Urban Climate 52 (2023) 101702

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim

Microclimate impacts of neighborhood redesign in a desert community using ENVI-met and MaRTy

Peter J. Crank[a,*], Ariane Middel[b,c,f], Paul Coseo[d,f], David J. Sailor[e,f]

[a] Department of Geography and Environmental Management, University of Waterloo, Canada
[b] School of Arts, Media and Engineering, Arizona State University, USA
[c] School of Computing and Augmented Intelligence, Arizona State University, USA
[d] The Design School, Arizona State University, USA
[e] School of Geographical Sciences and Urban Planning, Arizona State University, USA
[f] Urban Climate Research Center, Arizona State University, USA

A R T I C L E I N F O

Keywords:
Urban heat mitigation
Thermal equity
Urban micro-climate measurement
Urban overheating
Microscale atmospheric modeling
CFD microscale model

A B S T R A C T

Municipalities often consider heat mitigation strategies to address urban overheating, but the location of implementation rarely is co-located with the communities that are carrying the majority of the heat burden in the city. The City of Phoenix, is redeveloping a public housing community with a focus on urban cooling as a desired outcome. This research uses in situ measurements (including the mobile micro-meteorological measurement cart, MaRTy) and ENVI-met microscale modeling of the neighborhood to assess air temperature (T_{air}) cooling capabilities of the planned redesigns to the neighborhood. After validating the ENVI-met model of the current neighborhood with fixed and mobile measurements with an index of agreement $d > 0.9$ and $d > 0.8$, respectively, analysis of the planned urban design shows some cool spots connected to new shade and vegetated corridors with T_{air} cooling magnitudes as high as 3 °C. Yet, some exposed and building-adjacent areas were identified as potential hot spots in the planned neighborhood. These hotspots underscore the importance of continued collaboration among the City, researchers, and the community to address the needs of the community for the creation of healthier urban environments.

1. Introduction

1.1. Literature review

Efforts to combat urban overheating have taken on myriad of methods for determining the impact of mitigation strategies. From physical and remotely-sensed statistical models of the urban environment to observational studies and computationally-intensive numerical models, the field of urban climate and the focus on heat mitigation have exploded as cities have begun to address the challenges of urban overheating (Cornelius, 2018; Middel et al., 2020). Urban heat has predominated the field of urban climate since its inception (Howard, 1833; Oke et al., 2017). As such, designers, planners, and researchers have sought to ameliorate the burdens of urban climate (namely urban heat and urban air quality) through grey (e.g., white roofs) and green (e.g., street trees) infrastructure.

* Corresponding author at: Department of Geography and Environmental Management, 200 University Ave. West, Waterloo, ON N2L 3G1, USA.
E-mail address: peter.crank@uwaterloo.ca (P.J. Crank).

https://doi.org/10.1016/j.uclim.2023.101702
Received 26 June 2022; Received in revised form 6 September 2023; Accepted 22 September 2023
Available online 30 September 2023
2212-0955/

Urban greening has long been considered a high priority to cool cities due to the many other ecosystem services provided. Bowler et al. (2010) confirmed the localized cooling benefits of urban parks and green space. Their review found that parks and green space can provide air temperature (T_{air})cooling of about 1 °C with a measurable impact on the surrounding urban area up to 250 m. Similarly, others have found trees and green space to provide urban microclimate benefits to the surrounding neighborhoods in a variety of climates (Aram et al., 2020; Upmanis et al., 1998) including hot and arid Phoenix (Colter et al., 2019). These studies have relied on a mixture of urban data collection campaigns and numerical modeling to accomplish this work.

The use of in situ data collection to examine the impacts of urban form is a long-established methodology in urban climate (Mills, 2013). Yet, more nuanced approaches are needed to address the granular and individual impacts on the urban climate. In addition to traditional fixed weather stations, the use of traverse measurements via mobile weather stations has been brought forward as a key method for measuring near-surface atmospheric conditions. Middel and Krayenhoff (2019) introduced the MaRTy cart as a method for collecting data on the urban microclimate by directly measuring the net radiation at a location as well as T_{air}, relative humidity, wind speed, and wind direction. This cart permits fine-scale micrometeorological measurement of the urban microclimate.

Numerical modeling on the other hand relies on fluid mechanics and computational fluid dynamics (CFD) to model the urban environment's impact on the atmosphere. Many of these models use Reynolds-Averaged Navier Stokes (RANS) equations to resolve the micro-scale atmosphere and heat transfer between the urban form and the atmosphere. One such model is ENVI-met, a RANS CFD model developed by Bruse in Germany (Bruse, 2009; Bruse and Fleer, 1998; Huttner, 2012). ENVI-met has gained popularity due to the ease of use and general accessibility and is a physics-based model that has been developed and tested for the past 20 years. The recent ubiquity of use among researchers, planners, and architects is evidenced by its predominance among recent numerical modeling publications (Krayenhoff et al., 2021). Krayenhoff et al. (2021) reviewed and evaluated the state of the numerical modeling in urban microclimatology and found ENVI-met to be the most common, yet they also pointed to a need for more critical use of the suites of models currently in use to ensure the tools are being used properly. As with every model, there are limitations to ENVI-met. Various researchers have pointed to some of the limitations in ENVI-met's modeling of heat transfer from roofs and other surfaces (Crank et al., 2018; Maggiotto et al., 2014). Others have noted the challenges of modeling shade accurately in a complex urban environment (Crank et al., 2020; Gál and Kántor, 2020). To maximize the value of numerical models, it is recommended that in situ measurement data be used to validate the model for use in the location of interest (American Society of Mechanical Engineers., 2007; Blocken et al., 2007;

Fig. 1. Edison Eastlake's location and planned redevelopment. a) Map of Edison Eastlake neighborhood with the city and airport within the map domain; b) the overall design of the proposed redeveloped neighborhood; c) the plan view for the Frank Luke units, the Luke Krohn units, and Edison Park.

Krayenhoff et al., 2021).

1.2. Motivation for study

In many cases, the strategies for cooling have been implemented in areas of high commercial economic impact or affluent residential neighborhoods with the property values to support significant investment by the City to redevelop the urban environment (Guardaro et al., 2020). Yet, the areas of greatest need for heat amelioration are among the low-income, minority populations (Declet-Barreto et al., 2013; Harlan et al., 2006; Jenerette et al., 2016). The hotter neighborhoods frequently overlap with communities that have borne the brunt of “environmental racism”, which is “a complex of social and spatial practices which systematically disadvantage people marked by certain racial categories”, according to Bolin et al. (2005). Additionally, the communities often experience environmental racism have lower levels of individual adaptive capacity and are more likely to view extreme urban heat as a catastrophe to their health and lives (Guardaro et al., 2022).

The Edison Eastlake community in Phoenix is a historically ethnic minority community that has undergone a series of zoning and planning actions that burdened the community with environmental pollutants and hazards (Bolin et al., 2005). To address these disparities, the City of Phoenix was awarded a $30 M Choice Neighborhoods Grant in 2016 to redevelop the Edison Eastlake neighborhood into mixed-income neighborhoods linking housing improvements with appropriate services, schools, public assets, transportation, and access to jobs (HUD, 2016a). This redevelopment work has drawn attention and subsequent collaboration and

Fig. 2. Map of the weather stations, the mobile traverses, and the instruments used. A) shows the route for the traverses and the location of fixed weather stations (P7 was lost/disappeared during data collection), b) is the car traverse thermocouple, c) shows the two MaRTy carts (Middel and Krayenhoff, 2019), and d) shows a fixed weather station. The traverses in this neighborhood only used one cart.

engagement with the community, Arizona State University (ASU), and The Nature Conservancy. This co-production of knowledge has led to design plans that significantly increase tree canopy as well as providing more cooling grey infrastructure across the neighborhood using a community-informed and culturally contextual approach (Conservancy, 2019; Hamstead et al., 2020). The objective of this study is to examine the current thermal environment of the neighborhood and assess the potential thermal benefits and tradeoffs of the City's planned redevelopment of the neighborhood by employing fixed and mobile measurement data to drive a numerical model of the neighborhood.

2. Methods

2.1. Study site

The Edison Eastlake neighborhood (33.455220, −112.041858) is situated east of downtown Phoenix, just northwest of Sky Harbor International Airport (Fig. 1). The neighborhood is bounded to the north and east by the I-10 freeway. The Valley Metro Light Rail runs to the south of the neighborhood. These transportation infrastructures are significant heat sources for this neighborhood due to the added waste heat from vehicles and extra pavement. The housing stock of the neighborhood consists of 1–2 story buildings and is classified by Local Climate Zone (LCZ) as LCZ 6 (open low rise) (Stewart and Oke, 2012). The redevelopment centers on the City's plans to increase tree canopy, change the housing structures to be higher density with mixed incomes, and expand Edison Park to create more space for physical activity and community gathering (HUD, 2016; "*HUD Awards Choice Neighborhood Grants to 10 Cities*, 2016) (Fig. 1b & 1c).

Of note for the microclimate environment, the one to two story Frank Luke homes east of the hospital and the Luke Krohn homes northeast of the hospital will be demolished and replaced with three- and four-story apartments and condominiums. This will result in a change from LCZ 6 (open low rise) to LCZ 5 (open mid-rise). The housing units will be a mixture of government housing, low income, and middle-income housing designed to diversify the community and attract workers who seek an active transit lifestyle. Roof albedo in the redevelopment is also increased as the material changes from a dark shingle to white (or off-white) flat roof coating. Edison Park in the north of the neighborhood will be expanded southward, a green corridor will connect Edison Park to the major arterial road (Van Buren St – shown in Fig. 2) and the mass transit options to the south of the neighborhood. In addition to these introductions of green space and infrastructure, cooling grey infrastructure (mostly in the form of ramadas and shade) will also be implemented as a means of providing shade and encouraging community use of the outdoor space. The redevelopment by the City will result in two primary interventions: (1) the replacement of old one- and two-story apartment buildings with four-story apartment buildings (with lighter-colored roofing), and (2) an increase in the number of trees planted. These two interventions will increase the shade and cooling provided at the pedestrian height during the day.

2.2. Data collection

A long-term measurement campaign was initiated prior to neighborhood redevelopment during the summer of 2018. Multiple permanent weather stations were deployed in the neighborhood (Supplemental Table 1), collecting T_{air}, relative humidity, incoming solar radiation, wind speed and direction data. Two fixed weather stations with Onset HOBO meteorological instruments on top of city housing units collected general weather conditions for the neighborhood at 5-min intervals. These stations were set up to be 2 m above the roof surface and as far as physically possible from air conditioning units. Additionally, four temperature and relative humidity sensors were placed in other parts of the neighborhood on electrical poles. These pole-mounted stations were placed at a height of 3 m to minimize risk of vandalism (Fig. 2).

In addition, measurement traverses were conducted on June 19, 2019. These traverses collected 1-s data over the course of three hours (8–9 am, 12–1 pm, and 4:30–5:30 pm Local Standard Time (LST)) on all of the atmospheric parameters defining a pedestrian's thermal exposure using the MaRTy cart (Middel and Krayenhoff, 2019) and temperature with car-based traverses to aid in minimizing temporal trends in T_{air} during the traverse of the neighborhood (Fig. 2). The MaRTy cart collected T_{air}, relative humidity, wind speed and direction, as well as shortwave and long wave radiation from six directions. Using the cart's thermal exposure data, combined with surface temperatures, and the incoming solar radiation from fixed weather stations the data is used to improve the understanding of the atmospheric environment of the neighborhood, examine the microclimate's implications for pedestrians and residents, and most importantly for modeling purposes, validate data produced by numerical modeling of the neighborhood.

All data were postprocessed in R (version 3.5.1) to match units of measurement, location, time of measurement, and time zone. To relate simulation results to traverse observational data, the traverse measurements were time de-trended to remove the change in temperature due to the amount of time taken to complete the traverse. The traverse data are cropped to 15 min before and after the top of the hour to time de-trend the data and then compared to the numerical model output data for analysis. To reduce the noise of the traverse data, the MaRTy data were then smoothed to 20 s averaged intervals where a single point was taken every 20 s (though the environment was sampled every two seconds with the MaRTy traverse). The vehicle traverse data were smoothed to 10 s averaged intervals according to the same method (the environment was sampled every one second with the vehicle traverse).

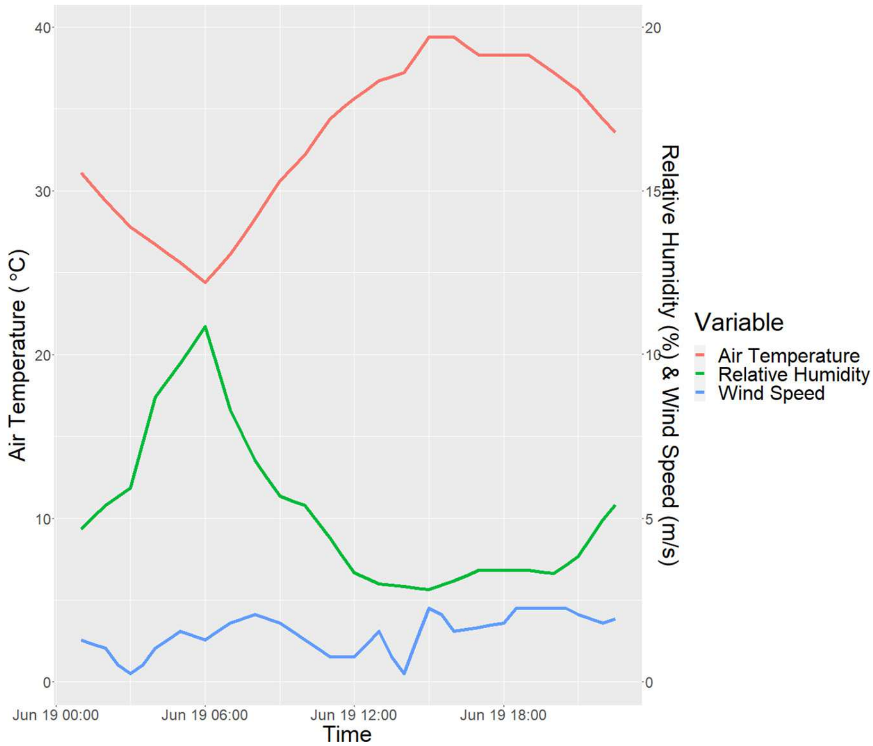
2.3. Atmospheric conditions

Phoenix, Arizona is a large metropolitan area in the US that is situated within the Sonoran Desert with a Köppen-Geiger Climate type of BWh (hot, arid desert) (Kottek et al., 2006). Maximum T_{air} for the month of June in Phoenix averages 40.1 °C with low relative humidity values, low wind speeds, and no cloud cover. On June 19, 2019, T_{air} was slightly cooler than average, topping out at just under 40 °C for the maximum temperature with sunny conditions and a low relative humidity (average of 10.2%). Winds were light throughout the day (3.2 m/s on average), mainly from the southeast in the morning and midday before switching to the west by mid-afternoon.

2.4. Numerical modeling

The baseline microclimate was evaluated using ENVI-met 5.1 (Bruse, 2009; Bruse and Fleer, 1998; Huttner, 2012). This newest version of the model has improved their radiative environment estimations, flow-following of particles through the domain, and “super-cool” roofing material representations (Simon et al., 2021a, 2021b; Sinsel et al., 2021). The ENVI-met model requires hourly

Table 1
ENVI-met input static parameters and settings.

Start Date	June 19, 2019
Start Time	01:00
Simulation duration	20 h
Full Forcing	Temperature, relative humidity, wind speed, and wind direction are forced using Sky Harbor International Airport weather data for June 19, 2019.
	
Tree types	Medium crown deciduous tree at 5 m height*; Fan palms *These trees are assumed to be young and not fully matured. Actual shading from the tree at maturity would be greater than what is simulated (Erlwein et al., 2021).
Soil moisture	10% RH; 26 °C 15% RH; 26 °C 20% RH; 26 °C 20% RH; 26 °C
Material Albedo0F[a]	Asphalt: 0.1 Dark concrete: 0.2 Grey concrete: 0.25 Light concrete: 0.3 Roof tile: 0.5 High-albedo roof tile: 0.7

[a] Albedo values used are default ENVI-met values for: Asphalt, Dark concrete, and roof tile. The grey concrete and light concrete albedo were lowered from 0.5 and 0.7 (respectively) to account for weathering and street-level use of the materials. The high-albedo roof tile was defined as 0.2 higher albedo than the standard roof tile used in the domain.

weather data as forcing (Table 1) to accomplish a fully forced model which is intended to have the best results when compared to observations (Simon et al., 2021b). To accomplish this, the nearby (<5 km) Phoenix Sky Harbor International Airport weather station data were obtained (Supplemental Fig. 1). The airport site is not identical to the community but is representative of the general urban climate of the City and away from waste heat sources that can influence the neighborhood's microclimate. Edison Eastlake's surface temperatures (~34 °C) are more similar to the airport (~35 °C) than to the average surface temperatures of the county as a whole (~31 °C) (Guardaro et al., 2019).

The ENVI-met domain of the built environment is created using LiDAR data and Google Earth imagery to recreate the buildings, surfaces, and vegetation in the model. The buildings and vegetation were imported through ENVI-met Monde (v. 5.1), and the surface characteristics were established using ENVI-met Spaces (v. 5.1) (Fig. 4). The baseline case domain is covered by 43.79% impervious surfaces (asphalt and concrete), 15.72% buildings, and 17.89% grass. The tree canopy of the baseline covered 5.06% of the domain (tree trunk and canopy directly overhead). The rest of the domain is bare soil comprised of sand or loamy soil. The redesigned domain is comprised of 40.74% impervious surfaces (asphalt and concrete), 22.37% buildings, and 12.09% grass (some grass was removed for new buildings). The redesigned neighborhood has a 9.74% tree coverage (an ~92% increase in tree canopy). The rest of the redesigned domain is bare soil comprised of sand or loamy soil. Building density and height were increased under the redevelopment plans to have more four-story apartment buildings, changing the LCZ of the neighborhood from LCZ 6 to LCZ 5 (Stewart and Oke, 2012).

To evaluate the output of ENVI-met, data collected through stationary weather stations in the neighborhood as well as traverse measurements of T_{air}, mean radiant temperature (T_{MRT}), wind, and humidity were used to study the temporal and spatial variation within the domains (Fig. 3). To accomplish this, (1) the output from ENVI-met was exported as a csv for each variable and time of analysis, (2) the output was converted into a grid format using the coordinates of neighborhood; (3) the field measurement data for the same variable (T_{air}, humidity, dew point temperature, and T_{MRT}) and time were then overlaid for analysis spatially. The analysis via sampling the raster data at the points of measurement was completed for each hour of traverse measurement data. This sampling method used a spatial join of the data to allow for error or imprecision in the georeferencing of the data. The join permitted points from the traverse data as far as 1.5 m apart to be joined to the ENVI-met output. The in-situ traverse measurements are then compared to the spatially analyzed data from ENVI-met according to Declet-Barreto et al. (2013). Fixed sites were used to create receptor points within ENVI-met for validation at each hour from 06:00–20:00 LST.

To assess model accuracy, we use four common statistical metrics of quantifying errors: R^2 (Fields et al., 2012), Mean Bias Error (MBE) (Willmott and Matsuura, 2006), Root Mean Square Error in its standard (RMSE), systematic ($RMSE_s$), and unsystematic ($RMSE_u$) formats (Willmott and Matsuura, 2006), and Wilmott's Index of Agreement (*d*). The most complex of the metrics is Willmott's *d*, a unitless metric from 0 to 1 where 1 indicates perfect agreement and 0 has no agreement between the data (Willmott, 1981). Acceptable values for Willmott's *d* start at about 0.7 for T_{air} and 0.5 for T_{MRT} (Acero and Arrizabalaga, 2016; Crank et al., 2020; Roth and Lim, 2017). RMSE is typically expected to be <2 °C for T_{air} and anywhere from 5 to 20 °C for T_{MRT} (Acero and Arrizabalaga, 2016; Crank et al., 2020; Roth and Lim, 2017). MBE, as well as $RMSE_u$ and $RMSE_s$, do not have specific thresholds in the literature but are

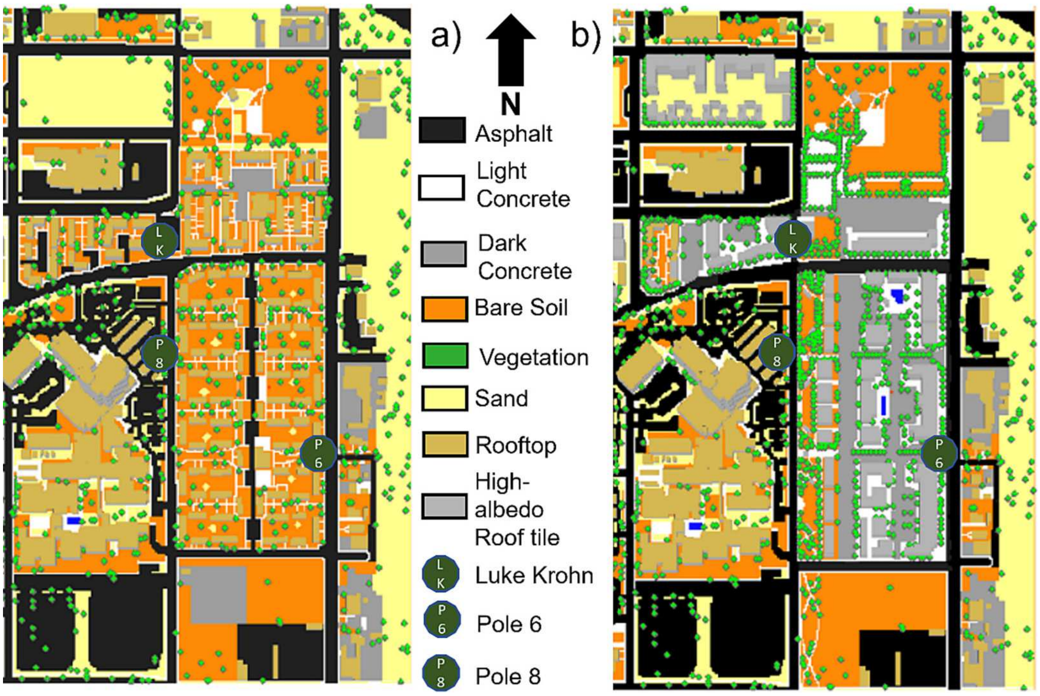


Fig. 3. A birds-eye view of the ENVI-met domains. a) shows the current neighborhood layout. b) is the redesigned neighborhood. Of note: new trees modeled in the redesign are modeled at just 5 m heights to simulate early stage (e.g., year 1) impacts of the redesign.

used to show the directionality of the bias (MBE) and the source of error within RMSE ($RMSE_u$ and $RMSE_s$). Due to poor validation of T_{MRT}, which is discussed in the results, the radiative load was not considered in this study.

Simulation output from the baseline model and the redesign model are then compared to assess the efficacy of the redesign for cooling the urban microclimate. Using T_{air}, hourly difference plots are created to visualize the magnitude and spatial difference between models. This analysis excludes initial hours of the simulation (4:00–7:00 LST) to allow for model spin up and post-sunset hours (after 20:00 LST) due to known issues with ENVI-met's estimate of heat storage and release pre-sunrise and post-sunset (Mahmoud, 2011; Middel et al., 2014). This research focuses on model output from 8:00, 12:00, and 17:00 LST. The three hours selected allow for analysis of the morning impacts, peak insolation, and peak ambient T_{air} times. Key changes to design components included in the model are: (1) higher albedo roofing on new construction and (2) increased shading and vegetation for transit corridors through the neighborhood (the vegetation modeled is for the first few years immediately following installation). The tree canopy is assumed to be at 5 m in height with small crowns such as would be typical for the trees within the first one to three years of installation. Full maturity in the tree canopy would yield different results (Erlwein et al., 2021) but those are more long-term results and would be considered an extension of this research.

3. Results

3.1. Air temperature validation

The simulation output shows good diurnal agreement with the observational data of fixed weather stations (Fig. 4). Observational data from the neighborhood were slightly warmer than forcing data from the airport. Yet, ENVI-met overestimated T_{air} for pole-mounted sites and underestimated roof-top sites. ENVI-met is known for overestimating T_{air} in urban canyons (Crank et al., 2020; Gál and Kántor, 2020) which is where the pole-mounted sites were located. Table 2 details the errors of ENVI-met to observed data. Among the fixed weather station sites, ENVI-performs well ($d > 0.91$) at all locations with the Luke Krohn site performing the best ($d = 0.98$). Additionally, the RMSE and MBE values for ENVI-met show strong agreement across sites for observations and modeled output, with MBE values confirming overestimation at the pole-mounted sites throughout the day. RMSE values show some unsystematic bias in the data resulting in RMSE values above 2 °C for all sites except for Luke Krohn.

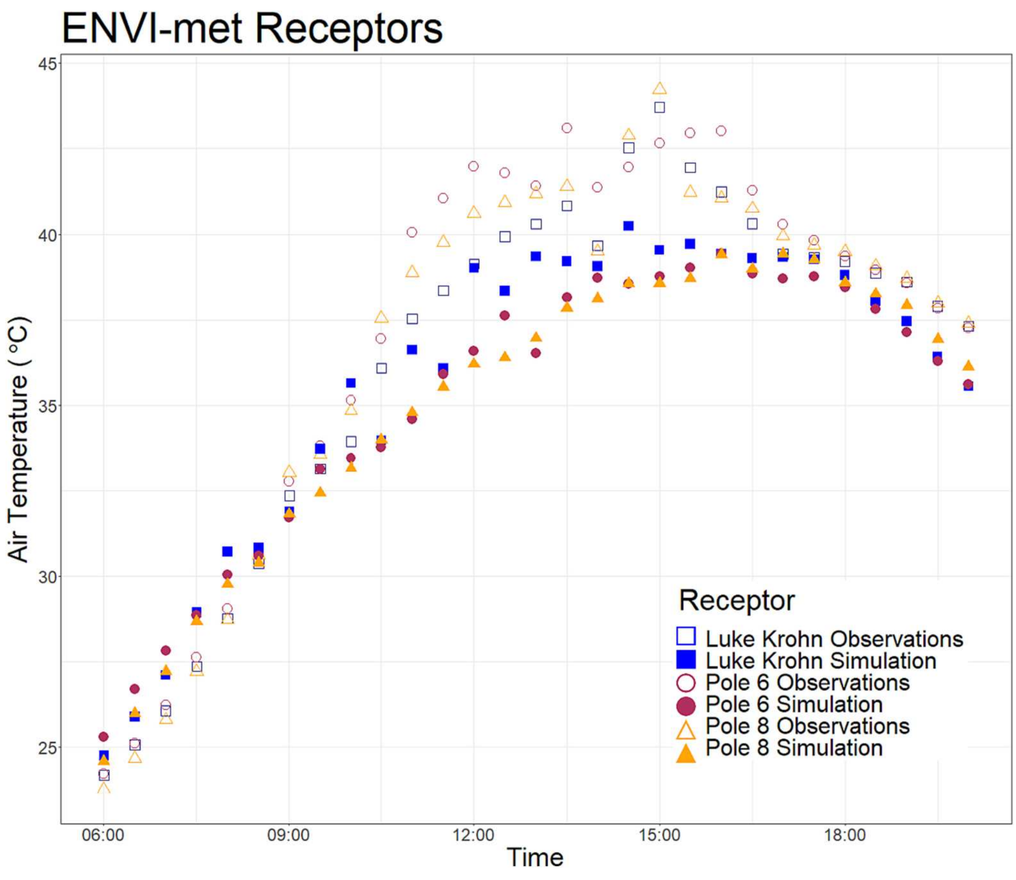


Fig. 4. Plot of June 19, 2019 temperature data from each fixed validation point, the ENVI-met output, and the data from Sky Harbor used to drive the ENVI-met model.

Using the traverse measurement data to examine the validity of the ENVI-met model produced worse results (Table 2). RMSE values were 3.60 °C for MaRTy and 4.50 °C for the car (with most of the error connected to the unsystematic RMSE). Yet, both car and MaRTy traverse data resulted in good agreement with the modeled output ($d > 0.80$). Willmott's Index of Agreement shows that ENVI-met performs worse at estimating vehicle data than the MaRTy data. The car temperature data vary more than MaRTy with the exception of the noon traverse where they are very similar (Fig. 5). Yet, the RMSE for both sets of traverse data were much higher than those of the fixed stations.

3.2. Validation of T_{MRT}

The T_{MRT} data from MaRTy were smoothed to a 20 s interval (10 data points averaged together) before being compared to the ENVI-met output. The resulting R^2 values are low (below 0.4) with small improvements among the other validation metrics ($0.39 < d < 0.68$) (Table 3). The afternoon traverses falls below the minimum values for T_{MRT} validation of $d = 0.5$ (Acero and Arrizabalaga, 2016; Crank et al., 2020; Roth and Lim, 2017) with the morning, noon, and diurnal validation metrics exceeding $d = 0.6$. Further, the MBE indicates a systematic *over*-estimation of T_{MRT} by ENVI-met of nearly 10 °C (Table 3). The temporal averaging of the T_{MRT} data diminished the range of values observed. The traverse data of T_{air} show more variability than T_{air} from the ENVI-met simulation (Fig. 6). During each of the traverses, there are locations where ENVI-met overestimated and underestimated (Fig. 6). Across all three traverses, ENVI-met had no systematic pattern to estimating T_{MRT} (Fig. 6). Due to the poor validation results that stem from errors in the calculation of reflected solar radiation in shaded locations, further analysis of T_{MRT} was removed from the scope of this study; please see the Supplemental Materials for a more thorough treatment of T_{MRT}. Until the issues associated with calculating reflected solar radiation are resolved, ENVI-met will continue to estimate T_{MRT} inaccurately (Crank et al., 2020, 2018; Gál and Kántor, 2020; Maggiotto et al., 2014).

3.3. Redesign scenario: Air temperature distribution

Given the acceptable validation of T_{air} by the model, the T_{air} impacts of the redesign were assessed by the model through comparing the differences at each location between the baseline simulation and the redesign. Fig. 7 show ENVI-met results for T_{air} at 8 am (panel a), 12 pm (panel b), and 5 pm (panel c) on June 19, 2019. Overall, there is some cooling in the areas of redevelopment, particularly in the vegetated corridor that previously was bare soil (lower portion of the domain) or housing units. The cooling extends to the north side of the apartment buildings, especially at noon. The magnitude of the cooling in these locations is around 1–3 °C. Yet, there are noticeable hotspots where buildings are being replaced with open parking lots and/or parks.

T_{air} reduction is more pronounced during the noon and afternoon hours. The redesign also shows a downwind effect where the cooler air from the redesign is being advected downwind of the redeveloped buildings and parks. While certainly weaker than the cooling seen directly beside the redesign elements, there is noticeable cooling to the north and east of all redesign elements. Table 4 documents the statistical summary of ambient T_{air} across all hours of simulation. The average air temperature difference was calculated by taking summary statistics of the domain output for each hour (Table 4).

4. Discussion

The temperature difference between the current environment and the planned redesign shows some modest cooling potential, particularly in places where the City's interventions of increased building height and tree canopy are implemented. Yet, these cooling opportunities also fall within the range of error as documented by the RMSE (Table 2). Results are limited by the weak validation of T_{MRT}, despite validation of incoming solar radiation (Supplemental Fig. 2 and Supplemental Table 2), a major component of the T_{MRT} calculation (Höppe, 1992; Middel and Krayenhoff, 2019; Thorsson et al., 2014). The calculation of T_{MRT} in ENVI-met over-estimates in shaded locations due to an error in reflected shortwave radiation values for shaded locations (see Supplemental Materials for more details). Despite these errors in the estimation of T_{MRT}, ENVI-met is found to be valid for T_{air} in Edison Eastlake, the data are sufficient to examine differences between sites within the domain using the delta method (Hawkins et al., 2013; Hijmans et al., 2005; Jandaghian, 2018; Middel et al., 2021; Navarro-Racines et al., 2020; Wu et al., 2018).

The strong agreement between T_{air} in ENVI-met and fixed station observations shows the ability of the model to replicate the

Table 2
Table of T_{air} validation metrics for the data. Observations from fixed stations are compared to both ENVI-met and the data used to drive ENVI-met. Observations from traverse measurements are compared to ENVI-met.

Air Temperature (°C) Receptor Validation Metrics						
Site	R-Squared	RMSE	RMSEs	RMSEu	MBE	Willmott's Index of Agreement (d)
Luke Krohn - ENVI-met	0.96	1.51	1.07	1.07	0.63	0.98
Pole Station 6 - ENVI-met	0.94	2.95	1.19	2.69	1.98	0.93
Pole Station 8 - ENVI-met	0.94	2.62	1.28	2.28	1.66	0.95
MaRTy - ENVI-met	0.87	3.6	1.47	5.76	2.63	0.87
Car - ENVI-met	0.83	4.5	1.62	5.91	3.5	0.81

Air Temperature (°C) Receptor Validation Metrics

Site	R-Squared	RMSE	RMSEs	RMSEu	MBE	Willmott's Index of Agreement (d)
Luke Krohn - ENVI-met	0.96	1.63	0.92	1.34	0.59	0.98
Pole Station 6 - ENVI-met	0.95	3.27	0.94	3.13	2.25	0.91
Pole Station 8 - ENVI-met	0.94	2.92	1.09	2.71	1.94	0.93
MaRTy - ENVI-met	0.87	3.6	1.47	5.76	2.63	0.87
Car - ENVI-met	0.83	4.5	1.62	5.91	3.5	0.81

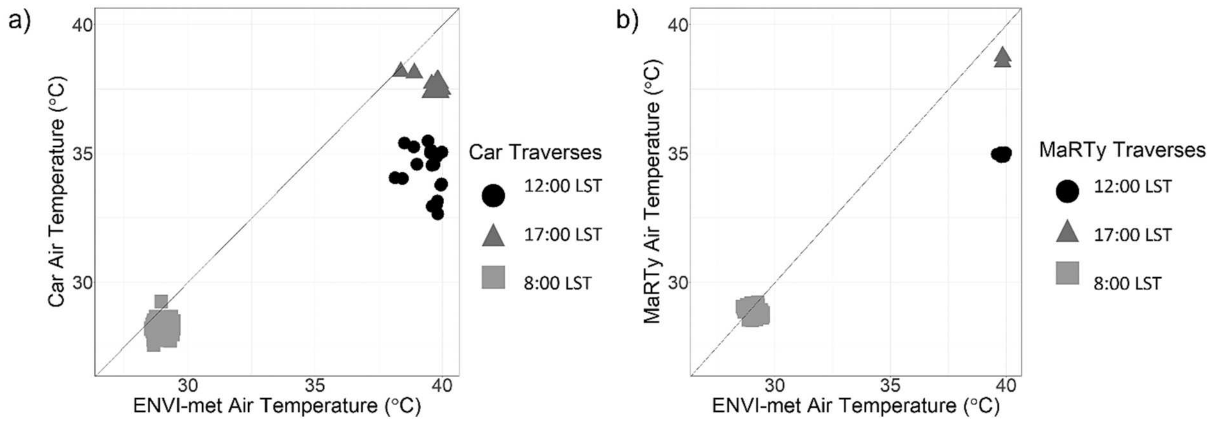


Fig. 5. Plot of T_{air} traverse data and corresponding ENVI-met. Each color delineates a different time of traverse (8:00, 12:00, 17:00 LST), a) is the T_{air} from the car traverse, and b) is the T_{air} from MaRTy.

Table 3
Table of TMRT validation metrics for the data. Observations from fixed stations are compared to both ENVI-met and the data used to drive ENVI-met. Observations from traverse measurements are compared to ENVI-met.

Mean Radiant Temperature Receptor (°C) Validation Metrics				
Site	Diurnal MRT	Morning MRT	Noon MRT	Afternoon MRT
R-Squared	0.18	0.19	0.37	0.01
RMSE	9.56	7.87	6.30	12.52
RMSEs	6.92	6.84	3.85	7.23
RMSEu	8.34	6.90	6.84	5.92
MBE	4.20	1.49	3.09	7.63
Willmott's Index of Agreement (d)	0.64	0.66	0.68	0.39

variability in the urban climate of the neighborhood. RMSE values for fixed weather stations were within the typical bounds of error compared to commonly reported values between 1.5 and 3 °C in places such as Spain (Acero and Arrizabalaga, 2016), Germany (Forouzandeh, 2018; Lee and Mayer, 2016), Singapore (Roth and Lim, 2017), and China (Zhang et al., 2018; Zhao and Fong, 2017). Each of these studies found higher RMSE values, but through careful analysis of the errors, some were able to point out the specific issues driving the error and move forward in their analysis from there. Some are less optimistic about the output and the implications for the efficacy of ENVI-met. Despite, the higher RMSE values, T_{air} values from the fixed weather stations and ENVI-met simulations have a strong Willmott's Index of Agreement, well above the threshold found in the literature (Acero and Arrizabalaga, 2016; Crank et al., 2020; Roth and Lim, 2017). This research supports ENVI-met's ability to model intra-domain variability in T_{air} within a real urban canyon and neighborhood.

4.1. *Urban microclimate impacts of the redesign*

The redesign with its increased building density, building height (from 1 to 2 stories up to 4 stories), increased green space, young tree canopy, and cooling grey infrastructure is modeled by ENVI-met to have modest benefits to the urban microclimate (up to ~2.5 °C of cooling for ambient T_{air}). Middel et al. (2014) found these increases in density resulted in cooler conditions due to increased shading, yet in their study they replaced desert and paved landscapes with buildings. Much of the redesigned space in the Edison Eastlake neighborhood was grass-covered with mature trees. Thus, the negation of the increased shade is occurring by replacing the grassy

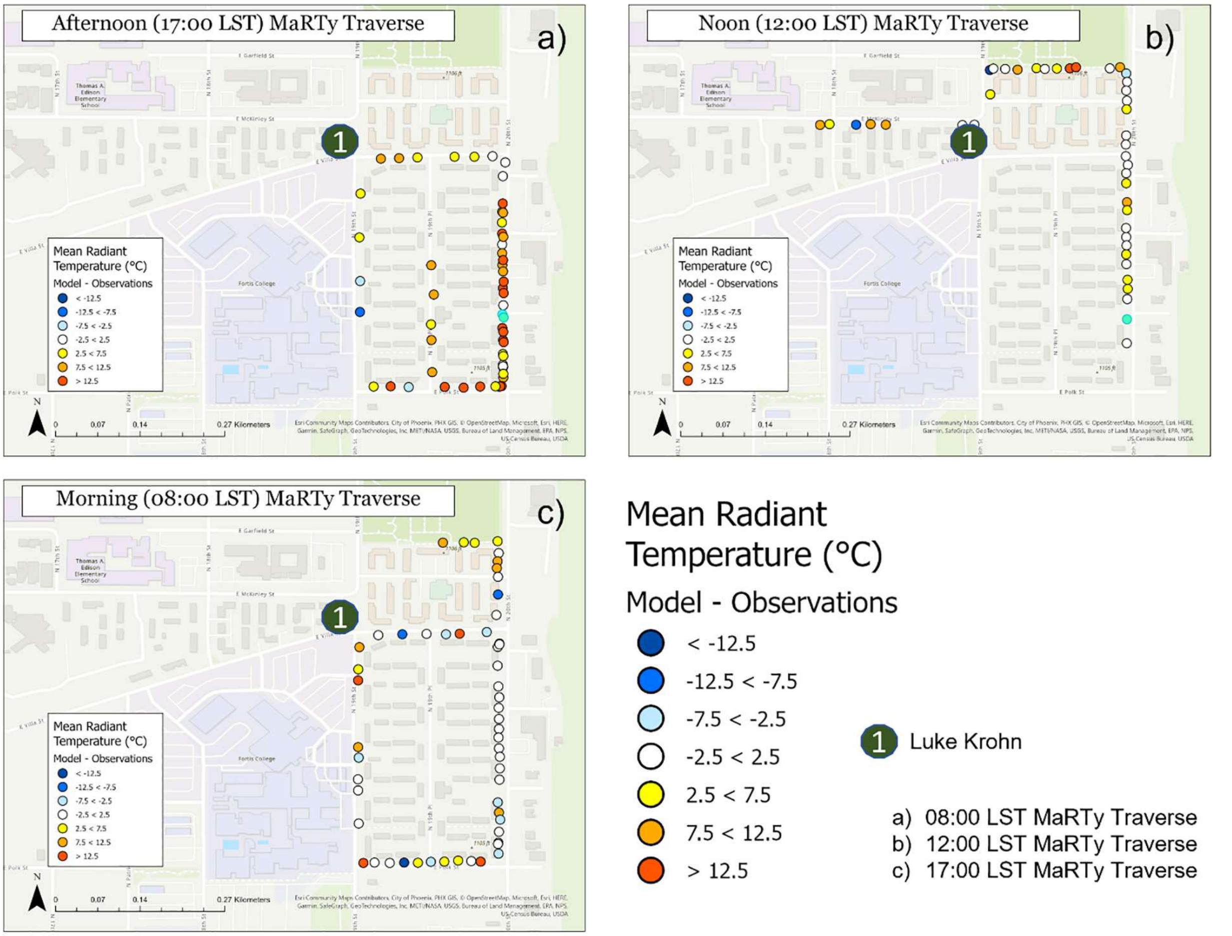


Fig. 6. Plot of Mean Radiant Temperature traverse data from MaRTy and corresponding ENVI-met. Each map (a, b, c) denotes the error between the observational data and the model output. Positive values indicate that the model over-estimated T_{mrt}.

surfaces with buildings, parking, and some tree cover. Ambient T_{air} is improved with pockets of cooling that are similar to what others have found through empirical studies of green space for cooling (Bowler et al., 2010; Middel et al., 2015; Santamouris et al., 2018). The downwind effect of the redesign is apparent, though the magnitude of its effect over longer distances is unclear given the constraints of the model. Nonetheless, Fig. 7 show the approximate distance (50–100 m) is in line with previous research on downwind cooling from targeted heat mitigation strategies (Crank et al., 2018; Eliasson and Upmanis, 2000; Ng et al., 2012; Taleghani et al., 2019).

Under shaded conditions (whether from trees or taller buildings), T_{air} cooling benefits are estimated to be between 2 and 3 °C based on ENVI-met modeling. This result supports the City's intent to provide thermal benefits to the community. Residents desired more shade in spaces they traverse and use while maintaining a safe environment (Conservancy, 2019; Guardaro et al., 2022, 2020, 2019). These expressed desires were addressed through the vegetated corridor as the design includes targeted cooling grey as well as the green infrastructure in pedestrian places (e.g., sidewalks and communal spaces) that can be utilized to foster community cohesion while still providing the cooling benefits necessary for outdoor community interaction during the summer months. The cooling benefits would be expected to increase as the trees mature; the modeling in this study only considered trees within the first five years of planting (a relatively small shade canopy). Thus, the study provides a conservative estimate for the cooling of the tree shading implemented by the City.

A key strength of this approach is pre-construction identification of areas where the model indicates warming (such as the south, east, and west facing walls). Designers may then redesign some hot spots based on the model to target these locations for further shade or cooling infrastructure to provide enhanced thermal comfort and reduce the energy burden of residents living inside these units. Another potential temporary intervention would be to install grey shade infrastructures such as shade sails to create cooler conditions over the tree canopies. This could provide similar thermal benefits as full grown trees to residents (Middel et al., 2021), but also serve to help maturing trees grow and thrive in the harsh summer sun of Phoenix.

As the City of Phoenix implements their redevelopment plan, the results of our simulation work indicate some modest benefits to the urban microclimate through the redesign. This examination indicates that cities may be able to retrofit areas from LCZ 6 (open low rise) to LCZ 5 (open mid-rise) adding more housing units (approximately tripling the density), taller buildings, additional urban

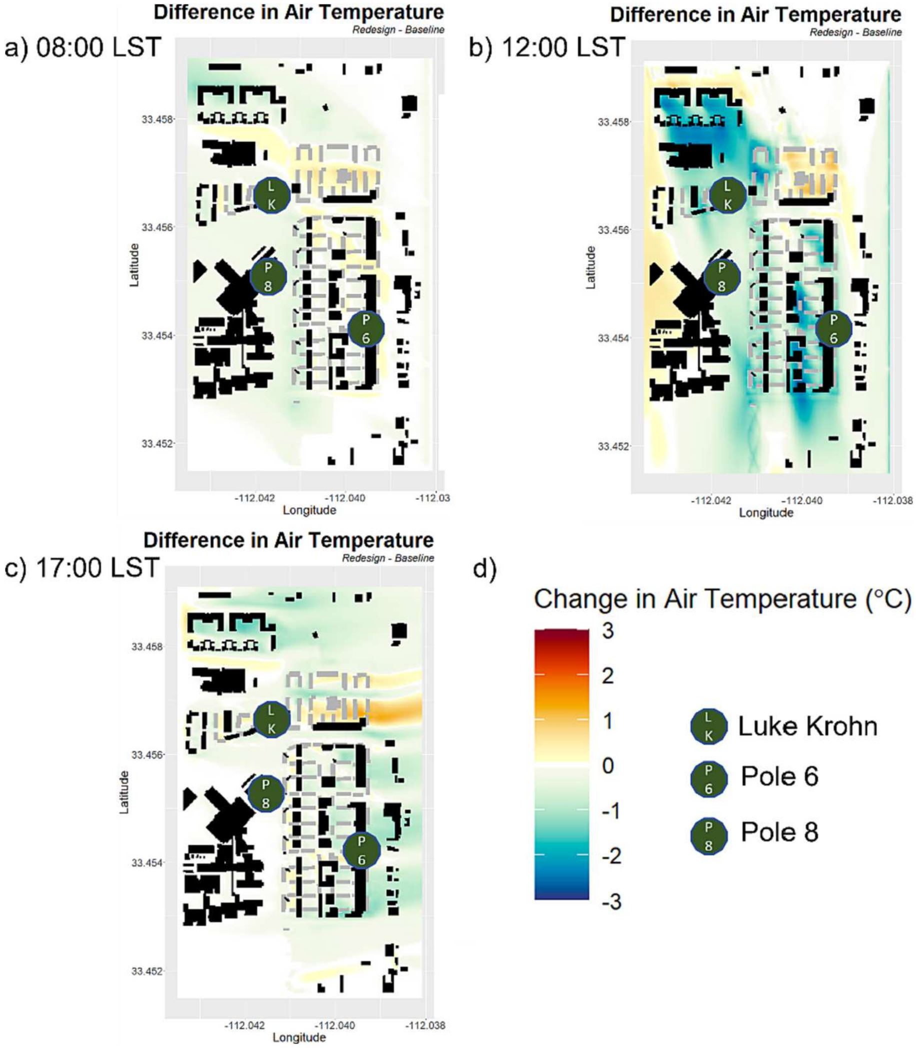


Fig. 7. T_{air} difference plots; a) is 8:00 LST, b) is 12:00 LST, c) is 17:00 LST, and d) is the legend.

Table 4

Averaged T_{air} effect of the redevelopment plans in Edison Eastlake. The values are minimum, maximum, mean, and standard deviation across the entire domain at each hour of output from ENVI-met simulations. Locations where buildings were exchanged for open space (or open space replaced with buildings) were removed from consideration as the temperature difference is not indicative of change in reality.

Air Temperature Difference Over Domain				
Hour	Min (°C)	Max (°C)	Mean (°C)	St.Dev. (°C)
0800	−1.29	0.88	−0.14	0.21
0900	−2.19	0.88	−0.28	0.38
1000	−2.91	1.86	−0.41	0.69
1100	−2.58	1.35	−0.48	0.60
1200	−2.76	1.20	−0.47	0.65
1300	−2.40	1.17	−0.33	0.59
1400	−1.34	1.23	−0.20	0.26
1500	−2.11	0.57	−0.27	0.40
1600	−2.03	1.28	−0.21	0.43
1700	−1.54	1.40	−0.23	0.36
1800	−1	0.76	−0.14	0.19
1900	−0.43	0.43	−0.05	0.08
2000	−0.23	0.23	−0.01	0.05

surfaces and materials and control the microclimate to decrease thermal conditions at best or at least maintain similar thermal conditions as less dense LCZ. These benefits are localized and connected to increases in vegetation across the domain, decreases in impervious surfaces, changes in urban configuration (mostly building height and density), and the creation of a vegetated corridor. Despite these changes, when considering the impact of the redesign at each cell in the domain, there are hotspots associated with south-facing portions of buildings.

Future development (and redevelopment) in Phoenix and the surrounding metropolitan area can leverage the knowledge gained from this study as our results show a strong downwind cooling effect from increasing building heights, the addition of trees, and the expansion of the park. Given the hot, arid climate of the region, these modifications have rapid impacts on the sensible heat of the neighborhood which is propagated downwind even under low (<5 m/s) wind conditions. Ultimately, the increase in density of the City in a desert climate is beneficial to providing cool spots within the hot urban desert climate. Historically, we have seen this at work in cities in the Middle East, North Africa, and southern Europe where streets were narrower, and buildings were built close together to shade each other from the solar irradiance in semi-arid and arid climates.

4.2. Implications for marginalized residents and communities

In many cities, legacies of environmental racism (such as redlining) are intimately linked with disparities in heat exposure and heat vulnerability (Hoffman et al., 2020). Urban climatologists working with cities develop more nuanced approaches that go beyond simple surface and air temperature (T_{air}) measures (Hamstead et al., 2020) because heat has both objective and subjective components as a place-based hazard (Wilhelmi and Hayden, 2010), which disproportionately burdens vulnerable communities (Buijs et al., 2016; Harlan et al., 2006; Hoffman et al., 2020; Jesdale et al., 2013; Santamouris et al., 2007). Recently, cities in the US and Europe have begun to seek out city-university-community partnership opportunities to rectify injustices through redeveloping whole neighborhoods with a bent toward creating healthy urban environments for residents (Guardaro et al., 2020).

A growing number of cities pursue these justice-oriented, place-based heat mitigation partnerships that include participatory action research approaches (Guardaro et al., 2020). Kemmis et al. (2014) describe a critical participatory action research as one where those communities that are impacted most are equal partners in researching root causes and impacts to provide meaningful pathways toward urban resilience. For Kemmis et al. (2014), this type of research aims to transform activities and outcomes for greater self-understanding of community members, practitioners, decision-makers, and stakeholders who are impacted by practice, in this case the practice of heat mitigation. Importantly, social formations that orient and inform practice discourses including "… the things that are done (doings), and the patterns of social relationships between those involved and affected (relatings)" are critical factors to developing desirable place-based social transformations (Kemmis et al., 2014, pp. 16–17). Participatory action research integrates recognition (e.g., greater understanding of residents lived experiences), procedural (e.g., community members participate in research and actions), and distributional (e.g., thermal comfort is prioritized for hot neighborhoods with heat vulnerable residents) justice dimensions (Fekih et al., 2021; Guardaro et al., 2022; Guardaro et al., 2020; Langemeyer and Connolly, 2020; Puansurin et al., 2018; Tonekaboni et al., 2019) to better assess, plan, and implement mitigation strategies for urban resilience (Ahern, 2011; Meerow et al., 2016).

The results of this study show that the implementation of heat mitigation strategies within the Edison Eastlake neighborhood are resulting in cooler T_{air} within and downwind of the neighborhood. Thus, choosing to implement these redesign elements within a marginalized community is aiding in providing more thermal equity by improving the thermal environment of the neighborhood relative to its wealthier (and whiter) neighborhood counterparts in other parts of the City.

4.3. Limitations

The limitations of this research are split between two main categories: modeling and observational methodology. From a modeling perspective, the constant wind speed and direction required by ENVI-met resulted in limited ability to consider how these two variables perform relative to the observational data. Model performance issues could result from a combination of challenges including ENVI-met's ability to model building heights appropriately and the impact of proximity to solar panels and AC units that are not considered in the model. Future work could apply the new functionality of forcing solar radiation, wind speed, and wind direction to determine whether the model is adequately estimating these variables and assess whether this would improve the prediction of air or mean radiant temperature as suggested by Gál and Kántor (2020). Soil moisture remains a concern with the model. Despite using measured data from a representative environment (Middel et al., 2014), the uniformity of soil temperature/moisture (spatially and temporally) is not representative to the domain and uncertainties remain as to how much these factors influence the output of the model. Given previously published work that points to issues of ENVI-met not handling extreme heat in tropical and arid climates (Crank et al., 2020; Roth and Lim, 2017), the multi-site methodology to validation helps identify potential sources of error in the modeling parameters and in the modeling of the domain. However, the rooftop weather stations performed poorly relative to the pole-mounted stations. Computational time is another limiting factor for the model. The computational demand creates a high computational cost barrier to quickly assess issues in the model and study the impact of small parameterization changes Jandaghian (2018).

The transect methodology limits model validation accuracy. The traverses through the domain did not occur rapidly enough to complete each traverse within a 30-min sampling window. Any data outside of that window was discarded due to time de-trending concerns. The continuous traverse may not be the best methodology for validating a numerical model. The constant motion may have resulted in observation points being a few meters off in addition to tall buildings creating GPS inaccuracies greater than the buffer of ~1.5 m used to complete the spatial join of the traverse data to the ENVI-met data, resulting in errors when comparing to the static cells in ENVI-met. A "fuzziness" in spatio-temporal resolution is a significant limitation in model accuracy. Future work would benefit with taking a different traverse approach, for example, pre-selecting stops to allow the instruments to adjust to the location (Crank et al., 2020; Middel et al., 2021; Middel and Krayenhoff, 2019).

The dry conditions in a hot, arid environment make green space cooling a challenge to model (see points on the soil moisture parameterization). The hot, arid environment also contributes to the hotspots found in both parking lots and in parks. In Arizona, the primary driver of heat load (T_{air} and T_{MRT}) is shortwave radiation from the sun. Thus, hotspots can occur in green spaces that are inadequately shaded. Though somewhat counter-intuitive, the potential for grass to become a hotspot is often an overlooked caveat to the benefits of green space within the literature. Middel et al. (2021) point out the importance of shade to the thermal environment, even against the introduction of general green space. Additionally, the tree canopy modeled is for the first few years after redevelopment completion with a canopy at a height of only 5 m and minimal crown. Thus, the actual redesign may perform better than these results as maturing vegetation may provide additional evaporative cooling to the environment, converting more of the incoming solar radiation into latent heat flux, instead of converting to sensible heat (thus warming the surface and subsequently the ambient air). These two limitations in the modeling prevent evidence of greater cooling potentials. Future research could explore these limitations by re-simulating the neighborhood with a mature tree canopy as well as modeling future climate scenarios to simulate what impact climate change might have on the neighborhood (Erlwein et al., 2021). The ability to make assumptions on the cooling of the urban microclimate relies on the use of the delta method which is commonly used in global climate modeling studies and some micro, *meso*, and regional studies (Hijmans et al., 2005; Jandaghian, 2018; Middel et al., 2021; Navarro-Racines et al., 2020; Wu et al., 2018). Further improvement of the model is necessary to examine the impact of changes in soil moisture and the potential of irrigated surfaces in ENVI-met.

The estimation of surface temperature and the parameterization of heat transfer from surface materials is another area of concern that several studies have noted (Crank et al., 2020; Gál and Kántor, 2020; Maggiotto et al., 2014; Park, 2011). As Gál and Kántor (2020) pointed out, the overnight longwave upwelling radiation creates significant issues with T_{MRT} and with T_{air}. Thus, the night-time conditions are not considered in this study. Given that the nocturnal impacts of the increased vegetation were not explored, the generalizability of the redesign outcomes are restricted as modeling efforts did not consider whether the green space and tree canopy would elevate minimum temperatures overnight. However, another shortcoming in this vein is that the model does not permit buildings to retain heat once the solar radiation is removed from the model (i.e., at night). As such, ENVI-met is insufficient at modeling overnight conditions in urban areas; therefore, ENVI-met should only be used for daytime simulations until that parameterization in the model is updated and the question of overnight urban microclimate conditions from green space is capable of being studied (and then validated) using the model.

The model would further benefit from more information driving the model. The current configuration struggles to handle the forcing of variable wind speed, wind direction, or solar radiation when using large domains. These variables play a vital role in the variability of urban climate. Phoenix has a significant wind shift during the day, particularly in the summer. The model struggles with rapidly changing wind direction and wind speeds that are higher (and lower) than is typically seen under stable conditions in Germany. Thus, the hourly wind speed and direction forcing data had to be modified significantly just to allow the model to run. No analysis of the wind metrics was considered as a result. Additionally, the model parameterizes soil moisture to be constant across the domain. This is problematic when examining an urban space that has streets, sidewalks, bare soil, and grass within the domain. Each of these surfaces will have very different soil moisture contents, and this becomes increasingly noticeable and influential in hotter and drier climates such as Phoenix.

Finally, this model is limited to estimating the cooling based on conditions measured with the existing neighborhood design. To fully understand the effectiveness, future work must be done to collect data on the ambient environment once the redevelopment is complete. This can be done at varying times into the future (such as 1, 5, and 10 years after development completion) to examine the impact of maturing trees on the environment. This future work can then reassess the ENVI-met model to determine how well the model represents post-construction in-situ conditions. The evaluation only considered the plans the city is using in their redevelopment. Future work could build on this and explore how different design elements might have performed better than the final plan. These lines of research could consider the implementation of solar panels, reconfiguration of the buildings to create more of an enclosed green space, and even an addition of blue infrastructure (such as a pond or pool) to determine its effectiveness at cooling the neighborhood. Flood irrigation is a practice utilized by the Phoenix Parks and Recreation Department to irrigate the Edison Park. Thus, future research can explore the impacts of the bi-weekly flooding events in the summer on the thermal environment.

Each line of future research must grapple with the limitations surrounding ENVI-met modeling which have already been discussed. For radiative flux and load modeling (such as those necessary for T_{MRT} or thermal comfort modeling), SOLWEIG shows more consistent results; however, SOLWEIG (Lindberg et al., 2008) does not account for fluid flow (as is done in CFD models). When only considering fluid flow, OpenFOAM and other CFD models perform better (but do not perform well at estimating radiative loads) (Jänicke et al., 2021). New software (such as PALM-4 U) are showing promise at bringing together the fluid flow and radiative flux components of modeling for urban climate (Geletič et al., 2021; Maronga et al., 2020; Resler et al., 2021; Yang et al., 2021), but have not proven their capability to out-perform ENVI-met. Thus, ENVI-met remains the most accessible model with the capacity for modeling radiative flux/load and fluid flow within a neighborhood domain with complex geometries of buildings, surfaces, and vegetation. More work is needed to develop open-source models that can combine fluid flow and radiative flux which improve our current modeling capabilities for micro-scale urban climate analysis.

5. Conclusion

This study quantified the microclimate impact of redevelopment plans for a Phoenix neighborhood using in situ observations and microscale atmospheric modeling. Using the redesign plans from the City of Phoenix, the Edison Eastlake neighborhood redevelopment was modeled in ENVI-met and compared to the baseline model to assess the efficacy of the redevelopment at providing thermal benefits from the environment to the community. Validation results show that ENVI-met represented intra-neighborhood variability of T_{air} well but was less capable of simulating the spatial distribution of TMRT. Yet, results of this validation analysis provide sufficient evidence that the model can be used to model a neighborhood redesign and compare between designs to assess the effect of urban design modifications to the local microclimate using the delta method.

The City's interventions of increased building height and number of trees both result in larger shaded areas of the domain, resulting in modest cooling of the general neighborhood, with pockets of cooling from shade on the order of 1–3 °C for ambient T_{air}. Results confirm the possibility of cooling through redevelopment or at least increasing building densities while maintaining thermal conditions. Yet, there is a limit to the impact of the redesign for immediate cooling of the urban microclimate to the spatial reorganization of cool and hot spots. Although the Edison Eastlake neighborhood is unlikely to experience oasis-like levels of cooling and lushness from this redevelopment (particularly in the initial few years as the trees grow), this kind of redevelopment does provide pockets of cooling and greening that are respites during a hot, dry summer even as building density increases. These respites may not be quantitatively large in terms of space or cooling, yet they do provide the opportunity for thermal comfort to be experienced by all.

As the redevelopment takes place, there is a continued need to engage the community in the process and practice of heat mitigation, seeking to better understand their needs and why those needs exist. This includes the sharing of results with the City of Phoenix's new Office of Heat Response and Mitigation as well as with the community. Continuing participatory action research approaches with community engaged post-redevelopment analysis and mutual understanding can aid in determining the effectiveness of the plan for addressing those community needs. Urban planning and design are primarily a process of reorganizing physical spaces to benefit communities. In this case, the re-development is expressly using public funds (HUD, 2016; 2016a; HUD Awards Choice Neighborhood Grants to 10 Cities, 2016) to improve the comfort, attractiveness, and livability of the neighborhood. Yet, if the outcome of the redevelopment does not adequately address the expressed needs of the community, is this a public service? Is this an appropriate use of public funds? These are questions that cannot be addressed by this research, yet the results of this study can better inform the community, designers, and the City on the anticipated overall success aspects of the redevelopment at providing the cooling benefits sought by the residents and potential future hot spots that may need to be addressed in the future. Quay (2010) suggests these types of approaches can contribute a better understanding of the urban systems to help the City and community members anticipate governance needs longer term.

This kind of work is needed from the urban climate community, to share knowledge and expertise with community members, professionals in city planning offices and design firms. The urban climate community also gains valuable community and practitioner knowledge of living with and working with the heat hazard, but this work must also be shared with the community. Participatory science and co-production of knowledge is essential to designing (and re-designing) cities to be healthy urban environments for all. Ultimately, the benefit or burden of this redevelopment will be assessed and experienced by those living in this neighborhood. An aspirational hope for this redevelopment is to disrupt and repair legacies of environmentally racist practices and the subsequent heat burden on Edison Eastlake residents, but the success of this remains to be seen.

Regardless of where the burden falls, this study suggests that cooling is possible and as such, the City can use their design plans to cool the neighborhood (even just slightly) and begin to address the broader concerns that residents have in Phoenix of thermal inequity and the need for neighborhood planning that is designed for the benefit of all. This study can also be used to aid the City in identifying areas, methods and a culture of practice for fine tuning their design to provide shade elements for pedestrian hot spots as well as to reduce energy costs in the hot summer months. These two outcomes are directly connected to residents' experiences in the neighborhood and the livability of the community. As the City is attempting to overhaul this neighborhood to improve the residents' experience and attract more active transit-minded residents, these metrics of thermal comfort and energy usage are essential to ensuring the City is reaching their goals for the community. Using green and grey shade infrastructure to improve the urban microclimate of a neighborhood could provide cooling to the outdoor environment, as found in this research, in addition to various other community benefits such as lowered energy costs in the summer, community engagement, and nature contact.

Declaration of Competing Interest

The authors declare they have no actual or potential competing financial interests.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to thank Dr. Leah Jones-Crank for helping with figure creation and photo editing. The authors would also like to thank the reviewers and editors of this manuscript at various stages for their insights and critiques that have made this manuscript stronger and clearer in its communication of scientific merit. The authors also acknowledge the funding for this project by the Healthy Urban Environments Initiative with Arizona State University and the Maricopa County Industrial Development Authority under grant number AWD00033817. Finally, the authors would like to acknowledge the City of Phoenix's Housing Department for being receptive to our study and feedback on the redevelopment, as well as acknowledging the residents and community advocates who has worked hard to ensure that the voices and opinions of the residents are both heard and respected.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2023.101702.

References

Acero, J.A., Arrizabalaga, J., 2016. Evaluating the performance of ENVI-met model in diurnal cycles for different meteorological conditions. Theor. Appl. Climatol. https://doi.org/10.1007/s00704-016-1971-y.

Ahern, J., 2011. From fail-safe to safe-to-fail: sustainability and resilience in the new urban world. Landsc. Urban Plan. 100, 341–343. https://doi.org/10.1016/j.landurbplan.2011.02.021.

American Society of Mechanical Engineers, 2007. J. Fluids Eng. Transact. ASME ser I 108. https://doi.org/10.1115/1.2960953.

Aram, F., Solgi, E., Garcia, E.H., Mosavi, A., 2020. Urban heat resilience at the time of global warming: evaluating the impact of the urban parks on outdoor thermal comfort. Environ. Sci. Eur. 32, 117. https://doi.org/10.1186/s12302-020-00393-8.

Blocken, B., Stathopoulos, T., Carmeliet, J., 2007. CFD simulation of the atmospheric boundary layer: wall function problems. Atmos. Environ. 41, 238–252. https://doi.org/10.1016/j.atmosenv.2006.08.019.

Bolin, B., Grineski, S., Collins, T., 2005. The geography of despair: environmental racism the the making of South Phoenix, Arizona, USA. Hum. Ecol. Rev. 12, 156–168.

Bowler, D.E., Buyung-Ali, L., Knight, T.M., Pullin, A.S., 2010. Urban greening to cool towns and cities: a systematic review of the empirical evidence. Landsc. Urban Plan. 97, 147–155. https://doi.org/10.1016/j.landurbplan.2010.05.006.

Bruse, 2009. ENVI-met Manual [WWW Document]. ENVI-met. URL. http://www.envi-met.info/documents/onlinehelpv3/cnt.htm (accessed 6.29.18).

Bruse, M., Fleer, H., 1998. Simulating surface-plant-air interactions inside urban environments with a three dimensional numerical model. Environ. Model. Softw. 13, 373–384. https://doi.org/10.1016/S1364-8152(98)00042-5.

Buijs, A.E., Mattijssen, T.J.M., Van der Jagt, A.P.N., Ambrose-Oji, B., Andersson, E., Elands, B.H.M., Steen Møller, M., 2016. Active citizenship for urban green infrastructure: fostering the diversity and dynamics of citizen contributions through mosaic governance. Curr. Opin. Environ. Sustain. 22, 1–6. https://doi.org/10.1016/j.cosust.2017.01.002.

Colter, K.R., Middel, A.C., Martin, C.A., 2019. Effects of natural and artificial shade on human thermal comfort in residential neighborhood parks of Phoenix, Arizona, USA. Urban For. Urban Green. 44 https://doi.org/10.1016/j.ufug.2019.126429.

Conservancy, T.N., 2019. Heat Action Planning Guide for Neighborhoods of Greater Phoenix (Reports).

Cornelius, K., 2018. Here Comes the Sun - PHOENIX Magazine. Phoenix Magazine.

Crank, P.J., Sailor, D.J., Ban-Weiss, G., Taleghani, M., 2018. Evaluating the ENVI-met microscale model for suitability in analysis of targeted urban heat mitigation strategies. Urban Clim. 26, 188–197. https://doi.org/10.1016/j.uclim.2018.09.002.

Crank, P.J., Middel, A., Wagner, M., Hoots, D., Smith, M., Brazel, A., 2020. Validation of seasonal mean radiant temperature simulations in hot arid urban climates. Sci. Total Environ. 749, 141392. https://doi.org/10.1016/j.scitotenv.2020.141392.

Declet-Barreto, J., Brazel, A.J., Martin, C.A., Chow, W.T.L., Harlan, S.L., 2013. Creating the park cool island in an inner-city neighborhood: heat mitigation strategy for Phoenix, AZ. Urban Ecosyst. 16, 617–635. https://doi.org/10.1007/s11252-012-0278-8.

Eliasson, I., Upmanis, H., 2000. Nocturnal airflow from urban parks-implications for city ventilation. Theor. Appl. Climatol. 66, 95–107. https://doi.org/10.1007/s007040070035.

Erlwein, S., Zölch, T., Pauleit, S., 2021. Regulating the microclimate with urban green in densifiying cities: joint assessment on two scales. Build. Environ. 205 https://doi.org/10.1016/j.buildenv.2021.108233.

Fekih, M.A., Bechkit, W., Rivano, H., Dahan, M., Renard, F., Alonso, L., Pineau, F., 2021. Participatory air quality and urban Heat Islands monitoring system. IEEE Trans. Instrum. Meas. 70 https://doi.org/10.1109/TIM.2020.3034987.

Fields, A., Miles, J., Fields, Z., 2012. Discovering Statistics Using R.

Forouzandeh, A., 2018. Numerical modeling validation for the microclimate thermal condition of semi-closed courtyard spaces between buildings. Sustain. Cities Soc. 36, 327–345. https://doi.org/10.1016/j.scs.2017.07.025.

Gál, C.V., Kántor, N., 2020. Modeling mean radiant temperature in outdoor spaces, a comparative numerical simulation and validation study. Urban Clim. 32, 100571. https://doi.org/10.1016/j.uclim.2019.100571.

Geletič, J., Lehnert, M., Krč, P., Resler, J., Krayenhoff, E.S., 2021. High-resolution modelling of thermal exposure during a hot spell: a case study using PALM-4U in Prague, Czech Republic. Atmosphere 12, 175. https://doi.org/10.3390/atmos12020175.

Guardaro, M., White, J., Berisha, V., Hondula, D.M., Beute, S., Feagan, M., Grimm, N.B., Messerschmidt, M., Perea, M., Ramirez, M., Olivas, E., Beuno, J., Crummey, D., Winkle, R., Rothballer, K., Mocine-McQueen, J., Maurer, M., Coseo, P., Crank, P.J., McCauley, L., 2019. Creating Urban Heat Solutions in the Valley of the Sun.

Guardaro, M., Messerschmidt, M., Hondula, D.M., Grimm, N.B., Redman, C.L., 2020. Building community heat action plans story by story: a three neighborhood case study. Cities 107. https://doi.org/10.1016/j.cities.2020.102886.

Guardaro, M., Hondula, D.M., Ortiz, J., Redman, C.L., 2022. Adaptive capacity to extreme urban heat: the dynamics of differing narratives. Clim. Risk Manag. 35 https://doi.org/10.1016/j.crm.2022.100415.

Hamstead, Z., Coseo, P., AlKhaled, S., Boamah, E.F., Hondula, D.M., Middel, A., Rajkovich, N., 2020. Thermally resilient communities: creating a socio-technical collaborative response to extreme temperatures. Build. Cities 1, 218–232. https://doi.org/10.5334/bc.15.

Harlan, S.L., Brazel, A.J., Prashad, L., Stefanov, W.L., Larsen, L., 2006. Neighborhood microclimates and vulnerability to heat stress. Soc. Sci. Med. 63, 2847–2863. https://doi.org/10.1016/j.socscimed.2006.07.030.

Hawkins, E., Osborne, T.M., Ho, C.K., Challinor, A.J., 2013. Calibration and bias correction of climate projections for crop modelling: an idealised case study over Europe. Agric. For. Meteorol. 170, 19–31. https://doi.org/10.1016/j.agrformet.2012.04.007.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965–1978. https://doi.org/10.1002/joc.1276.

Hoffman, J.S., Shandas, V., Pendleton, N., 2020. The effects of historical housing policies on resident urban areas. Climate 8, 1–15.

Höppe, P., 1992. A new procedure to determine the mean radiant temperature outdoors. Wetter und Leben 44, 147–151.

Howard, L., 1833. Climate Of London, 3.

HUD, 2016a. Choice Neighborhoods - Department of Housing and Urban Development. U.S. Department of Housing & Urban Development, pp. 6–7.

HUD, 2016b. Choice Neighborhoods 2016 Implementation Grant Awards [WWW Document]. URL. https://www.hud.gov/sites/dfiles/PIH/images/FY17 (accessed 1.1.18).

HUD Awards Choice Neighborhood Grants to 10 Cities. ForeignAffairs.co.nz, 2016.

Huttner, S., 2012. Further Development and Application of the 3D Microclimate Simulation ENVI-met, 147. Johannes Gutenberg-Universitat in Mainz, Mainz.

Jandaghian, Z., 2018. Effects of Increasing Surface Reflectivity on Urban Climate (Air Quality and Heat-Related Mortality).

Jänicke, B., Milošević, D., Manavvi, S., 2021. Review of user-friendly models to improve the urban Micro-climate. Atmosphere 12, 1291. https://doi.org/10.3390/atmos12101291.

Jenerette, G.D., Harlan, S.L., Buyantuev, A., Stefanov, W.L., Declet-Barreto, J., Ruddell, B.L., Myint, S.W., Kaplan, S., Li, X., 2016. Micro-scale urban surface temperatures are related to land-cover features and residential heat related health impacts in Phoenix, AZ USA. Landsc. Ecol. 31, 745–760. https://doi.org/10.1007/s10980-015-0284-3.

Jesdale, B.M., Morello-Frosch, R., Cushing, L., 2013. The racial/ ethnic distribution of heat risk-related land cover in relation to residential segregation. Environ. Health Perspect. 121, 811–817. https://doi.org/10.1289/ehp.1205919.

Kemmis, S., McTaggart, R., Nixon, R., 2014. The Action Research Planner: Doing Critical Participatory Action Research, The Action Research Planner: Doing Critical Participatory Action Research. https://doi.org/10.1007/978-981-4560-67-2.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Köppen-Geiger climate classification updated. Meteorol. Z. 15, 259–263. https://doi.org/10.1127/0941-2948/2006/0130.

Krayenhoff, S.E., Broadbent, A.M., Zhao, L., Georgescu, M., Middel, A., Voogt, J.A., Martilli, A., Sailor, D., Erell, E., 2021. Cooling hot cities: a systematic and critical review of the numerical modelling literature. Environ. Res. Lett. 16 https://doi.org/10.1088/1748-9326/abdcf1.

Langemeyer, J., Connolly, J.J.T., 2020. Weaving notions of justice into urban ecosystem services research and practice. Environ. Sci. Pol. 109, 1–14. https://doi.org/10.1016/j.envsci.2020.03.021.

Lee, H., Mayer, H., 2016. Validation of the mean radiant temperature simulated by the RayMan software in urban environments. Int. J. Biometeorol. 60, 1775–1785. https://doi.org/10.1007/s00484-016-1166-3.

Lindberg, F., Holmer, B., Thorsson, S., 2008. SOLWEIG 1.0 - modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. Int. J. Biometeorol. 52, 697–713. https://doi.org/10.1007/s00484-008-0162-7.

Maggiotto, G., Buccolieri, R., Santo, M.A., Leo, L.S., Di Sabatino, S., 2014. Validation of temperature-perturbation and CFD-based modelling for the prediction of the thermal urban environment: the Lecce (IT) case study. Environ. Model. Softw. 60, 69–83. https://doi.org/10.1016/j.envsoft.2014.06.001.

Mahmoud, A.H.A., 2011. Analysis of the microclimatic and human comfort conditions in an urban park in hot and arid regions. Build. Environ. 46, 2641–2656. https://doi.org/10.1016/j.buildenv.2011.06.025.

Maronga, B., Banzhaf, S., Burmeister, C., Esch, T., Forkel, R., Fröhlich, D., Fuka, V., Gehrke, K.F., Geletič, J., Giersch, S., Gronemeier, T., Groß, G., Heldens, W., Hellsten, A., Hoffmann, F., Inagaki, A., Kadasch, E., Kanani-Sühring, F., Ketelsen, K., Khan, B.A., Knigge, C., Knoop, H., Krč, P., Kurppa, M., Maamari, H., Matzarakis, A., Mauder, M., Pallasch, M., Pavlik, D., Pfafferott, J., Resler, J., Rissmann, S., Russo, E., Salim, M., Schrempf, M., Schwenkel, J., Seckmeyer, G., Schubert, S., Sühring, M., von Tils, R., Vollmer, L., Ward, S., Witha, B., Wurps, H., Zeidler, J., Raasch, S., 2020. Overview of the PALM model system 6.0. Geosci. Model Dev. 13, 1335–1372. https://doi.org/10.5194/gmd-13-1335-2020.

Meerow, S., Newell, J.P., Stults, M., 2016. Defining urban resilience: a review. Landsc. Urban Plan. 147, 38–49. https://doi.org/10.1016/j.landurbplan.2015.11.011.

Middel, A., Krayenhoff, E.S., 2019. Micrometeorological determinants of pedestrian thermal exposure during record-breaking heat in Tempe, Arizona : Introducing the MaRTy observational platform. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2019.06.085.

Middel, A., Hab, K., Brazel, A.J., Martin, C.A., Guhathakurta, S., 2014. Impact of urban form and design on mid-afternoon microclimate in Phoenix local climate zones. Landsc. Urban Plan. 122, 16–28. https://doi.org/10.1016/j.landurbplan.2013.11.004.

Middel, A., Chhetri, N., Quay, R., 2015. Urban forestry and cool roofs: assessment of heat mitigation strategies in Phoenix residential neighborhoods. Urban For. Urban Green. 14, 178–186. https://doi.org/10.1016/j.ufug.2014.09.010.

Middel, A., Turner, V.K., Schneider, F.A., Zhang, Y., Stiller, M., 2020. Solar reflective pavements-a policy panacea to heat mitigation? Environ. Res. Lett. 15 https://doi.org/10.1088/1748-9326/ab87d4.

Middel, A., AlKhaled, S., Schneider, F.A., Hagen, B., Coseo, P., 2021. 50 grades of shade. Bull. Am. Meteorol. Soc. 1–35. https://doi.org/10.1175/bams-d-20-0193.1.

Mills, G., 2013. Urban climatology: history, status and prospects. Urban Clim. 10, 479–489. https://doi.org/10.1016/j.uclim.2014.06.004.

Navarro-Racines, C., Tarapues, J., Thornton, P., Jarvis, A., Ramirez-Villegas, J., 2020. High-resolution and bias-corrected CMIP5 projections for climate change impact assessments. Sci. Data 7. https://doi.org/10.1038/s41597-019-0343-8.

Ng, E., Chen, L., Wang, Y., Yuan, C., 2012. A study on the cooling effects of greening in a high-density city: an experience from Hong Kong. Build. Environ. 47, 256–271. https://doi.org/10.1016/j.buildenv.2011.07.014.

Oke, T.R., Mills, G., Christen, A., Voogt, J.A., 2017. Urban climates, Urban Climates. Cambridge University Press. https://doi.org/10.1017/9781139016476.

Park, S., 2011. Human-Urban Radiation Exchange Simulation Model by Supervisory Committee Human-Urban Radiation Exchange Simulation Model, p. 241.

Puansurin, K., Wongtragoon, U., Singchan, B., Suwanmaneepong, S., 2018. The study of participatory monitoring of air quality and urban heat, case study Udon Thani province, Thailand. Int. J. Agricult. Technol. 14, 1693–1708.

Quay, R., 2010. Anticipatory governance. J. Am. Plan. Assoc. 76, 496–511. https://doi.org/10.1080/01944363.2010.508428.

Resler, J., Eben, K., Geletič, J., Krč, P., Rosecký, M., Sühring, M., Belda, M., Fuka, V., Halenka, T., Huszár, P., Karlický, J., Benešová, N., Ďoubalová, J., Honzáková, K., Keder, J., Nápravníková, Š., Vlček, O., 2021. Validation of the PALM model system 6.0 in a real urban environment: a case study in Dejvice, Prague, the Czech Republic. Geosci. Model Dev. 14, 4797–4842. https://doi.org/10.5194/gmd-14-4797-2021.

Roth, M., Lim, V.H., 2017. Evaluation of canopy-layer air and mean radiant temperature simulations by a microclimate model over a tropical residential neighbourhood. Build. Environ. 112, 177–189. https://doi.org/10.1016/j.buildenv.2016.11.026.

Santamouris, M., Kapsis, K., Korres, D., Livada, I., Pavlou, C., Assimakopoulos, M.N., 2007. On the relation between the energy and social characteristics of the residential sector. Energ. Build. 39, 893–905. https://doi.org/10.1016/j.enbuild.2006.11.001.

Santamouris, M., Ban-weiss, G., Osmond, P., Paolini, R., Synnefa, A., Cartalis, C., Muscio, A., Zinzi, M., Morakinyo, T.E., Ng, E., Tan, Z., Takebayashi, H., Sailor, D., Crank, P., Taha, H., Pisello, A.L., Rossi, F., 2018. Progress in urban greenery mitigation science – assessment methodologies advanced technologies and impact on cities. J. Civ. Eng. Manag. 24, 638–671. https://doi.org/10.3846/jcem.2018.6604.

Simon, H., Heusinger, J., Sinsel, T., Weber, S., Bruse, M., 2021a. Implementation of a lagrangian stochastic particle trajectory model (Lasttram) to simulate concentration and flux footprints using the microclimate model ENVI-met. Atmosphere 12. https://doi.org/10.3390/atmos12080977.

Simon, H., Sinsel, T., Bruse, M., 2021b. Advances in simulating radiative transfer in complex environments. Appl. Sci. 11, 5449. https://doi.org/10.3390/app11125449.

Sinsel, T., Simon, H., Broadbent, A.M., Bruse, M., Heusinger, J., 2021. Modeling the outdoor cooling impact of highly radiative "super cool" materials applied on roofs. Urban Clim. 38, 100898. https://doi.org/10.1016/j.uclim.2021.100898.

Stewart, I.D., Oke, T.R., 2012. Local climate zones for urban temperature studies. Bull. Am. Meteorol. Soc. 93, 1879–1900. https://doi.org/10.1175/BAMS-D-11-00019.1.

Taleghani, M., Crank, P.J., Mohegh, A., Sailor, D.J., Ban-Weiss, G.A., 2019. The impact of heat mitigation strategies on the energy balance of a neighborhood in Los Angeles. Sol. Energy 177, 604–611. https://doi.org/10.1016/j.solener.2018.11.041.

Thorsson, S., Rocklöv, J., Konarska, J., Lindberg, F., Holmer, B., Dousset, B., Rayner, D., 2014. Mean radiant temperature - a predictor of heat related mortality. Urban Clim. 10, 332–345. https://doi.org/10.1016/j.uclim.2014.01.004.

Tonekaboni, N.H., Kulkarni, S., Ramaswamy, L., 2019. Edge-based anomalous sensor placement detection for participatory sensing of urban Heat Islands. In: 2018 IEEE International Smart Cities Conference. ISC2 2018. https://doi.org/10.1109/ISC2.2018.8656705.

Upmanis, H., Eliasson, I., Lindqvist, S., 1998. The influence of green areas on nocturnal temperatures in a high latitude city (Goteborg, Sweden). Int. J. Climatol. 18, 681–700. https://doi.org/10.1002/(SICI)1097-0088(199805)18:6<681::AID-JOC289>3.0.CO;2-L.

Wilhelmi, O.V., Hayden, M.H., 2010. Connecting people and place: a new framework for reducing urban vulnerability to extreme heat. Environ. Res. Lett. 5 https://doi.org/10.1088/1748-9326/5/1/014021.
Willmott, C.J., 1981. On the validation of models. Phys. Geogr. 2, 184–194. https://doi.org/10.1080/02723646.1981.10642213.
Willmott, C.J., Matsuura, K., 2006. On the use of dimensioned measures of error to evaluate the performance of spatial interpolators. Int. J. Geogr. Inf. Sci. 20, 89–102. https://doi.org/10.1080/13658810500286976.
Wu, Y., Zhong, P., Xu, B., Zhu, F., Fu, J., 2018. Evaluation of global climate model on performances of precipitation simulation and prediction in the Huaihe River basin. Theor. Appl. Climatol. 133, 191–204. https://doi.org/10.1007/s00704-017-2185-7.
Yang, S.-Q., Feng, L., Tian, H.-H., Liu, Y.-X., 2021. Urban micro-scale thermal environment simulation supported by UAV thermal infrared data. Environ. Sci. 42 https://doi.org/10.13227/j.hjkx.202005254.
Zhang, L., Zhan, Q., Lan, Y., 2018. Effects of the tree distribution and species on outdoor environment conditions in a hot summer and cold winter zone: a case study in Wuhan residential quarters. Build. Environ. 130, 27–39. https://doi.org/10.1016/j.buildenv.2017.12.014.
Zhao, T.F., Fong, K.F., 2017. Characterization of different heat mitigation strategies in landscape to fight against heat island and improve thermal comfort in hot-humid climate (part II): evaluation and characterization. Sustain. Cities Soc. 35, 841–850. https://doi.org/10.1016/j.scs.2017.05.006.