: > 20% cover), building-specific roof albedo (red: 0.05 – 0.25, orange: 0.25 – 0.50, light orange: 0.50 – 0.90), and a sample mobile transect segment (white dots).

Source: Research Team

All but two transects yielded statistically significant correlations (probability value < 0.05) of air temperature to albedo or canopy cover fraction, and correlations for all but two transects were negative (when albedo or canopy cover or both increase, temperature decreases).

4.4.2 Multiple Regressions

Multiple regression was carried out for albedo and canopy cover as predictors to observed air temperature from the transects. This analysis applies only to the downtown area, LA1, since the SFV5 analysis involved only variations in one predictor (canopy cover) because the variability in albedo in SFV5 is small.

The correlations were overwhelmingly negative—as albedo and canopy cover increase, temperature decreases—and statistically significant except in one transect, where the role of canopy cover was insignificant, and in two other transects, in which the role of albedo was insignificant.

4.4.3 Classification and Regression Tree

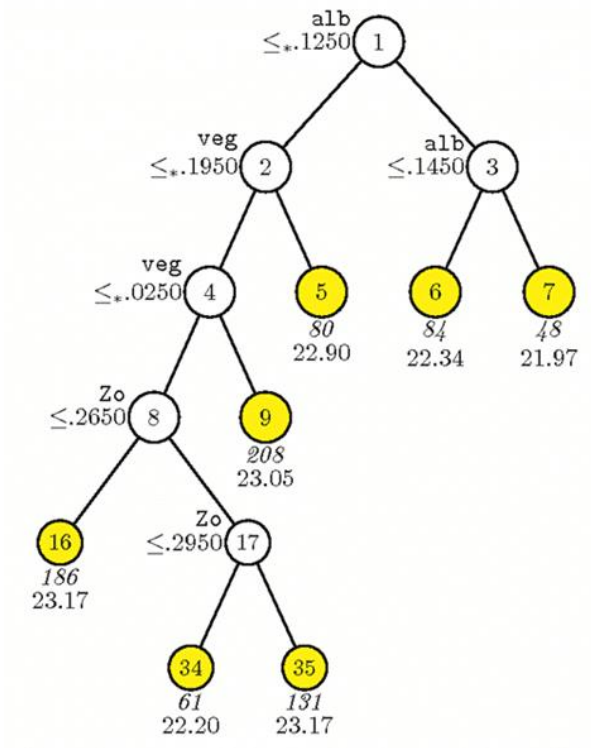
A classification and regression tree (CART) analysis was undertaken to assess the multiple interactions among predictors of mobile-observed air temperature. This analysis is an extension to the multiple regression analysis above and provides additional information. In the CART analysis, the roughness length parameter was introduced as an additional predictor to evaluate the role, if any, relative to that of albedo and canopy cover.

A CART is interpreted in the following manner: the variable above each node (circle) is a "splitting" variable, that is, the criterion used in the correlation. The top splitting variable (that is, the most important) is given above the top node. The yellow nodes are "terminal" nodes that show the results (regression or classification) in which the research team is interested. At each node, there is a logical criterion: for values smaller than the criterion, follow the path to the left of the node. For values larger than the criterion, follow the path to the right. Each node is numbered inside the circle. The number in italics below each node is the number of observational samples, and the number below that is the predicted value (in this case, air temperature) at the end of each path leading to a terminal node.

The example discussed here is for a daytime (13:00 LDT) transect in the downtown area (LA1) carried out on April 22, 2016. This transect segment consists of 798 temperature observations. The following can be deduced from this CART analysis (Figure 11):

- In this transect segment, the most influential variable (top splitting node) is albedo. The analysis shows that the contribution of higher albedo just in this transect is to lower air temperature by 0.81 ˚C (1.45 °F), which is significant.
- Temperature is lower where albedo is larger. For grid-level albedo greater than 0.125, the temperatures are lowest—for example, compare terminal Nodes 6 and 7 with Nodes 5, 9, 16, 34, and 35.
- In this transect, where albedo is lower than 0.125, canopy cover also has a significant effect. Comparing Node 5 (where canopy cover is greater than 0.195) and Nodes 9, 16, 34, and 35 (where cover is lower than 0.195), the contribution of canopy cover is to cool the air by 0.12 ˚C (0.22 °F). This effect is smaller than the effects of albedo in this specific transect.
- The effects of roughness length are secondary and vary from one subtree to another.

Figure 11: CART for Daytime Transect in Downtown Los Angeles



This CART example is for 13:00 LDT in the downtown area (LA1) on April 22, 2016. It represents 798 temperature observations from mobile transects. Temperature is the dependent variable; albedo, vegetation cover, and roughness length are the independent variables (predictors).

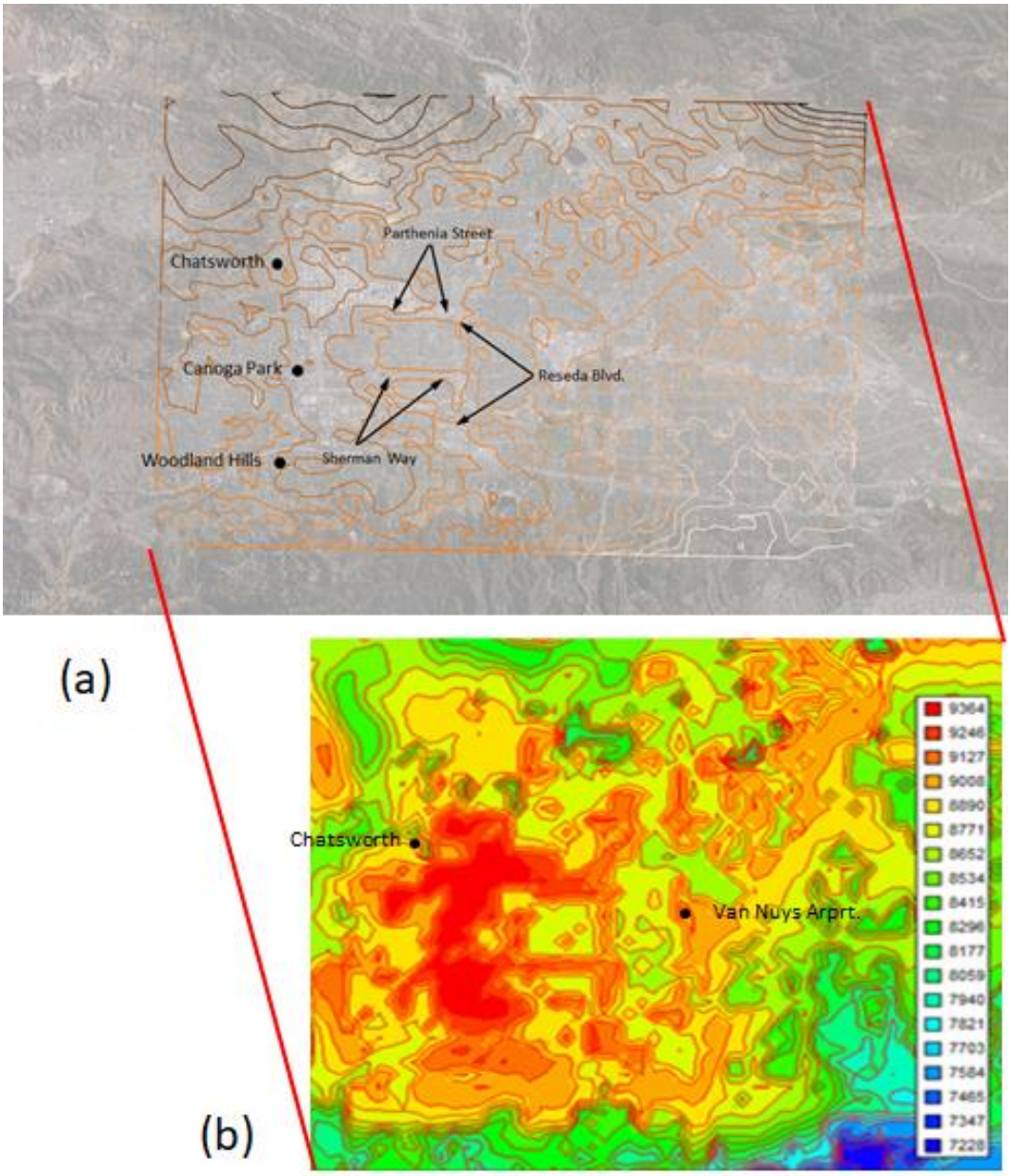
Source: Research Team

4.5 Detection of Intraurban Heat and Cool Islands

Because the Los Angeles region is one large urban climate archipelago (a built-up area stretching from the ocean to the mountains), there is no rural reference against which the urban temperature is compared as in a "conventional" urban heat island definition. As such, the task was to identify intraurban variations in heat or cool islands or both as a function of LULC (as an embedded signal) and correlate the temperature variations to changes in LULC and surface physical properties. As discussed above, the research team's LULC analysis coupled with the fine-scale meteorological modeling result allowed the team to identify such signals in the study areas, as depicted in Figure 12.

The model performance evaluation in this study demonstrated that the WRF model and the modifications to the associated urban modules performed in this project can reproduce reasonably well the observations in the temperature, including the locations of UHI and UCI spots. As such, the model can be reliably applied to other urban areas and regions in California, as well as for other applications such as in designing community- or neighborhood-scale UHI mitigation strategies.

Figure 12: Modeled Heat and Cool Islands in the San Fernando Valley



Total degree-hours (DH) for interval May 30 – June 16 (2013) in the San Fernando Valley 500-m domain. (SFV5 is in the western part of this domain.) The derived average temperature (computed as DH/hour), blue to red, is 17.7–22.9 °C (63.9 – 73.2 °F) for this period. Color bar is total DH, range: 7,228 – 9,364.

Source: Research Team

4.6 Neighborhood-Scale Interactions Between Air Temperature and Land Cover

The research team chose two study areas ("regions") of interest within the Los Angeles Basin that met two requirements: (1) the study area should be sufficiently small such that distance from the coast does not dominate temperature variations, and (2) there should be sufficient variation in land-cover properties of interest (for example, roof albedo) to enable discerning effects of land cover on measured air temperatures. The first region encompasses an area of roughly 500 square kilometers (km^2) and includes downtown Los Angeles; the research team refers to this region as Central Los Angeles (Central Los Angeles contains all of LA1). The second region encompasses roughly 160 km^2 and is within the San Fernando Valley; the research team refers to this region as SFV_R.

The research team investigated the effects of LULC properties on observed air temperatures for different neighborhoods in each region, using Weather Underground near-ground air temperatures measurements recorded in July 2015. Here a "neighborhood" is an area of 500 m radius, centered on a weather station (Figure 13).

Figure 13: Neighborhood Surrounding a Personal Weather Station

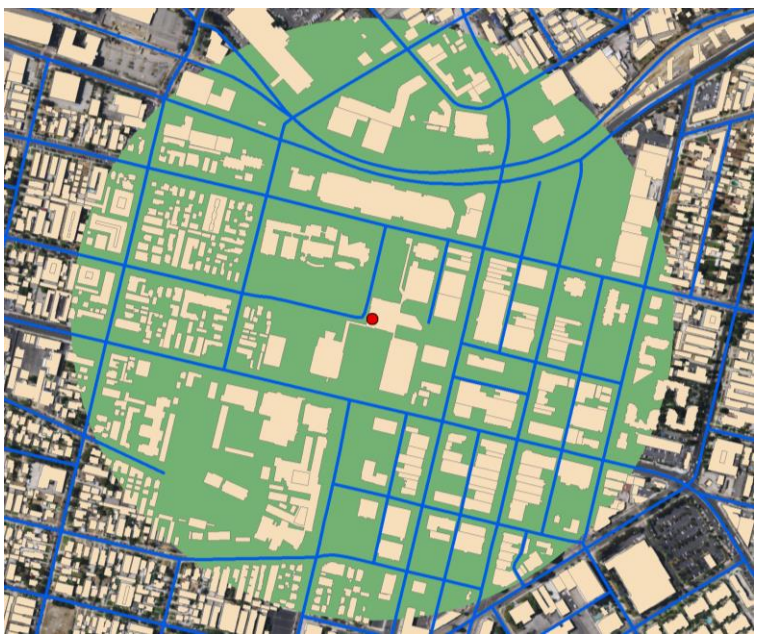


Image shows the aggregation area, or "neighborhood" (green circle of radius 500 m), around an example weather station (red dot) in SFV. The underlying imagery shows the building footprint dataset.

Source: Research Team

The research team focused on roof albedo (and solar power reflected from roofs) and tree cover, although further LULC parameters were analyzed. The research team found that the sensitivity of air temperatures to these LULC properties varied by region, likely due to the related different baseline land cover and meteorology. Increases in roof albedo were associated with observed air temperature reductions. Average daily sensitivities were 1.84 ˚C and 0.25 ˚C

per 0.1 increase in roof albedo in neighborhoods in Central Los Angeles and SFV, respectively. Observed sensitivities in air temperature to albedo were substantially higher than reported by previous modeling studies.

In Central Los Angeles, variations in solar power reflected from roofs (and thus roof albedo) appear to dominate variations in observed air temperature relative to the effects of tree fractions. This observation is based on current neighborhood-to-neighborhood variability in tree fraction in this region and may not predict how adding more trees would affect temperatures. For SFV_R, observations suggest an overnight (00:00 – 07:00 LT) temperature reduction of up to about 1.5 ˚C per 0.1 increase in tree fraction at night. To the team's knowledge, this study is the first to report observational evidence that roof albedo increases are associated with neighborhood-scale temperature reductions.

CHAPTER 5: Lessons Learned and Policy Implications

5.1 Lessons Learned

The research team envisioned installing more than 10 stationary research-grade monitors in select locations to detect differences in air temperature from variations in LULC. However, installing stationary monitors proved more challenging than planned, while the mobile transects were easier than expected. Therefore, the research team installed fewer stationary monitors (four installed) than originally planned but completed 15 mobile transects to provide the observational data necessary for this analysis.

The research team had strong institutional partners for this project in the Los Angeles Basin. The team's plan was to use their facilities across the basin to site the stationary monitors. Since they were governmental organizations, the research team expected they would be able to make a long-term (5+ years) commitment to hosting the monitors and ensuring the security of the monitors over time. However, the research team struggled to secure the many layers of approval needed to place monitors at buildings. The research team spent 18 months negotiating agreements, sites, and installation with partners. For future work, the research team would suggest allowing more time to negotiate all the approvals or include some financial agreement to ensure participation from specific facilities or both.

There were some beneficial changes the research team made from the project plan that aided implementation. For the mobile transects, the research team completed the first few transects using personal vehicles as planned. However, switching to the Uber ride-share service saved time and money by reducing both vehicle and staff costs. For future work, using ride-share services to help conduct mobile transects and measurements could be a good collaboration to take advantage of their large network of drivers and broad service area. Some of the ride-share fleet could be equipped with specialized sensors that track location and air temperatures across the city while the vehicles are in service.

5.2 Policy Implications

The research team found empirical evidence that there is intraurban temperature variability correlated to LULC properties. The albedo and vegetation coverage values in the analysis are existing conditions in Los Angeles neighborhoods where there has not been a concerted effort to address UHIs. This finding suggests that there are opportunities for community cooling using existing technologies and practices to increase urban albedo and canopy cover. Knowing that these are effective cooling measures, cities can also accelerate the implementation of these UHI countermeasures in heat-vulnerable neighborhoods. Addressing UHIs helps locally offset future warming in cities from climate change. This action helps the city build resiliency to future extreme heat events.

Local and state government policy makers can conduct similar modeling to identify local UHI areas to target policies to increase roof albedo and canopy cover. They can also review their city/community LULC datasets to identify areas where there is potential to increase roof albedo and vegetation cover. This review will help them develop targeted strategies to implement UHI countermeasures. In turn, these strategies can conserve city resources, program budgets, and staff while improving climate resiliency in the most heat-vulnerable communities. For example, the City of Los Angeles' Department of Water and Power runs a residential cool roof rebate program. Department officials can direct communication efforts to residential areas identified as local UHIs following the method of modeling used for this study. The installation of cool roofs in these UHI areas provide the neighborhood cooling benefits and building energy savings, while conserving program funds from citywide outreach and implementation.

The California Natural Resources Agency also offers urban greening grants to cities, counties, and nonprofits. Local or state agencies can review LULC datasets to target areas of low canopy coverage within disadvantaged communities for project implementation. If planted appropriately, trees could achieve the program objectives as well as providing the cooling benefit in heat-vulnerable communities.

CHAPTER 6: Conclusions

California's urban heat islands are exacerbated by climate change in a manner that can compromise electricity sector resilience and public health. It is important to understand the factors that contribute to UHI, as well as how UHI can be mitigated. In this study, the research team carried out a multidimensional assessment of urban temperature variations based on state-of-the-science numerical modeling and several types of observations, including mobile transects and personal weather stations. The research team sought to understand spatial air-temperature variations in local heat and cool islands and the relationship to land-use and land-cover properties in the Los Angeles Basin.

The research team collected detailed LULC datasets for the Los Angeles Basin that were used as inputs for the meteorological modeling and analysis. The research team also developed a database of historical micrometeorological information from existing weather station networks.

The research team collaborated with the City of Los Angeles, County of Los Angeles, and Los Angeles Unified School District to find sites and hosts for stationary monitors in two study areas that the research team identified, San Fernando Valley (SFV5) and downtown Los Angeles (LA1). The research team used fine-resolution climate models to assess the potential local UHI or UCI signals or both in these two areas. The results of the modeling informed the design of mobile-transect routes and siting of the stationary monitors. The research team designed a highly accurate and affordable stationary monitor that was installed in three locations in the SFV5 study area and at the University of Southern California campus west of downtown Los Angeles. To supplement the data collected from the stationary monitors, the research team completed 15 mobile transects. The research team designed and constructed an apparatus that is easily mounted on the roof of a car to measure air temperature along the transect routes.

The research team assessed data from personal weather stations in the Weather Underground network to relate observed intraurban temperature variations to LULC and surface physical properties. The research team also analyzed observational micrometeorological data from mobile transects and correlated them with neighborhood-scale albedo and vegetation canopy cover.

The research team found the first observational evidence from analysis of high-spatial-density weather stations that increases in roof albedo at neighborhood scale are associated with reductions in near-surface air temperature. This evidence was corroborated with the analysis from mobile transect measurements, which revealed a cooling effect from areawide increase in albedo or canopy cover or both. The albedo and canopy cover values in this analysis are existing conditions in Los Angeles neighborhoods where there has not been a concerted effort to address UHIs. This finding suggests that there are opportunities for community cooling using existing technologies and practices to increase urban albedo and canopy cover. Knowing

that these are effective cooling measures, cities can also accelerate implementation of these UHI countermeasures in heat-vulnerable neighborhoods.

In addition, the calibrated meteorological model accurately identified the localized urban heat islands and urban cool islands observed in this study. Therefore, the model can be applied by stakeholders, including city and state government, to characterize the intraurban microclimate variations elsewhere in California, and stakeholders can use the model to analyze the benefits from launching UHI countermeasures.

GLOSSARY AND ACRONYMS

Term	Definition
AGL	Above ground level
Albedo	Solar reflectance
Anemometer	Wind speed meter
Aspirated radiation shield	Shield through which air is drawn to improve accuracy of air temperature measurement by an enclosed thermometer
CART	Classification and regression tree: a multiple-regression statistical analysis often represented graphically with a tree-like structure
Central Los Angeles	A study region in Central Los Angeles used in the research team's analysis of personal weather station measurements
Climate archipelago	The complex climate effects of a large, continuous urban area in which upwind portions can affect downwind portions
Cool roof	Roof whose surface stays cool in the sun by exhibiting high solar reflectance (ability to reflect sunlight) and high thermal emittance (ability to emit thermal radiation)
Dry-bulb air temperature	Air temperature measured by a dry thermometer
EPIC (Electric Program Investment Charge)	The Electric Program Investment Charge, created by the California Public Utilities Commission in December 2011, supports investments in clean energy technologies that benefit electricity ratepayers of Pacific Gas and Electric Company, Southern California Edison Company, and San Diego Gas & Electric Company.
GPS	Global positioning system
LA1	Study region near downtown Los Angeles used in the team's climate-modeling analysis
LAUSD	Los Angeles Unified School District
LDT	Local daylight time
LULC	Land use/land cover
MAE	Mean absolute error. This is a measure of the average deviation of a model prediction of a property, such as temperature, from the observed value of the property at the same location, time, and overall conditions.

Mesonet	A regional network of weather stations
Meso-urban	Scales that range from the regional to the sub-urban
Mobile transect	Measurement of temperature along a path
Monitor	A device that measures and records weather parameters
PWS	Personal weather station (a privately owned, consumer-grade stationary monitor)
Pyranometer	Sunlight meter
Roughness length parameter	An indicator of the ability of a surface to exchange heat and momentum with the atmosphere
RSME	Root mean square error: the root of the mean of the squares of the errors (see definition of MAE above). RMSE is more sensitive to outliers than MAE.
SFV	San Fernando Valley
SFV_R	A study region in the San Fernando Valley used in the team's analysis of personal weather station measurements
SFV5	Selected study region within the San Fernando Valley used in the team's climate-modeling analysis
TSM	Transect-specific (WRF) modeling: Weather simulations of the exact routes and at the exact times of the mobile transects
Thermistor	Semiconductor thermometer
UCI	Urban cool island
UHI	Urban heat island
UHIE	Urban heat island effect
Urban climate archipelago	The climate of an expansive continuous urban area or chains of urban areas that is large enough to produce its own characteristics and influences on the climate system
USC	University of Southern California
WRF	Weather Research and Forecasting (a numerical weather prediction system)

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APPENDICES

Appendix A-1: *Land-Use/Land-Cover Analysis and Atmospheric Modeling to Support Site Identification and Selection for Fixed Meteorological Monitors and Mobile-Observation Routes* (Task 2 Report, Part I). Publication number CEC-500-2019-020-APA1.

Appendix A-2: *Land-Use/Land-Cover Analysis and Atmospheric Modeling to Support Site Identification and Selection for Fixed Meteorological Monitors and Mobile-Observation Routes* (Task Report Appendix A). Publication number CEC-500-2019-020-APA2.

Appendix B: *Preliminary Mobile Measurements of Air Temperature via Transect* (Task 2 Report, Part II). Publication number CEC-500-2019-020-APB.

Appendix C: *Monitoring Plan, Instrumentation Design, and Sensor Deployment* (Task 3 Report, Part I). Publication number CEC-500-2019-020-APC.

Appendix D: *Atmospheric Modeling to Support Site Identification and Selection for Fixed Weather Stations: Siting of Weather Stations* (Task 3 Report, Part II) . Publication number CEC-500-2019-020-APD.

Appendix E: *Model Validation and Development of Correlations Between Observed Air Temperature and Surface Physical Properties* (Task 4 Report, Part I) . Publication number CEC-500-2019-020-APE.

Appendix F: *Air-Temperature Response to Neighborhood-Scale Variations in Albedo and Canopy Cover in the Real World: Fine-Resolution Meteorological Modeling and Mobile Temperature Observations in the Los Angeles Climate Archipelago* (Task 4 Report, Part II) . Publication number CEC-500-2019-020-APF.

Appendix G: *Observational Evidence of Neighborhood-Scale Reductions in Air Temperature Associated With Increases in Roof Albedo* (Task 4 Report, Part III) . Publication number CEC-500-2019-020-APG.