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LOS ANGELES' URBAN HEAT ISLAND CONTINUES TO GROW: URBANIZATION, LAND USE CHANGE INFLUENCES

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Abstract: The Los Angeles urban heat island has been recently described as a large, coastal, urban archipelago. Rather than one symmetric UHI, the sprawling metropolitan region can be thought to have several heat islands of differing sizes and magnitudes. Both of these parameters are dynamic, changing over time. The current study focuses on this dynamic nature, showing diurnal, seasonal and spatial aspects to the Los Angeles heat islands. Rather than finding one value for the surface air heat islands, we present the evolving magnitudes based on observational data not models. We also show the significance of the city's changing land use as a primary cause for the growing heat islands. Using downtown Los Angeles weather data (DTLA), the downtown heat island is defined by the difference between a suburban residential site, an open space site near suburbs and DTLA. Hourly temperature differences are presented for all months and seasons. Another comparison of the downtown heat island is made using the coastal airport (LAX) data. The influences of coastal sea breezes, complex topography, and a climatic rapid warming away from the coast will also be discussed as it hinders evaluating the urbanization inputs. From the two inland sites, there are definite heat island characteristics when compared to the downtown location. DTLA shows continued warming over the 2000-2010 period of nearly 7°C/century for Tmin and 10°C/century for Tmax, which is pretty frightening. The inland sites warm much less during the day and showed a slight cooling for Tmin over the decade. Land use change in the urban Los Angeles County and impervious surface percentages are also calculated for the 1970-2010 period.

Keywords: Los Angeles urban heat island; land use change, urban microclimates.

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INTRODUCTION

As a result of rapid urbanization and industrialization, numerous environmental problems have emerged, ranging from the local to the global scale. To cope with these problems, we need to monitor and understand environmental changes, especially in urban areas, where most people live and, are the nodes of the largest environmental changes that have taken place (Detwyler and Marcus 1972). On the local and regional scales, much attention has been focused on urban-induced or -modified weather and climate (Changnon 1981; Cotton and Pielke 1995; Oke 1970, 1982, Arnfield 2003). During the past several decades, extensive studies have been carried out to document the differences in air temperature, wind speed, humidity, precipitation, surface energy flux, boundary layer height, and atmospheric chemistry, between urban areas and surrounding rural areas, and to explain these differences (e.g., Arnfield 2003; Landsberg 1981; Oke 1982; Draxler 1986; Oke 1987; Deosthali 2000; Shepherd *et al*. 2002; Zhang 2004).

Among the urban–rural differences, the most notable and well documented is the increase in air temperature in urban areas relative to their surroundings, called the urban heat island (Arnfield 2003; Oke 1982). Many of the causes that contribute to the urban heat island effect are listed by Oke (1982) including: increased absorption of incoming short-wave radiation due to urban canyon geometry; increased long-wave radiation from the sky due to air pollution; decreased long-wave radiation loss due to reduction of the sky view factor; anthropogenic heat additions; increased sensible heat storage, decreased evapotranspiration due to removal of vegetation; and decreased total turbulent heat transport resulting from reduced wind speed. Many factors influence urban heat island intensity, including local and synoptic weather, season, time of day, size of the city and its geographical location, urban morphology, and anthropogenic heat sources.

It is well known that the urban heat island intensity is strong on clear and windless nights and exhibits diurnal and seasonal variations (Ackerman 1985; Bornstein 1968; Cayan and Douglas 1984; Yague *et al.* 1991; Jauregui 1997; Klysik and Fortuniak 1999; Montavez *et al.* 2000; Morris *et al.* 2001; Kim and Baik 2005). Summer has the largest UHI intensities in warm climates, while winter nights show the largest UHI effect in colder regions. Oke (1973); Imhoff *et al*, (2010) and Park (1986) demonstrated that the urban heat island intensity increases as the urban population increases, and they provided functional relations associating urban heat island intensity with population. Undoubtedly, one cannot disregard population as a contributor to the urban heat island, for the more people reside in an area, the greater the possibility open space areas become modified and developed, only to cause human activity to make changes to the climate. This growth can be seen in the Los Angeles County, which holds an estimated population of 10,105,518 in 2018, making it the most populous county in the nation (U.S. Census Bureau, 2019). Such an immense growth occurred through most of the twentieth century, when automobiles and public transportation, such as the light rail system, created an opportunity for people to move away from the urban center and develop communities around the periphery of Los Angeles (Selby, 2006). Goodridge (1996) compared temperature trends for California cities. His results showed that cities with populations over 1 million had the highest warming rate (3.14°F/century or 1.744°C/century) for 29 cities, while 100,000-1 million population cities recorded 1.39°F (0.772°C)/century (51 cities) and less than 100,000 had the lowest rate, 0.405°F (.225°C)/century (27 cities).

While air temperature differences are commonly associated with the urban heat island (UHI), the temperatures of urban surfaces can also be used to show urban heating differences, usually through remote sensing of surface heating. A notation for the surface heat island is often sUHI. On average, more than 50% of urban landscapes are dark, man-made surfaces that get hotter in the sunlight and hold more heat than natural landscapes such as grass or tree canopy (Akbari *et al*., 2012). These lower albedo values in most built up urban centers lead to large surface temperature differences with more reflective or vegetative surfaces. In the summer of 1993, Taha (1997) performed low altitude flights over the Los Angeles Basin, and found that the highest albedo (0.20) was near Downtown L.A. due to the extensive vegetation present at that time of year. In the urbanized region of the basin, the albedo was between 0.12 and 0.16. Ban-Weiss *et al* (2015) used remote sensing to measure the average albedo of the LA urban area as 17%. Dousset *et al*. (2003) used AVHRR satellite data to measure surface temperature over downtown and suburban Santa Monica to the west and Chino Hills to the east in late June 1986 at 4:25 PDT. While the suburban sites experienced cooling, the downtown LA area remained 5°C warmer than Chino Hills and 2°C warmer than Santa Monica. Another study of surface temperature data was done by Tayyebi & Jenerette (2016) using AVIRIS and MASTER (MODIS/ASTER) overflights of the LA Basin in May 22 (daytime) and June 1 (night), 2013. Another NASA mission also used AVIRIS and MODIS/ASTER overflight data and 18 ground surface stations in the southern California area in September 2013 to measure spatial and temporal patterns of temperatures and windflow. The strength of the sea breeze was found to diminish the UHI in the coastal plain. Vahmani and

Ban-Weiss (2016) utilized MODIS-based data in July 2012 to model influences of land use, vegetation and albedo on surface and near surface air temperatures in the LA Basin. They found distance from the ocean to be a main contributor to temperature variations. During the daytime, distance from the ocean most strongly influences temperatures in grid cells that are within about 50 km from the ocean. They concluded from their model that increased vegetation would decrease both surface daytime temperatures and nighttime air temperatures. In the NASA ECOSTRESS mission, Thermal Radiometer Experiment on Space Station captured new imagery of variations in surface-temperature patterns in Los Angeles County in July and August 2018 at different times of the day. The high-resolution images show surface urban heat island features of extreme heating during the summer afternoon as well as the differential cooling during the night showing heat pockets where higher heat capacity reduces cooling (Hully *et al.* 2019).

The Los Angeles regional urban heat island

Los Angeles is not an ideal location for UHI studies. The diversity of topographic features and irregular nearby coastline creates hundreds of microclimates in the metro region. The city also resides in a large megalopolis or urban sprawl that extends nearly unbroken along the southern California coast from the Mexican border to Santa Barbara, some 300 km to the NW and inland over 100 km from the coastline. Finding the rural surroundings means choosing stations that are distant and in a different climatic zone. Often the "rural" locations chosen for UHI calculations are farther inland and at higher elevations. Sakakibara and Owa (2005) in their study of the Tokyo UHI concluded that choosing rural sites need to be at the same distance from the ocean as the urban site and in pre-urban land use areas to estimate the urban effect accurately. The same problem holds for Los Angeles UHI estimates.

Metropolitan Los Angeles lies mainly in Los Angeles County. The County has 110 km of coastline. The City of Los Angeles resides on a 32 km to 64 km wide coastal plain bounded on the north and east by relatively high mountains; while on the south and west lies the Pacific Ocean. Elevations within the city range from sea level at its Pacific beaches to 5080 feet (1548 m) at Mt. Lukens (Bruno and Ryan 2000). Some of the mountains in the San Gabriel Range north of the city exceed 10,000 feet (3048 m) in elevation. Transitions between vegetation and climate zones, highly dependent upon elevation and distance from the ocean, can be striking. The diversity theme extends to Los Angeles weather, which can be deceiving as within a mild Mediterranean climate. However, the area has occasions of winter storms that can produce amazing rainfall rates and flooding. In fact, the 24-hour record rainfall for the entire state of California, 26.12 inches (663.4 mm), occurred in the foothills of the San Gabriel Mountains, just a few miles north of downtown Los Angeles (Bruno and Ryan 2000).

The downtown (Civic Center) weather station has moved several times both horizontally and vertically (Bruno and Ryan 2000). For much of the continuous long-term record (1878-present), the location has remained close to the present city center. However, in 1998, the official LA city station moved considerably closer to the coast at a lower elevation on a park-like campus of the University of Southern California. This move (1/3 the distance to the Pacific Ocean) created a significantly cooler and drier climate (Patzert *et al.* 2015). This complicates urban heat island measurements.

While continental cities such as St; Louis, MO. and Winnipeg, Canada, have singular urban heat island structures, with a dominant central business district (CBD) and distinct surrounding rural areas, including relatively low terrain, the Los Angeles UHI has been described as an urban heat archipelago because it's like a whole chain of urban heat islands that run into each other (Taha 2017). Most UHI studies compare the temperatures in the CBD core to the rural surroundings or more peripheral airports. This does not work well for Los Angeles. The LA UHI is both spatially and temporally variable. Due to its massive urban sprawl and subsequent growth of several urban centers, along with no distinct rural fringe, the County is made up of several UHIs as population and development creates non-uniform hot spots throughout the Los Angeles Basin. The UHIs also vary diurnally and seasonally, as will be shown in this paper. Weather patterns and even coastal ocean conditions influence the strength of these UHIs.

The Los Angeles heat islands have the greatest magnitude of any city in the state. This was calculated recently by Taha (2015) using an Urban Heat Island Index for CA. The urban heat island index is calculated taking the difference between temperatures in an urban census district and subtracting the non-urban temperature producing a monthly value in degree-hours during the summer months (Taha 2015). An urban WRF model was used for the summers of 2006 and 2013. UHI temperatures for census sites were derived from modeled UHII by dividing hours/day by number of days and hours in the study period. The problem of non-urban reference points is not addressed and assumed to be upwind, which is coastal. As Taha states, highest UHII and thus UHI values tend to be downwind further inland in foothills of mountains to the north and east of the LA Basin. This does not separate out the coastal effect from the UHI effect of urban development. Shepherd *et al* (2013) describe some of the problems defining UHI in archipelagos. They define Urban Climate Archipelagos (UCAs) as a chain of distinct urban entities with discernible aggregate impacts on at least one segment of the climate system.

In this study, we describe the downtown UHI using fixed temperature differences between the urban core downtown and separate suburban sites, both upwind and downwind of downtown Los Angeles (DTLA). The effects of land use change and distance from the Pacific coast will also be explored.

The study area

The Los Angeles urban heat island has been recently described as a large, coastal, urban archipelago (Shepherd 2013; Taha 2017). Rather than one symmetric UHI, the sprawling metropolitan region can be thought to have several heat islands of differing sizes and magnitudes. Both of these parameters are dynamic, changing over time.

While there are more than one UHI situated within the LA County, most of the investigation centers on the downtown Los Angeles (DTLA) heat island. Since there are no close by rural stations, measurements of temperature differences were taken at three suburban locations (**Fig. 1**). To the east of DTLA is the suburban Claremont (C), 70 km from the nearest coastline at an elevation of 1645 ft. (501 m) in the foothills of the San Gabriel Mountains. Whittier Hills (W) is located in mostly undeveloped land near a densely populated suburb at 34 km from the coast, at an elevation of 950 ft. (290 m), with diminishing coastal effects with increasing distance to the Pacific. DTLA weather station, which is presently located on the USC campus 21 km from the coast, elevation 184 ft. (56 m) was moved from its previous downtown location to a park-like campus nearer the coast. Other comparative measurements look at the coastal Los Angeles International Airport (LAX) approximately 20 km southwest of DTLA.

DATA AND ANALYSES METHODS

In this study, we examine the UHI by focusing on a coastal upwind station (LAX), the downtown Los Angeles National Weather Station (DTLA) and two suburban downwind residential sites, Claremont (C) and Whittier (W) (see **Fig. 1**). Temperature data was derived from the Western Regional Climate Center (WRCC) and consisted of the following groups: average maximum, average minimum, and yearly average temperatures for the years 1945 – 2019. For Claremont and Whittier Hills hourly temperatures were analyzed for the years 2000–2010. Meteorological Terminal Aviation Routine Weather Report, METAR and Remote Automatic Weather Station, RAWS (Remote Automated Weather Stations) data from Claremont and Whittier Hills provide diurnal temperature data for the decade. Days with missing hourly data were omitted from analyses. Trend analyses for the 2000-2010 years were done for annual average minimum and maximum temperatures for Claremont, Whittier Hills and DTLA.

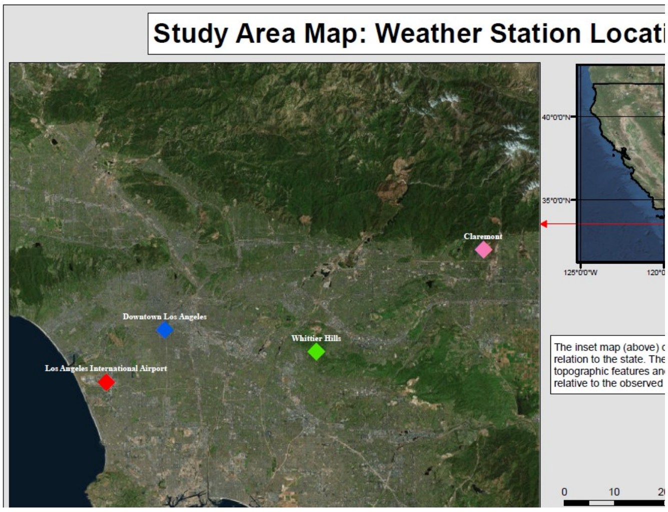


Fig. 1 Study Area.

To analyze sea and land breeze phenomena, wind data were attained from two weather sources: National Resources Conservation Service (NRCS) National Water and Climate Center (NWCC), and the National Oceanic and Atmospheric Administration (NOAA), National Climatic Data Center (NCDC). From the NWCC site, four wind rose figures were collected for the 2003 summer months, June – September. In retrospect, wind speed and wind direction were retrieved from NCDC for Downtown LA, in connection to the same wind period as Los Angeles International Airport (LAX). As the LAX wind rose shows a consistent westerly sea breeze throughout the summer, wind analyses are not included here.

To analyze the land use and land cover component of this study, historical land cover data was accessed from the United States Geologic Survey (USGS) for 1970–1980 conterminous U.S. coverage. Also, Landsat imagery from 1992–2011 was downloaded from the Multi-Resolution Land Characteristics Consortium (MLRC). From this site, land cover data was attained representing 16-class land cover classification schemes depicted across the whole United States, at a spatial resolution of 30 meters. Furthermore, generated land use maps were collected from the Department of City Planning, City of Los Angeles.

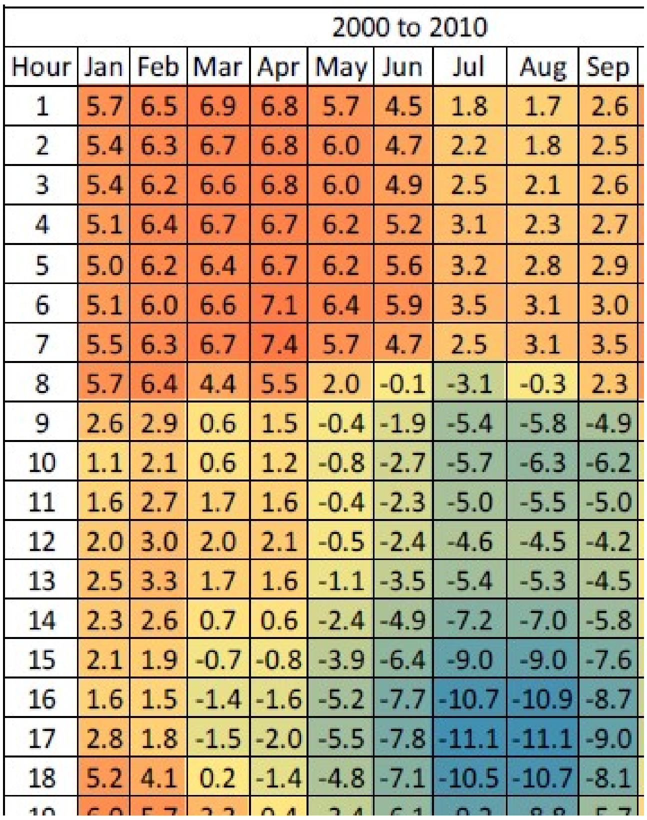
Landsat satellite imagery from 1970–2011 was derived from the USGS, and the MRLC. ArcMap 10.2 was used to generate land cover maps. For 1970, 27 different types of land use are classified, 20 for the year 1992, and 15 for the remaining years due to the exclusion of perennial snow/ice. At length, this research also analyzed the impervious changes in land cover for the years 2001–2011. Overall, one general map of the Southern Los Angeles County border was created, followed by five land cover maps for the years 1970-1980, 1992, 2001, 2006, and 2011, and one impervious land cover change map.

For population census information, especially around the developing cities near LAX, population change was noted between 1970 and 2010. The most recent estimate of LA County population was obtained from the U.S. Census.

RESULTS AND DISCUSSIONS

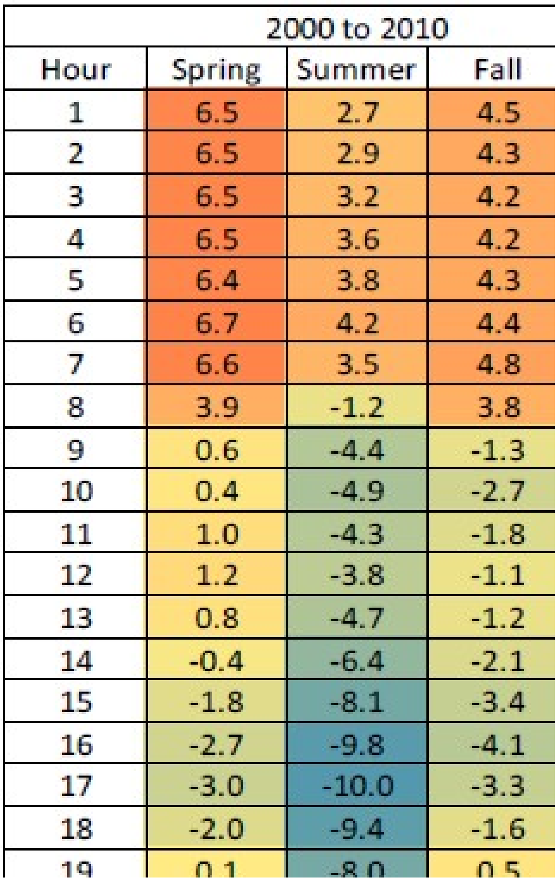
Table 1 shows the hourly temperature differences between DTLA and Claremont. Positive values (red) represent a warmer downtown than the suburb, while negative values (blue) show the opposite. Table 2 aggregates the hourly temperature differences by meteorological seasons. **Table 3–4** show the same hourly differences between DTLA and Whittier Hills. For Claremont, the UHI shows up well as downtown is warmer than the suburb throughout the year during the nighttime hours. In summer, the inland Claremont is much warmer than downtown particularly in summer afternoons.

Table 1. Average of hourly temperature differences (°F) between Downtown Los Angeles



	2000 to 2010								
Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	5.7	6.5	6.9	6.8	5.7	4.5	1.8	1.7	2.6
2	5.4	6.3	6.7	6.8	6.0	4.7	2.2	1.8	2.5
3	5.4	6.2	6.6	6.8	6.0	4.9	2.5	2.1	2.6
4	5.1	6.4	6.7	6.7	6.2	5.2	3.1	2.3	2.7
5	5.0	6.2	6.4	6.7	6.2	5.6	3.2	2.8	2.9
6	5.1	6.0	6.6	7.1	6.4	5.9	3.5	3.1	3.0
7	5.5	6.3	6.7	7.4	5.7	4.7	2.5	3.1	3.5
8	5.7	6.4	4.4	5.5	2.0	-0.1	-3.1	-0.3	2.3
9	2.6	2.9	0.6	1.5	-0.4	-1.9	-5.4	-5.8	-4.9
10	1.1	2.1	0.6	1.2	-0.8	-2.7	-5.7	-6.3	-6.2
11	1.6	2.7	1.7	1.6	-0.4	-2.3	-5.0	-5.5	-5.0
12	2.0	3.0	2.0	2.1	-0.5	-2.4	-4.6	-4.5	-4.2
13	2.5	3.3	1.7	1.6	-1.1	-3.5	-5.4	-5.3	-4.5
14	2.3	2.6	0.7	0.6	-2.4	-4.9	-7.2	-7.0	-5.8
15	2.1	1.9	-0.7	-0.8	-3.9	-6.4	-9.0	-9.0	-7.6
16	1.6	1.5	-1.4	-1.6	-5.2	-7.7	-10.7	-10.9	-8.7
17	2.8	1.8	-1.5	-2.0	-5.5	-7.8	-11.1	-11.1	-9.0
18	5.2	4.1	0.2	-1.4	-4.8	-7.1	-10.5	-10.7	-8.1

Table 2. Averages of hourly temperature differences (°F) between Downtown Los Angeles and Claremont by season for 2000 to 2010

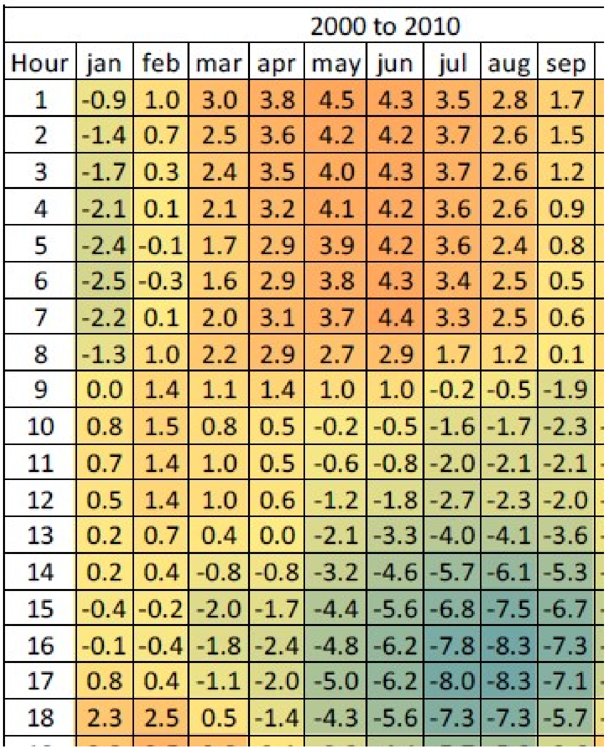


	2000 to 2010		
Hour	Spring	Summer	Fall
1	6.5	2.7	4.5
2	6.5	2.9	4.3
3	6.5	3.2	4.2
4	6.5	3.6	4.2
5	6.4	3.8	4.3
6	6.7	4.2	4.4
7	6.6	3.5	4.8
8	3.9	-1.2	3.8
9	0.6	-4.4	-1.3
10	0.4	-4.9	-2.7
11	1.0	-4.3	-1.8
12	1.2	-3.8	-1.1
13	0.8	-4.7	-1.2
14	-0.4	-6.4	-2.1
15	-1.8	-8.1	-3.4
16	-2.7	-9.8	-4.1
17	-3.0	-10.0	-3.3
18	-2.0	-9.4	-1.6
19	0.1	-8.0	0.5

Summer temperatures throughout the region increase away from the coast. However, even in summer, the downtown retains its heat, while the suburb cools making the UHI positive at night. In winter, the continental inland location cools and is generally cooler with distance from the coast, making DTLA warmer than Claremont throughout the day, but again peaking during the nighttime hours. Whittier Hills is less developed and closer to the coast than Claremont. While the same seasonal pattern appears in **Tables 3–4** as with Claremont, the values are reduced. Instead of cooler temperatures than DTLA at night for all seasons, Whittier Hills is slightly warmer in winter. This may be due to local microclimates, where the winter cool air is at lower elevations than the elevated hills.

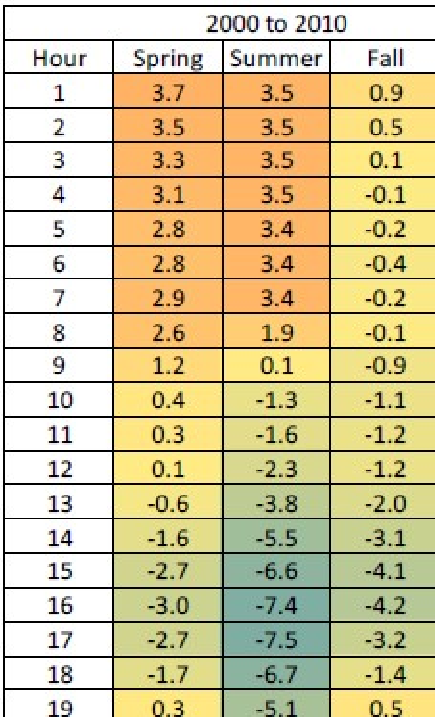
Microclimates, diversity of land use, elevation and distance from the coast make teasing out the urbanization effect difficult in these examples. Seasonal differences from the coast toward inland locations may be more dominant than heat island effects downtown. This is well demonstrated by the large counter-heat island in summer afternoon temperatures well inland, like at Claremont. Taha (2015) using the urban heat island index found highest UHII values to the north and

Table 3. Average difference in temperatures (°F) between Downtown Los Angeles and Whittier Hills by month for 2000 to 2010



	2000 to 2010								
Hour	jan	feb	mar	apr	may	jun	jul	aug	sep
1	-0.9	1.0	3.0	3.8	4.5	4.3	3.5	2.8	1.7
2	-1.4	0.7	2.5	3.6	4.2	4.2	3.7	2.6	1.5
3	-1.7	0.3	2.4	3.5	4.0	4.3	3.7	2.6	1.2
4	-2.1	0.1	2.1	3.2	4.1	4.2	3.6	2.6	0.9
5	-2.4	-0.1	1.7	2.9	3.9	4.2	3.6	2.4	0.8
6	-2.5	-0.3	1.6	2.9	3.8	4.3	3.4	2.5	0.5
7	-2.2	0.1	2.0	3.1	3.7	4.4	3.3	2.5	0.6
8	-1.3	1.0	2.2	2.9	2.7	2.9	1.7	1.2	0.1
9	0.0	1.4	1.1	1.4	1.0	1.0	-0.2	-0.5	-1.9
10	0.8	1.5	0.8	0.5	-0.2	-0.5	-1.6	-1.7	-2.3
11	0.7	1.4	1.0	0.5	-0.6	-0.8	-2.0	-2.1	-2.1
12	0.5	1.4	1.0	0.6	-1.2	-1.8	-2.7	-2.3	-2.0
13	0.2	0.7	0.4	0.0	-2.1	-3.3	-4.0	-4.1	-3.6
14	0.2	0.4	-0.8	-0.8	-3.2	-4.6	-5.7	-6.1	-5.3
15	-0.4	-0.2	-2.0	-1.7	-4.4	-5.6	-6.8	-7.5	-6.7
16	-0.1	-0.4	-1.8	-2.4	-4.8	-6.2	-7.8	-8.3	-7.3
17	0.8	0.4	-1.1	-2.0	-5.0	-6.2	-8.0	-8.3	-7.1
18	2.3	2.5	0.5	-1.4	-4.3	-5.6	-7.3	-7.3	-5.7

Table 4. Average difference in temperatures (°F) between Downtown Los Angeles and Whittier Hills by season for 2000 to 2010



	2000 to 2010		
Hour	Spring	Summer	Fall
1	3.7	3.5	0.9
2	3.5	3.5	0.5
3	3.3	3.5	0.1
4	3.1	3.5	-0.1
5	2.8	3.4	-0.2
6	2.8	3.4	-0.4
7	2.9	3.4	-0.2
8	2.6	1.9	-0.1
9	1.2	0.1	-0.9
10	0.4	-1.3	-1.1
11	0.3	-1.6	-1.2
12	0.1	-2.3	-1.2
13	-0.6	-3.8	-2.0
14	-1.6	-5.5	-3.1
15	-2.7	-6.6	-4.1
16	-3.0	-7.4	-4.2
17	-2.7	-7.5	-3.2
18	-1.7	-6.7	-1.4
19	0.3	-5.1	0.5

east of downtown along the foothills, the typical hot spots for the LA Basin. His UHII values though were calculated using upwind (more coastal) temperatures. In Tokyo, Sakakibara and Owa (2005) also found similar results with small inland cities showing a stronger UHI in the urban center especially late nights in summer. To eliminate the distance from coast bias, we can look at the comparisons of temperature trends for the 11-year period.

Figures 2–7 show the annual average values for minimum (Tmin) and maximum temperatures (Tmax), 2000-2010, for DTLA, Claremont and Whittier Hills. You can see that there is quite a bit of variability for the two suburban sites, with low trend correlations. DTLA shows more of a steady increase, particularly for Tmin. Claremont and Whittier Hills both show warming with Tmax and cooling with Tmin. Comparing the warming rates, DTLA minus C and W, the DTLA Tmin trend value is 1.78 °F/decade higher than C and 1.48 °F/decade higher than W. DTLA's Tmax trend was 1.19 °F/decade higher than C and 0.76 °F/decade higher than W. Although this is a short record, it does point out the relative warming rates of the downtown UHI being much larger than the two suburbs to the east. A longer record would have shown that downtown LA has warmed an average of nearly 6 °F over the last century (LaDochy *et al*. 2007). Over the study period, DTLA has warmed over twice that value for Tmin and thrice for Tmax. Looking at suburbs to the west of downtown, we now consider the temperature difference between DTLA and the Los Angeles International Airport, LAX and land use change.

Fig. 2 DTLA annual average Tmin

Fig. 3 DTLA annual average Tmax

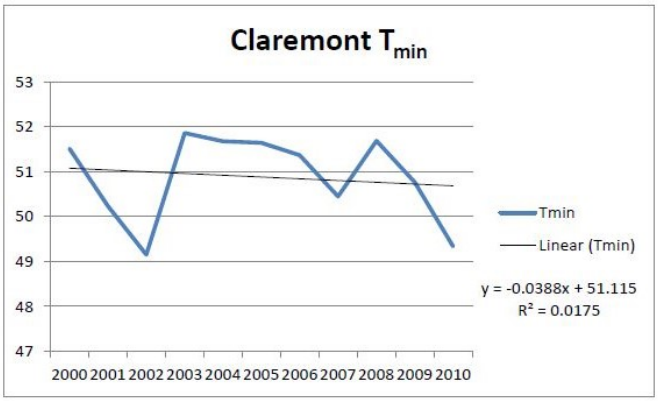


Fig. 4. Claremont annual average Tmin

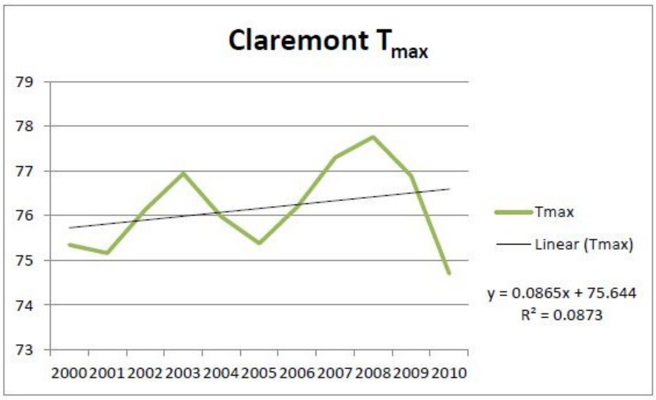


Fig. 5. Claremont annual average Tmax

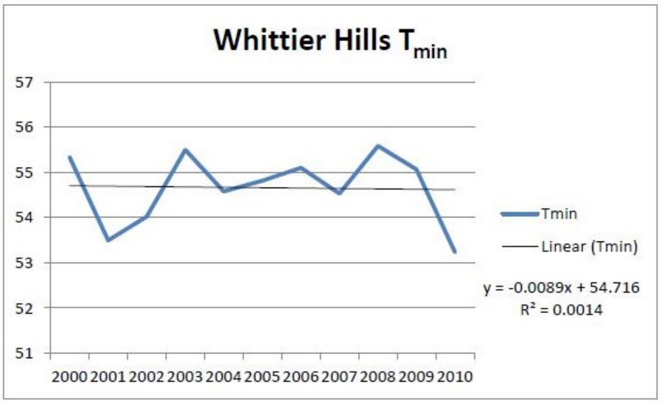


Fig. 6 Whittier Hills Annual Avg. Tmin

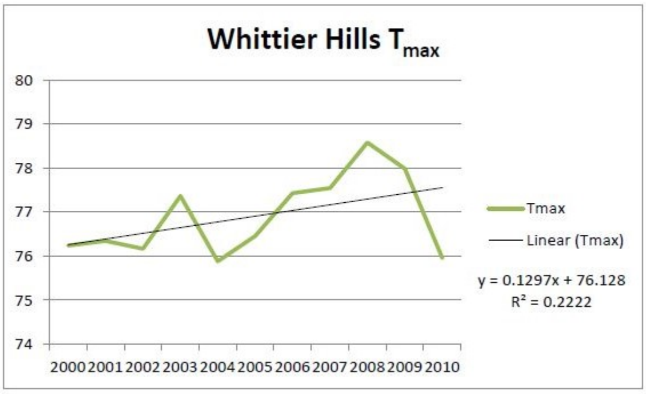


Fig. 7 Whittier Hills Annual Avg. Tmax

Land use change

What is causing this enhanced warming in the downtown LA heat island? One obvious factor would be population growth. Los Angeles has experienced the greatest increase in population, starting from 2,811,801 in 1970 to 3,792,621 in 2010 (U.S. Census Bureau, 2019). This was the fastest growth rate of the top 10 cities in California. Peterson (2017) describes Los Angeles being hotter by as much as 6 degrees °F than surrounding communities.

Figures 8–15 show the land use changes in the LA Basin from 1970 to 2011, while Figure 16 shows the land use classifications. **Tables 6–11** summarize the land use categories and change from 1970 to 2011 and the changes in impervious surfaces.

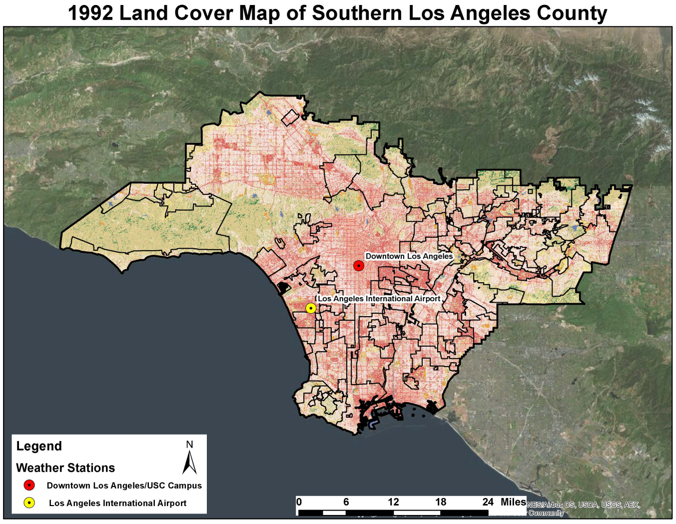


Fig. 8. Southern Los Angeles County map illustrating land use and land cover and locations of Downtown Los Angeles/ USC and LAX for the year 1992. The reddish color represents built-up areas.

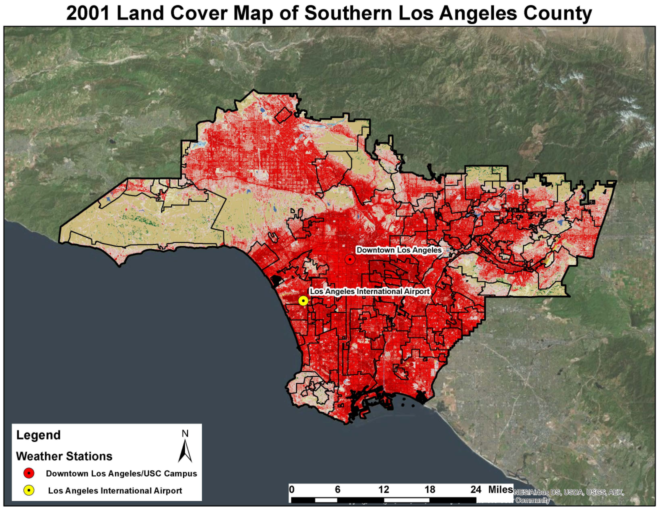


Fig. 9. Southern Los Angeles County map illustrating land use and land cover for the year 2001.

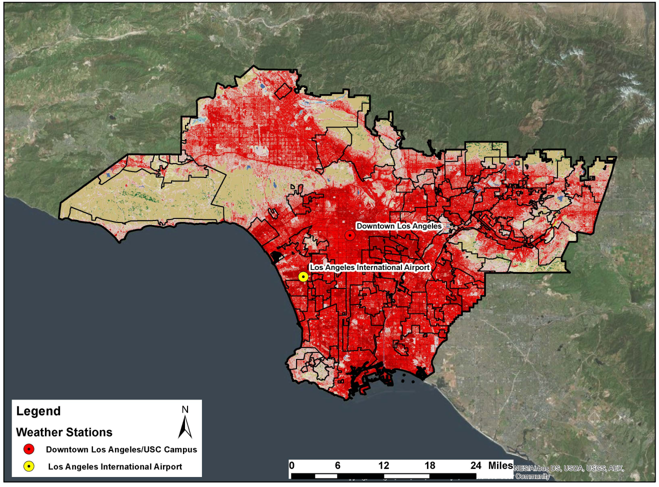

2006 Land Cover Map of Southern Los Angeles County

Fig. 10. Southern Los Angeles County map illustrating land use and land cover for the year 2006.

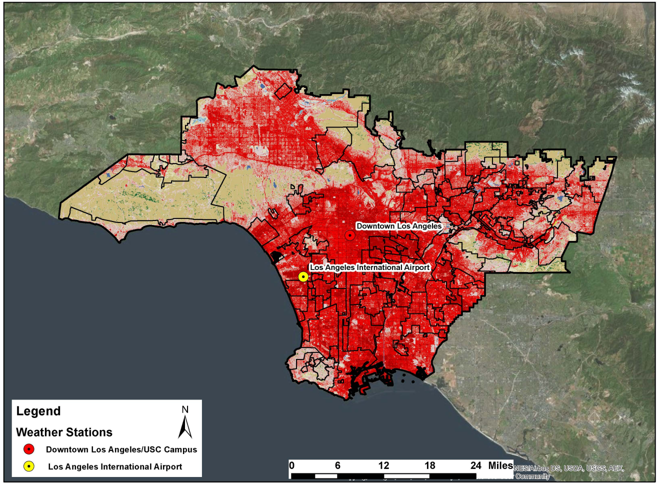
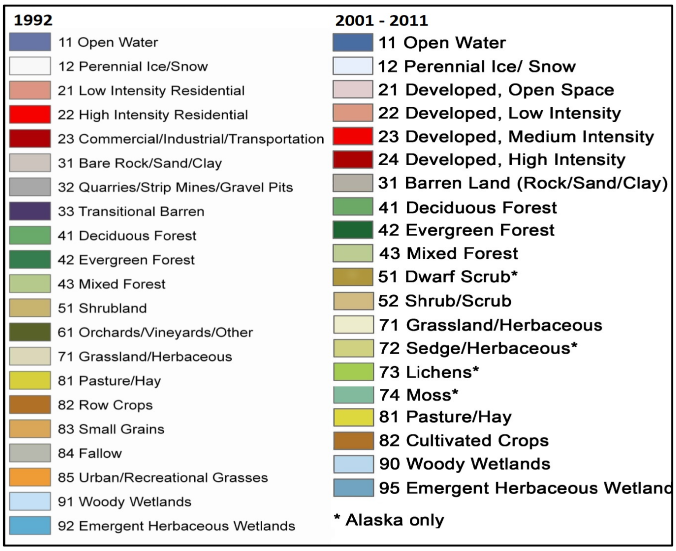

2011 Land Cover Map of Southern Los Angeles County

Fig. 11. Southern Los Angeles County map illustrating land use and land cover for the year 2011.


1992
- 11 Open Water
- 12 Perennial Ice/Snow
- 21 Low Intensity Residential
- 22 High Intensity Residential
- 23 Commercial/Industrial/Transportation
- 31 Bare Rock/Sand/Clay
- 32 Quarries/Strip Mines/Gravel Pits
- 33 Transitional Barren
- 41 Deciduous Forest
- 42 Evergreen Forest
- 43 Mixed Forest
- 51 Shrubland
- 61 Orchards/Vineyards/Other
- 71 Grassland/Herbaceous
- 81 Pasture/Hay
- 82 Row Crops
- 83 Small Grains
- 84 Fallow
- 85 Urban/Recreational Grasses
- 91 Woody Wetlands
- 92 Emergent Herbaceous Wetlands

2001 - 2011
- 11 Open Water
- 12 Perennial Ice/ Snow
- 21 Developed, Open Space
- 22 Developed, Low Intensity
- 23 Developed, Medium Intensity
- 24 Developed, High Intensity
- 31 Barren Land (Rock/Sand/Clay)
- 41 Deciduous Forest
- 42 Evergreen Forest
- 43 Mixed Forest
- 51 Dwarf Scrub*
- 52 Shrub/Scrub
- 71 Grassland/Herbaceous
- 72 Sedge/Herbaceous*
- 73 Lichens*
- 74 Moss*
- 81 Pasture/Hay
- 82 Cultivated Crops
- 90 Woody Wetlands
- 95 Emergent Herbaceous Wetland

* Alaska only

Fig. 12 National Land Cover Database (NLCD) land cover classifications for the year 1992 on the left, and 2001 through 2011 on the right (MRLC, n.d.).

This study observed five different years of land cover change at the southern Los Angeles County level, for the years 1970–2011. As population has increased, the composition of land use in the southern LA County continues to change, basically eliminating open space and increasing urban, impervious surfaces. Figure 8 displays a map of southern Los Angeles County showing land use and land cover for the combined years of 1970 and 1980. It should be noted that for this particular map, the choice of color for land use classes varies from the succeeding maps, however, it still embodies the main component of the map-land cover. **Figure 9** encompasses similar data to Figure 8, except the year examined is 1992 and only land cover is examined. The same model applies to Figure 10, exhibiting a map of 2001 land cover information. Figure 11 portrays 2006 land cover, and Figure 12 incorporates similar material for the year 2011. For reference on the land cover classifications, Figure 13 presents land cover classes from the National Land Cover Database (NLCD) for 1992, and 2001 – 2011. In addition to the maps, tables were generated according to each land cover map year: **Table 2** for 1970 – 1980, **Table 3** for 1992, **Table 5** for 2001, **Table 6** for 2006, and **Table 7** for 2011, each representing the percent of pixel count (area) for each land cover type. The greatest change one can recognize is in **Figures 8–9**, years 1992 and 2001. **Figure 12** shows that the change was mainly from "low intensity residential" to "developed medium intensity" and "developed high intensity" categories particularly near the downtown location.

Tables 5–9 disclose the percent of area centered on the 4 summarized land cover categories. Once more though, there is a discrepancy in the data for **Table 6** denoting 1970–1980. Structured on complete observation, this can be due to the dataset assessing land cover over a 10-year period, and therefore resulting in findings being higher than in 1992. Regardless, in Table 5, the data shows the studied area to be at 70.74 percent 'developed or built-up land' with 'agriculture' following at 26.65 percent for the years 1970 – 1980. **Tables 6–9** show the continued reduction of agricultural land (undeveloped) and increases in developed or built-up land.

Table 5. 1970–1980 land cover description for southern Los Angeles County and percent of pixel count over land cover type.

1970-1980 Land Cover Description	% of pixel count (area) over land cover type
Developed or Built-Up Land	70.74
Agriculture	26.65
Barren	1.93
Open Water/Wetlands	0.69
Total	100.00

Table 6. 1992 land cover description for southern Los Angeles County and percent of pixel count over land cover type.

1992 Land Cover Description	% of pixel count (area) over land cover type
Developed or Built-Up Land	58.85
Agriculture	38.98
Barren	1.79
Open Water/Wetlands	0.39
Total	100.00

Table 7. 2001 land cover description for southern Los Angeles County and percent of pixel count over land cover type.

2001 Land Cover Description	% of pixel count (area) over land cover type
Developed or Built-Up Land	78.19
Agriculture	20.92
Barren	0.32
Open Water/Wetlands	0.56
Total	100.00

Table 8. 2006 land cover description for southern Los Angeles County and percent of pixel count over land cover type.

2006 Land Cover Description	% of pixel count (area) over land cover type
Developed or Built-Up Land	78.63
Agriculture	20.60
Barren	0.23
Open Water/Wetlands	0.54
Total	100.00

Table 9. 2011 land cover description for southern Los Angeles County and percent of pixel count over land cover type.

2011 Land Cover Description	% of pixel count (area) over land cover type
Developed or Built-Up Land	78.83
Agriculture	20.42
Barren	0.23
Open Water/Wetlands	0.52
Total	100

Table 10. 2001 percentage of impervious land cover by value.

% Value	2001 Percentage of developed surface over 30-m
0-20	35.45
21-40	10.22
41-60	22.29
61-80	19.99
81-100	12.04

Table 11. 2006 percentage of impervious land cover by value.

% Value	2006 Percentage of developed surface over 30-m
0-20	34.55
21-40	9.81
41-60	22.47
61-80	20.6
81-100	12.57

Table 12. 2011 percentage of impervious land cover by value.

% Value	2011 Percentage of developed surface over 30-m
0-20	34.03
21-40	9.66
41-60	22.59
61-80	20.88
81-100	12.84

Table 13. Downtown Los Angeles, USC and LAX annual average temperature comparison 1970-2019 averaged by decades.

Stations	1970s	1980s	1990s	2000s	2010s
DTLA	61.4	62.2	62.6	62.7	64.0
LAX	63.0	63.4	63.6	63.0	64.1

In conjunction with the infrastructure, the percent of impervious surface was measured in southern Los Angeles County. **Table 10** displays percentage of developed surface over 30 meters for 2001, **Table 11** denotes 2006 impervious data, and **Table 12** exemplifies impervious findings for 2011. Data was not available for 1992, and therefore could not be reviewed. Figure 12 is used as the legend to view the percent values of developed surfaces for all three years. Ranging from 0 to 100 percent, the legend characterizes the intensity of impervious surfaces with 0 percent signifying no development, and 100 percent indicating extreme development. **Tables 10–12** show decreasing percentages for the lowest impervious classes, less than 40%, with increases in the higher, more impervious classes. Due to the large expanse of development in Los Angeles, it has transformed the area to being covered by asphalt at approximately 10 percent-mostly through sprawling network of roads and parking lots (Yale Environment 360, 2017). Netburn (2017) adds by stating that traditional asphalt absorbs up to 90 percent of the sun's radiation, affecting the surrounding air during the day, and into the night. Likewise, Bartholomew (2017) finds that during the summer months, temperatures have risen an average of 10 degrees on account of asphalt paving in Los Angeles. Further, in an area with wide coverage of pavement and development, downtown Los Angeles is expected by mid-century, to see an average of 22 days of extreme heat, with high temperatures exceeding those of 95 degrees Fahrenheit (Lin II & Krishnakumar, 2015). This is not global warming, but urban heat island effect.

Over 10 years, 2000-2009, Lee *et al.* (2017) found for residential areas of single-family homes, urban green cover (trees/shrubs and grass) declined 14–55% of green cover in 2000 on lots with additional recorded development and 2–22% of green cover in 2000 for single-family lots for which new permits were not recorded. Extrapolating the results to all single-family home lots in LA County chosen cities indicate a 1.2 percentage annual decrease in tree/shrub cover (5.6% of existing tree/shrub cover) and a 0.1 percentage point annual decrease in grass cover (2.3% of existing grass cover). The authors contend that newer homes are bigger and take up more of the lots with impervious surfaces. Roof colors decrease albedos leading to more absorption of sunlight, greater heat penetration into buildings and more need for air conditioning, also leading to excess heat.

Temperature data was examined at Downtown Los Angeles/USC and LAX weather stations to associate land use, land cover changes with surface temperatures. **Table 13** shows the mean annual temperature trends from 1970-2019 for each decade, while **Figure 13** represents annual average mean temperatures at

Downtown Los Angeles/USC from 1945–2019 and the annual average mean temperatures for LAX from 1945–2019. While the coastal LAX decadal temperatures start off milder than inland DTLA, the downtown temperatures have warmed faster over the period. The sudden drop in annual temperatures in 1998 corresponds to the move of the DTLA station from downtown DWP (Department of Water and Power) building to a more coastal, and cooler, USC campus (Patzert *et al*., 2016).

Figures 13–14 shows the warming trends for DTLA and LAX since 1945. LAX records began during 1944 when the airport was opened in a remote coastal section of the growing city. Most UHI studies choose to compare the temperature differences between the airport, usually rural, and the city core. That would also apply for Los Angeles except for two reasons. The airport is located along the coast while DTLA is further inland, and the rapid urbanization around LAX, making it more an urban/suburban portion of the sprawling city. The coastal sea surface temperatures influence both locations, but LAX to a much greater extent.

Studies have shown that the sea breeze is stronger and leads to cooler temperatures along the immediate coast during La Niña years and negative phases of the Pacific Decadal Oscillation (PDO) (LaDochy *et al.* 2007; Lebassi *et al.* 2011; Sequera *et al.* 2014).

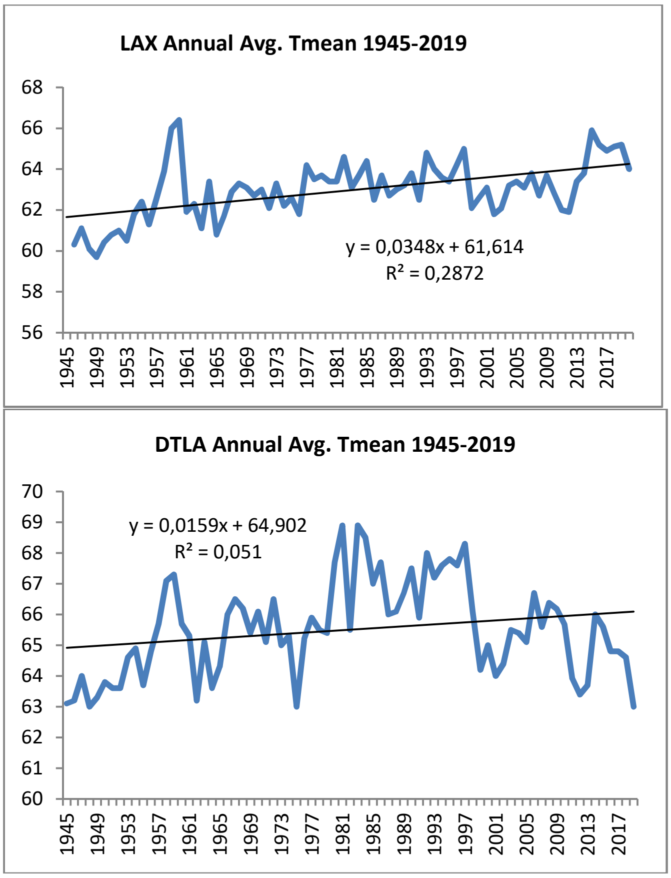


Fig. 13 Annual Average Mean Temperatures, 1945-2019 for LAX and DTLA (NOAA NCDC).

This can be seen in the maximum temperatures when sea breezes have the most influence. There is a significant jump in Tmax values in 1977 through 1997, when the PDO switched from the cooler negative phase to a warmer, positive phase. Starting in 1998, the PDO switched back to the cooler phase with a drop in Tmax temperatures. DTLA has been fully developed for the last few decades, while LAX has been infilling open spaces throughout its 75 years. The Tmin rate of warming at LAX is 5.4°F/century compared to its T max rate of 1.6°F/century. The trend R^2 is also much higher for Tmin vs. Tmax (51% variability explained by year vs. 5%). One might also speculate that daytime urban effect temperatures at LAX would be moderated by the cool sea breeze, while the offshore land breeze at night may carry inland heat towards LAX.

The influence of the sea breeze further complicates the characteristics of the LA UHI. This is shown in the previous UHI measurements using Claremont and Whittier Hills. While the west side of the city enjoys a natural air conditioner during warm summer days, the cooling diminishes further inland. During heat waves, there often is an offshore breeze negating any cooling sea breeze. High temperatures along with the stored heat at night lead to unhealthy stifling conditions, particularly to low income residents without air conditioners or cooling centers. City temperature records show that heat waves have become more frequent, more severe and of longer duration over the last several decades (Tamrazian *et al*. 2008; Hulley *et al*. 2020). With increasing population and development, the LA UHIs are predicted to lead to more heat waves and higher heat-related deaths (Gershunov and Guirguis 2012; Sheridan *et al*. 2012).

CONCLUSIONS

Urban heat islands do vary spatially and temporally in relation to land use and land cover changes as well as with elevation and distance from the coast. The results attest urban heat islands occur in areas where development exceeds, leading surface temperatures to rise at a faster rate. Land use change is associated with the intensification of the downtown UHI. As in Chicago, where for every 10% increase in impervious area, the surface temperature increases by 0.7 degrees Celsius (Coseo *et al*., 2014). The Chicago study found that the best predictors of nighttime UHI temperatures in neighborhoods were % impervious surfaces and % tree canopy. Los Angeles' UHI is much more complex due to diverse topography and coastal urbanization. The southern California urban sprawl has been described as an urban archipelago with numerous heat islands of differing magnitudes. In this study we focus on the downtown LA heat island, comparing its warming trend

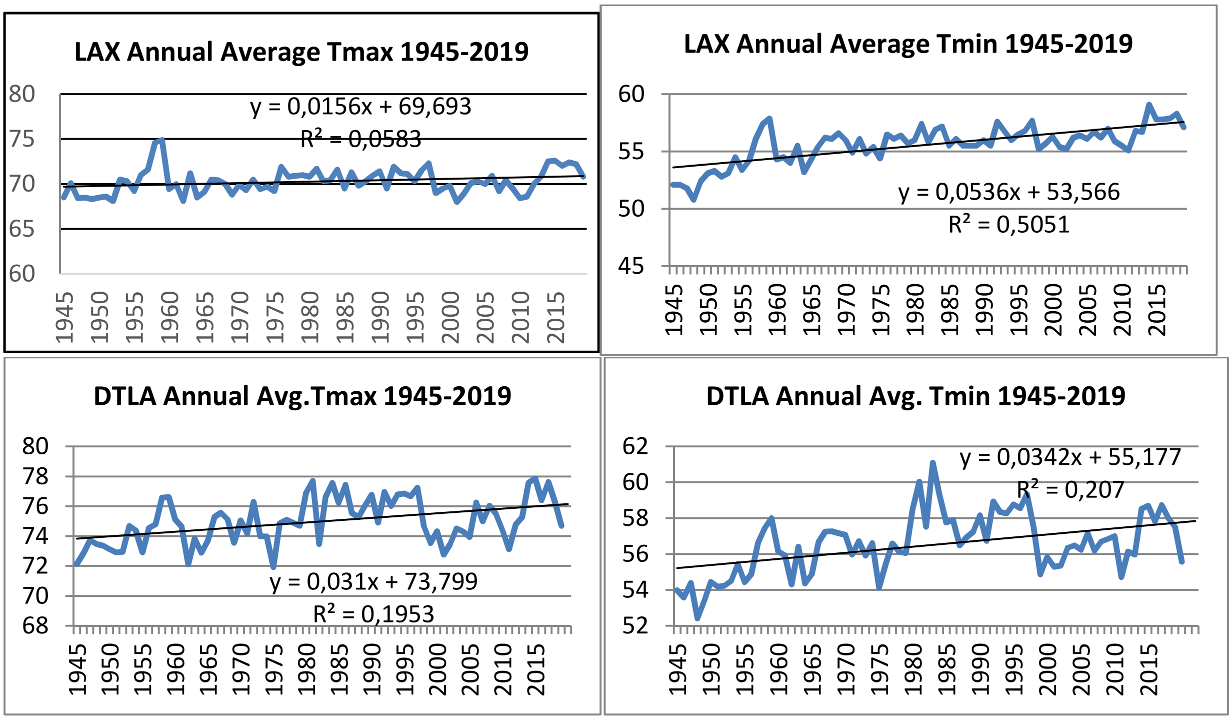


Fig. 14. Annual average maximum and minimum temperatures, 1945-2019 for LAX and DTLA (NOAA NCDC).

with suburban residential neighborhoods. The downtown UHI is dynamic, changing spatial and temporally as seen from comparisons of hourly temperatures between downtown Los Angeles (DTLA) and Claremont and Whittier Hills to the east. Interior heating away from the coast and topography complicate identifying the UHI effect.

Similarly using the LAX site along the coast, the difference with DTLA temperatures is complicated by the strength of the sea breeze. A further complication was the move of the downtown Los Angeles weather station away from the city core 1/3 the distance toward the coast in 1998. Using the combined DTLA/USC data caused UHI measurements to diminish as temperatures cooled by approximately 1°F compared to its former location (Patzert *et al*. 2016). By calculating the urban land use change in the southern LA County, we show that decreasing vegetation and open space and increasing urban densities have made the LA UHIs the largest in the state. The rate of warming of the DTLA UHI is predicted to lead to increasing heat waves and health issues. The City of LA has begun several programs to reduce the city's temperatures by 3°F (Netburn 2017) with a Million Tree Planting (McPherson *et al*. 2008), cool roofs (Ban-Weiss *et al*. 2015; Taha 1997), cool pavements (Mohegh *et al*. 2017; Deaton 2017; Levinson *et al*. 2017) and cool walls (Levinson *et al*. 2018). How successful these programs will be is yet to be realized, yet they do present real solutions to a growing health issue.

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