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Monitoring the urban heat island effect and the efficacy of future countermeasures in the Los Angeles Basin

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ABSTRACT

To understand spatial air-temperature variations in local urban heat islands (UHIs) and urban cool islands (UCIs), and their relationship to land-use and land-cover (LULC) properties in the Los Angeles Basin, we sought to (a) use fine-resolution climate models to identify UHI / UCI areas, (b) relate observed intra-urban temperature variations (from mobile transects and stationary monitors) to LULC and surface physical properties, and (c) calibrate/validate the fine-resolution meso-urban climate models that were used in identifying the UHI / UCI. We conducted a multi-dimensional assessment of urban temperature variations based on numerical modeling and several types of observations, including mobile transects, dense networks of personal weather stations, and sparse but more accurate research-grade stationary weather monitors. To identify the causative factors of the UHI / UCI at the neighborhood scale, we collected detailed LULC datasets, such as 1-m 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 to site the stationary monitors based on the definition of UHI / UCI areas.

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 was corroborated with the analysis from mobile transect measurements and correlation of observed air temperature with neighborhood-scale albedo and vegetation canopy cover, which revealed a cooling effect from area-wide increase in albedo and/or canopy cover.

Introduction

Cities need to characterize urban heat and related causes to design and implement urban heat island countermeasures appropriate to current and future climates. This project set out 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 (e.g., local generation of heat and transport of heat from upwind sources), LULC properties, and surface physical properties. We 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, we collected data from existing weather networks; conducted detailed, fine resolution meteorological modeling; installed research-grade stationary weather monitors; and performed mobile transects. We 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 (SFV); and “LA1”, a region that includes and extends to the southeast of downtown Los Angeles. We installed three research-grade stationary monitors in the SFV5 study area, and another at the University of Southern California campus west of downtown Los Angeles. To supplement the data collected from these stationary monitors we designed and executed multiple mobile transects. To identify the causative factors of the local heat and cool islands at the neighborhood scale, we collected detailed LULC datasets for the L.A. Basin, such as 1-m. 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.

Identifying and Characterizing Study Regions in the Los Angeles Basin

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 L.A. Basin. These sources included the California Irrigation Management Information System (CIMIS), WeatherBug, and Weather Underground. 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 by Mohegh et al. (2018) and in Appendix G of Levinson et al. (2019).

Study Area Characterization

LULC analysis was the first step in identifying urban areas with delineations or transitions of interest—i.e., changes in physical properties. This analysis, performed 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, is detailed in Appendix A of Levinson et al. (2019).

Study Area Selection

Error! Reference source not found. 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 L.A. 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 Appendix A of Levinson et al. (2019).

To quantitatively evaluate the model prediction of temperature tendency and spatial gradients in temperature in the modeled areas, we 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 and design of the mobile monitor are detailed in Appendices B and C, respectively, of Levinson et al. (2019).

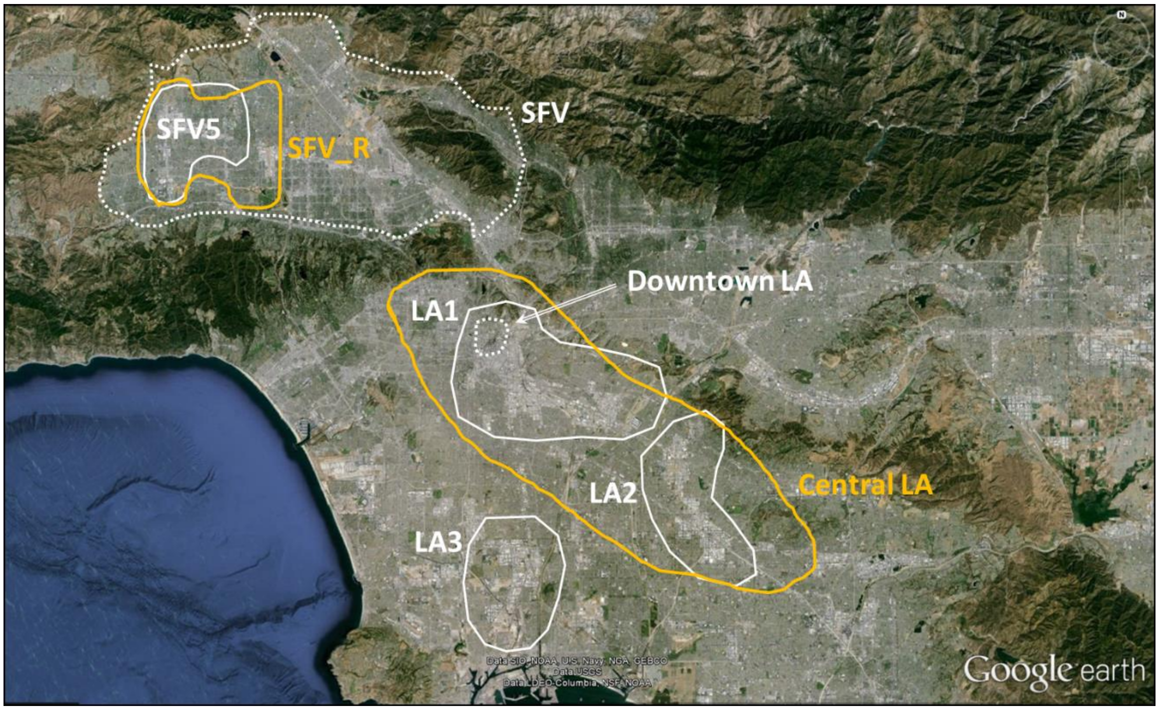

Figure 1. Boundaries of initial study areas LA1, LA2, LA3, and SFV5 (solid white lines) considered for meteorological modeling, installation of new stationary monitors, and mobile transects; LA1 and SFV5 were selected. Also shown are the boundaries of study areas Central L.A. and SFV_R (solid gold lines) used in analysis of personal weather station data, and the boundaries of the San Fernando Valley (SFV) and downtown L.A. (dotted white lines).

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.

Developing a Monitoring Plan, Designing Instrumentation, and Deploying a Sensor Network to Measure the Urban Heat Island Effect in the Selected Study Regions

Note that mobile monitor design and stationary monitor design, placement, installation, and placement are detailed in Appendix C of Levinson et al. (2019).

Mobile Monitor Design

Horizontal variations in air temperature near the ground—say, 2 m 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.

Our mobile monitor contains five elements: a shielded temperature sensor aspirated by vehicle motion; a quick-install mount to attach the shielded sensor to the roof of a vehicle (**Error! Reference source not found.**); a portable data logger to record the temperature time series; a global positioning system (GPS) to record the position time series; and a dash camera (dash cam) to record time-stamped video of the transect from the perspective of the driver.

Stationary Monitor Design

We 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.

[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.

- 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.

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 (e.g., 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.

Installing and Calibrating Monitors

After extensive negotiation, we received partner approvals to install four monitors. 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.

Figure 2. 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.

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

Collecting and Analyzing Weather Data from Fixed and Mobile Monitors

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, our plan 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.

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

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.

In all, 15 transects were carried out in the summers of 2016 and 2017 in SFV5 and LA1, as detailed in Appendix E of Levinson et al. (2019).

Calibration of Climate Model to Mobile Observations

We 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. We found good agreement between along-transect roadway observations and area-averaged model results. The calibration process is detailed by Taha et al. (2018a,b).

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. This work is detailed in Taha et al. (2018a,b).

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. 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).

Multiple Regression. 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.

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.

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.

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.

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 (e.g., 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.

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 local time) 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.

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.

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 L.A. 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.

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