

# Characterizing Individual Occupation and Travel Heat Burdens through Exposure and Reprieve

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# CHARACTERIZING INDIVIDUAL OCCUPATION AND TRAVEL HEAT BURDENS THROUGH EXPOSURE AND REPRIEVE

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## ABSTRACT

Heat exposure for urban populations has become more prevalent as the temperature and duration of heat waves in cities increase. Occupational exposure to heat is a major concern for personal health, and excessive heat exposure can cause devastating outcomes. While occupational heat exposure studies have traditionally focused on environmental temperature, work intensity, and clothing, little is known about the daily exposure profile of workers, including their daily travel and working patterns. This study developed a novel measure of exposure and reprieve dynamics, the moving average hourly exposure (MAHE) to balance short-duration but high-exposure events and capture the inability to reprieve from exposure events. MAHE was assessed by combining an activity-based travel model (ABM) and the Occupational Requirement Survey to simulate urban workers' total daily heat exposure. The simulation considers daily travel, work schedules, and outdoor working frequency. The simulation was conducted for 1 million workers in Phoenix, Arizona, using Mean Radiant Temperature (MRT). The results show that 53% to 89% of workers in Phoenix's construction, agriculture, transportation, raw material extraction, and entertainment industries will likely experience MAHE over 38°C for at least an hour. These industries also have up to 34% of the laborers exposed to over 7 hours of continuous 38°C and above MAHE exposure. The location of the most intense heat exposure was identified near the downtown and central business districts, significantly different from the home locations of the workers in suburban and rural areas. Formulating the MAHE balances heat risk events with cooling benefits and aids in identifying individuals with prolonged high heat exposure.

Keywords: Urban, climate, occupational heat exposure, personal heat exposure

# 1 INTRODUCTION

As extreme heat events become more prevalent, affecting the health and well-being of urban populations, workers in certain occupations are often exposed to these harsh conditions for prolonged periods (Lee et al., 2022). Extended heat exposure can increase fatigue, diminish concentration, and lower alertness among workers (Varghese et al., 2018). Physical labor further strains workers in high-temperature environments by increasing their heart rate, blood flow, and sweating (Uejio et al., 2018). Further, clothing increases heat load due to being a thermal insulator and lowering sweat evaporation (Gao et al., 2018). These factors can increase workplace injuries during hot weather (Varghese et al., 2018). Outdoor workers, such as construction, agriculture, and military personnel, are among the most vulnerable to heat-related occupational injuries (Ioannou et al., 2022). Projected increases in extreme heat events may increase the risk of adverse health outcomes and occupational injuries among workers and reduce labor productivity (Kjellstrom et al., 2009). Understanding the individual-level experience of extreme heat is essential for building resilience to this significant public health challenge.

Simulating heat exposure at the individual-level has been a powerful tool for understanding people's experience in hot environments. Individuals are exposed to heat when engaging in outdoor travel and activities (i.e., walking, biking, gardening, and farming) since these pursuits typically occur in environments without temperature control systems (Hoehne et al., 2018; Hondula & Kuras, 2021; Karner et al., 2015; Li, Chester, Hondula, et al., 2023; Li, Chester, Middel, et al., 2023). *Personal heat exposure* (PHE) simulations capture human and environmental interactions and estimate the heat individuals experience while interacting with their surroundings (El-Sayed et al., 2012; Luke & Stamatakis, 2012; Tracy et al., 2018). Personal travel and activity behaviors (i.e., people's travel times, their indoor/outdoor activities schedules, and the path they take) and the built environment (i.e., local temperature and shading) are commonly considered in the PHE simulation (Karner et al., 2015; Li, Chester, Hondula, et al., 2023). Attributes related to personal physical tolerance to heat, such as individual metabolic rate, sweat rate, and body surface area impact on heat storage, are also considered in some PHE studies. (Glass et al., 2015). Finally, heat exposure simulations at the individual-level have also been powerful tools for identifying personal heat risk across populations (Kuras et al., 2017).

In addition to extreme heat exposure, heat vulnerability must be considered to understand the risk of extensive exposure and the reprieve effects of resting and cooling. Heat reprieve has been important for people to recover from excessive exposure and effectively prevent adverse health outcomes. Regulatory agencies, such as the Occupational Safety and Health Agency (OSHA) and the National Institute for Occupational Safety and Health (NIOSH), have recommended increasing rest time and hydration in a cooler environment for workers who are exposed to excessive temperature to have the opportunity to recover and mitigate the risk of excessive heat exposure (NIOSH, 2016; OSHA, 2015). OSHA also recommends controlling exposure time under high temperatures by implementing work/rest schedules, which guide the intervals for relief during rest periods (NIOSH, 2016). Outside of work, individuals cope with the extreme heat by leaving the hot area for a reprieve, such as cooling centers (Guardaro et al., 2022). Despite the importance of heat reprieve, incorporating its effects in the analysis of heat exposure is a complicated endeavor, and most studies on heat exposure currently do not account for the impact of heat reprieve in their simulations.

This study proposes a simulation framework to estimate workers PHE, considering the risk of extensive heat exposure and the benefits of reprieve (air conditioning). Exposure and reprieve should be

combined to recognize the complexity of interactions as individuals interact with their environments – outdoor heat and indoor air conditioning. The personal Moving Average Hourly Exposure (MAHE) is introduced to estimate the heat risk and reprieve effect quantitatively. Various travel patterns and activities, such as commuting and working, characterize an individual’s daily schedule. MAHE is calculated as the duration-weighted mean ambient MRT of people’s daily events and stored at the end of the hourly period. Formulating the MAHE in such a way can, on one hand, captures heat risk events such as outdoor activities and active trips in which people directly interact with ambient (outdoor) temperature. Conversely, MAHE can balance out high ambient temperature but short-duration events by considering the heat reprieve from activities that take place in cooler conditions, like indoor activities and in-vehicle trips, which usually occur under air conditioning and are frequently considered to have cooling benefits (Guardaro et al., 2022). The population with high MAHE, or several hours of continuous high MAHE, is likely unable to get enough reprieve from high-ambient temperature exposure events. The simulated MAHE is then presented to assist in identifying the demographic distribution of individuals with high and long-duration heat exposure.

## 2 METHODOLOGY

To estimate worker PHE using MAHE, three primary steps are followed: generating synthetic agents, modeling exposure during personal activities and trips, and summarizing individual MAHE. Synthetic agents, representing people in the study area, include individual occupational characteristics and daily activity/trip sequences. The exposure calculation for individual activities and trips captures the duration of these events, and the mean radiant temperature (MRT) people experienced. MAHE is then computed based on the sequence of daily events for synthetic populations, and the heat exposure is then associated with each activity and trip. This study leverages the previous research from Li, Chester, Hondula, et al. (2023) which created the synthetic population from the fine-scale transportation activity-based model (ABM) for the Phoenix Metropolitan Area (PMA) (the *Icarus* model). Using MRT the heat exposure of active trip for the synthetic population was previously simulated in Li, Chester, Middel, et al. (2023). Heat exposure of work-related activities is estimated using the Occupational Requirement Survey (ORS) (U.S. Bureau of Labor Statistics, 2024) and the MRT profile (Buo et al., 2023). All other activities and travel events are assumed indoors or under a constant 26.6°C air conditioning temperature (Li, Chester, Hondula, et al., 2023).

The synthetic population and their exposure during active travel were simulated using *Icarus*, a Python-based platform for PHE simulation (Li, Chester, Hondula, et al., 2023; Li, Chester, Middel, et al., 2023). The following subsection explains the *Icarus* model and the methodology employed to generate synthetic individuals and simulate their exposure during active travel, as in Li, Chester, Hondula, et al. (2023) and Li, Chester, Middel, et al. (2023). The specifics of occupational heat exposure estimation are also provided, followed by the formulation of the MAHE calculation. All details regarding the case study in the Phoenix Metropolitan area are provided subsequent to overall travel and occupational heat exposure methods.

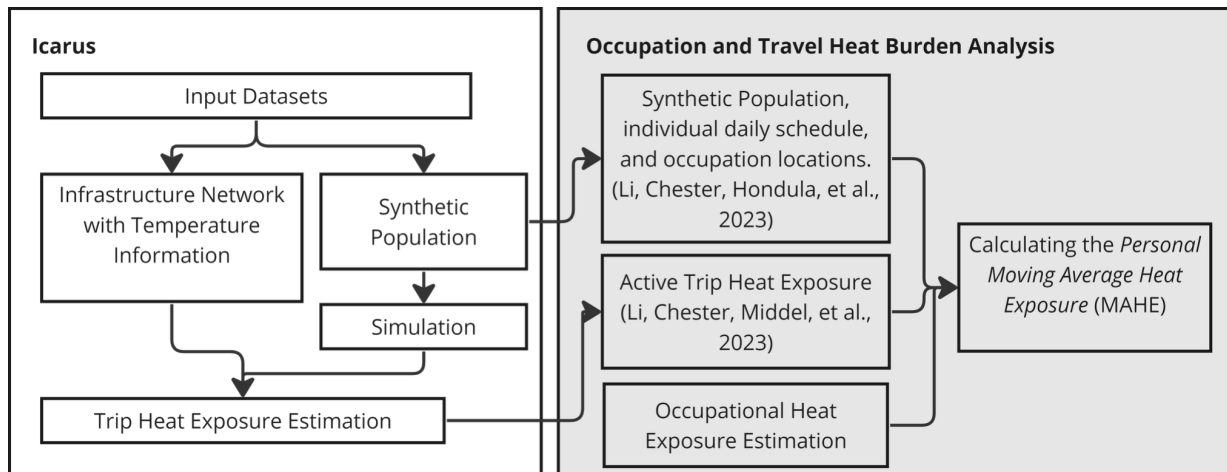


Figure 1. *Icarus Framework and Occupation and Travel Heat Burden Analysis. Icarus work from Li, Chester, Hondula, et al. (2023) and Li, Chester, Middel, et al. (2023) is shown in the white box (left), which provides the baseline simulation of MRT exposure from the synthetic population using ABM data. The contribution of this work (right, grey box) to assess active trip heat exposure plus occupational heat exposure culminates in the moving average hourly exposure (MAHE).*

### 2.1 *Icarus, synthetic population, and estimated travel heat exposure*

Icarus is a Python model designed to simulate PHE using ABM and supplementary datasets (Li, Chester, Hondula, et al., 2023). Previously, Icarus has been used to simulate people's outdoor travel heat exposure (Li, Chester, Middel, et al., 2023). It calculates PHE in selected study areas by initially generating synthetic agents through ABM, then models the exposure of these agents to heat during their activities and travel within the infrastructure network, incorporating space-time temperature data (Li, Chester, Hondula, et al., 2023). Icarus operates effectively with the region-specific ABM as its primary input. ABMs are disaggregated travel demand models that simulate individual and household travel behaviors (i.e., walking, biking, driving, and public transit) and activities (i.e., working, shopping, and staying at home), considering demographic details, social and economic engagements, and the location and timing of various events (Bowman & Ben-Akiva, 2001). The synthetic population of Icarus is directly replicated from the ABM of the study region, which consists of individual demographic features and event sequences.

Active trip exposure is calculated in Icarus by identifying travel patterns and estimating the ambient temperature individuals experience when that trip happens (Li, Chester, Hondula, et al., 2023; Li, Chester, Middel, et al., 2023). Icarus requires the ingestion of the study region parcel data, transportation network, and spatiotemporal heterogeneous MRT and air temperature data to simulate. Since ABMs are designed for transportation planning, the event locations are usually presented at the traffic Micro Analysis Zones (MAZs) level (Parsons Brinckerhoff, 2010). Parcel data are introduced to downscale the ABM event locations from MAZs to land parcels. The downscaling process entails determining the type of events, like working, shopping, or staying at home, and randomly allocating parcels within the event's MAZs to the specified event. As such, the origins and destinations of the active trips can be refined to land parcels. Icarus then routes active trips on the roadway network obtained from OpenStreetMap (OSM) (OpenStreetMap Contributors, 2015). To calculate the heat exposure of active trip, Icarus parses the spatiotemporal heterogeneous temperature data to streets and

parcels and then calculates the average temperature individuals experience along the roadways when the trip occurs.

## 2.2 *Estimation of outdoor work and heat exposure*

Occupational activities occur in diverse environments, and those that happen outdoors will likely be exposed to higher overall heat loads (particularly air temperature and MRT) due to direct exposure to the sun and environmental conditions that amplify heat effects without cooling strategies. While the ABM provides information regarding people's activity type and location, key information regarding whether an activity is indoor/ outdoor is not present. We assume all non-work related activities, such as shopping and dining out, are carried out indoors in an air-condition controlled environment with a constant MRT temperature of 26.6°C. As this study focuses on occupational exposure, we assume only work-related activities will likely occur outdoors. Whether work-related activity happens indoor/outdoor is further assessed based on the workers' industry. Labor-intensive jobs, such as agricultural and construction, are more likely to be outdoor than office work. The ORS survey is used to estimate the duration and frequency of outdoor work in different industries.

The occupational outdoor working *duration* and *frequency* are estimated based on industries and data from the ORS surveys (U.S. Bureau of Labor Statistics, 2024). The occupational outdoor duration indicates the length of time workers spend outside, and the occupational outdoor frequency denotes the percentage of individuals working outside. The ORS, released by the Bureau of Labor Statistics, provides job-specific outdoor *duration* and *frequency* for 468 occupations in the U.S. economy (U.S. Bureau of Labor Statistics, 2024).

### 2.2.1 *Estimation of Outdoor Work Duration*

To estimate outside time of outdoor workers, the qualitative outdoor *duration* is converted to quantitative values based on the exposure categories described in the ORS. Among the 468 occupations in ORS, 69% were identified with five detailed outdoor duration categories: '*not exposed to outdoors*', '*seldom*', '*occasionally*', '*frequently*', and '*constantly*'. The remaining 31% of occupations were classified as '*not exposed to outdoor*' or '*outdoor*'. The five-level classification is frequently used in occupations with intense outdoor working conditions, such as construction, farming, truck drivers, etc., while the ORS indoor/outdoor classification is more likely to be used in occupations with less outdoor exposure, like finance advisors, wholesale, etc. This study defines the five-level exposure categories corresponding to the outdoor duration from 0 minutes/hour (not exposed to outdoor) to 48 minutes/hour (constantly outdoor), with a 12 minutes/hour increment for each intermediate level. Exposure types labeled as '*not exposed to outdoor*' or '*outdoor*' correspond to 0 minutes/hour or 10 minutes/hour of outdoor work, respectively. As such, the qualitative job-specific outdoor duration provided by the ORS is converted into quantitative values, which are subsequently utilized in calculating occupational heat exposure.

### 2.2.2 Estimation of the outdoor working frequency

The ORS occupations are grouped by the industries given in ABM to estimate synthetic populations' outdoor frequency. While the ORS follows the Standard Occupational Code (SOC), the ABM follows the code designed by the North American Industry Classification System (NAICS). The SOC and NAICS are two different industry and occupation classification systems, and there is a lack of standardized methods to crosswalk these two systems (NIOSH, 2023). The ORS provides 468 occupations with outdoor exposure information, while ABM only has 24 industry categories (Parsons Brinckerhoff, 2010). The disparity between the number of occupations and industry categories further complicates the direct application of outdoor frequencies provided by the ORS to the synthetic population generated via ABM. Therefore, the ORS's detailed occupational outdoor exposure data are categorized by industry type to estimate the outdoor frequency for different industries. Given the different occupation classification codes utilized by ORS and ABM, a manual review of the ORS's 468 occupations was conducted, allocating them to the 24 industry sectors in ABM based on job descriptions, responsibilities, and typical industry associations. Specifically, 51 occupations from the ORS, which were most relevant to the job landscape in Arizona, were identified and organized into the 24 industry categories as defined in ABM. The classification details are provided in Appendix I.

The industry-level outdoor frequency is estimated using the occupational outdoor frequency from ORS. This study assumes an equal number of workers in each occupation, estimating the industry's outdoor exposure frequency by averaging the exposure frequencies of the selected job types within the industry, as shown in Equation 1.

$$r_{f,i} = 1/N \sum_{o=1}^N r_{f,o} \quad \text{eq(1)}$$

$f \in \{\text{'constant'}, \text{'frequent'}, \text{'occasional'}, \text{'seldom'}, \text{'outdoor'}, \text{'not exposed'}\}$

where  $r$  is the exposure frequency for each industry,  $f$  represents the exposure frequency category, which belongs to 'constantly', 'frequently', 'occasionally', 'seldom', 'outdoor', or 'not exposed',  $i$  represents the industry type given in ABM, such as *Transportation* in the previous example,  $o$  is the collection of occupations given in ORS that belong to the industry,  $i$ , and  $N$  is the number of occupation types in industry  $i$ . Table 1 provides an example of the *Transportation* industry exposure profile. ABM has people working in the *Transportation* industry, while ORS contains two occupation types for the *Transportation* industry: heavy and tractor-trailer truck drivers and light truck drivers. The exposure frequency profile for the two occupation types is combined using Equation 1 to get the exposure profile for the general transportation industry.

Table 1. Example of industry-level exposure frequency estimation

		exposure frequency profile				
		not exposed	seldom	occasionally	frequently	constantly
occupations from ORS	Heavy and tractor-trailer truck drivers	7.70%	21.10%	63.10%	5.90%	2.20%
	Light truck drivers	9.70%	0.00%	82.10%	4.30%	3.90%
industry from ABM	<b>Transportation</b>	8.70%	10.60%	72.60%	5.10%	3.10%

### 2.2.3 Occupational Heat Exposure Estimation

The heat exposure at work is estimated over working hours, considering the job type, outdoor frequency, duration, and the respective temperatures in each environment. It essentially averages the temperature exposure based on the time an individual spends indoors and outdoors and the thermal exposure in each environment. The temperature at worker job locations is obtained by spatially joining the temperature with the job location identified for the synthetic population. The occupational heat exposure for each working hour is calculated as Eq (2).

$$E_i = \frac{T_i * d_o + (60 - d_o) * 26.6}{60} \quad \text{eq(2)}$$

$$i = \left\{ \delta \in \mathbb{N} \mid \begin{cases} \left\lfloor \frac{t_{start}}{60} \right\rfloor \ll \delta \ll \left\lfloor \frac{t_{end}}{60} \right\rfloor & , \text{if } t_{end} - t_{start} > 60 \\ \delta = \left\lfloor \frac{t_{start}}{60} \right\rfloor & , \text{if } t_{end} - t_{start} \leq 60 \end{cases} \right\}$$

where  $E_i$  refers to the heat exposure an individual experiences at hour  $i$ ,  $T_i$  is the outdoor MRT at the job location during hour  $i$ , and the MRT captures the temperature difference in the diverse outdoor environment, including shading.  $T_{start}$  and  $T_{end}$  are the work start and end times, respectively, presented in minutes from 00:00, and  $D_o$  is the occupational outdoor duration, estimated based on worker's industry. The frequency of workers staying outdoors is used to stochastically select individuals' outdoor working duration,  $D_o$ . For example, a worker in the transportation sector is calculated to have a 3.1% chance of being outdoors 'continuously', which equals 48 minutes every working hour. This method allows for estimating occupational heat exposure by considering the nature of the job and the frequency of outdoor activity, as derived from the ORS. The calculated individual occupational heat exposure and the time spent on the job for every working hour are stored for the MAHE calculation.

Since the industries used in ABM have long names and it is difficult to plot their whole name, thus, we abbreviated each industry's name as follows: agriculture (NAICS 11), extraction (NAICS 21), utility (NAICS 22), and construction (NAICS 23) are shortened as *Agr*, *Ext*, *Uti*, and *Con*. Both Manufacturing I (NAICS 31) and Manufacturing II (NAICS 32) are comprised of businesses producing products from materials' chemical, mechanical, or physical transformation. These two industries are shortened as *Man I* and *Man II*. We use *Who* to represent the wholesale sector (NAICS 42). Retail sectors I and II (NAICS 44, 45) are represented as *Ret I*, and *Ret II*. Transportation (NAICS 48) and transportation-postal/warehousing (NAICS 49) sectors are demonstrated as *Tran*, and *Tran-P*. Information (NAICS 51), Finance I and II (NAICS 52, 53), and Professional I to III (NAICS 54-56) are presented as *Inf*, *Fin I*, *Fin II*, *Prof I*, *Prof II*, and *Prof III* respectively. Education (NAICS 61), medical, health care, and social assistance (NAICS 62) sections are presented as *Edu*, and *Med*. The Arts, Entertainment, and Recreation sector (NAICS 71) is shortened to *Art*. The entertainment sector (NAICS 72) is shortened as *Ent*. Services (NAICS 81) and administrative/military (NAICS 92) industries are abbreviated as *Ser* and *Adm*. The abbreviation is also shown in Table 3 as the bolded industry names.

### 2.2.4 Moving Average Hourly Exposure (MAHE)

People doing outdoor events, both travel and activities, can get heat reprieve after staying in a lower-temperature environment after extensive heat exposure. MAHE is introduced to capture the complexity of the outdoor/indoor alternation and the heat exposure and reprieve sequences. MAHE is

computed as the average MRT an agent is exposed to over each hour of the simulation's history. For instance, the MAHE at 5:00 calculates the mean heat exposure from 4:00 to 5:00 on the simulation day. The introduction of MAHE cancels the noise from high-temperature exposure but short-duration events. People may experience intensive heat exposure during their day if they briefly stay outdoors where the MRT is high. However, taking refuge indoors after the outdoor events offers them a temporary break and reduces the impact of the previous intensive heat exposure. Carrying out the personal MAHE calculation for the population level can identify the subgroups who potentially cannot get a reprieve after extensive heat exposure.

### 2.2.5 Phoenix Case Study

Our study context is the PMA. As the sixth largest metropolitan region in the US, the PMA has a population of 4.2 million (United States Census Bureau, 2023) and an average of 175 days per year with a daily maximum air temperature exceeding 32°C (90°F) (Lawrimore et al., 2016). Occupational heat exposure has been a persistent problem in Phoenix, as the hot summer stresses the labor force working or traveling outdoors (Bandala et al., 2023; Hoehne et al., 2019). PHE was estimated and extensively studied by Li, Chester, Hondula, et al. (2023) and Li, Chester, Middel, et al. (2023) providing a critical foundation for future analyses. Li, Chester, Middel, et al. (2023) focused their analysis in the 2,070 km<sup>2</sup> (800 square miles) urbanized region, a 6% area of the PMA (Figure 2) since the high resolution MRT data were only available for in the area. This study uses the datasets utilized by Li et al., 2023a, b, and confines the analysis to the same study region (Figure 2) for consistency.

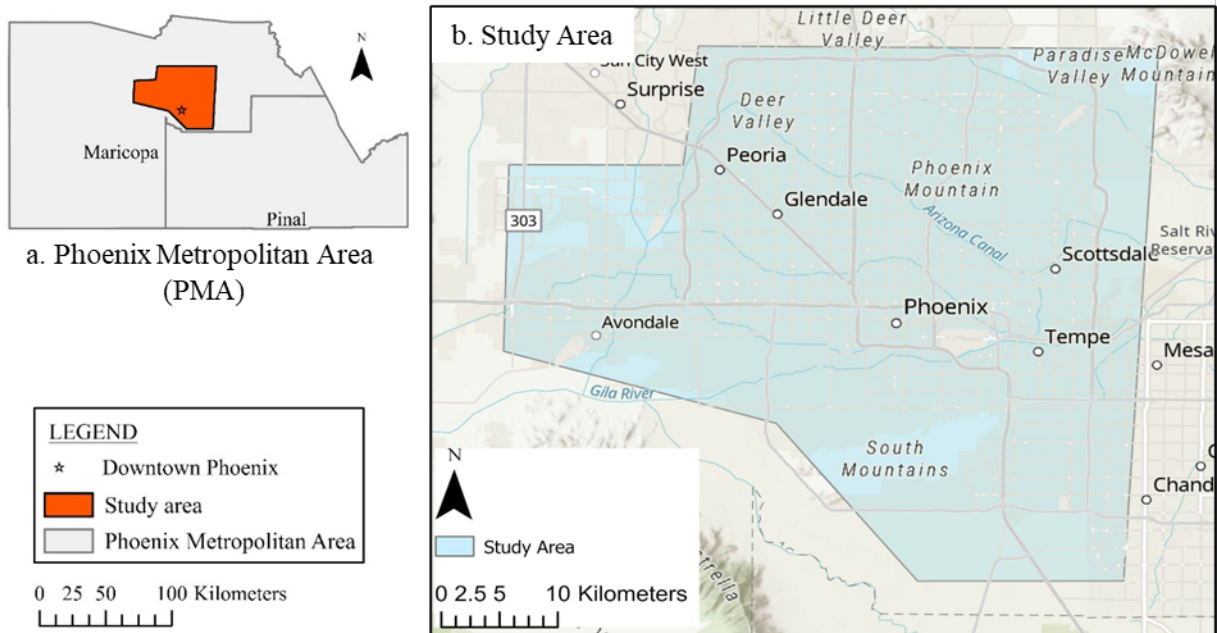


Figure 2. Map of the Phoenix Metropolitan Area (PMA) (a) and study area (b).

### 2.2.6 ABM data and parcel data

The ABM used for the study contains 3.8 million people and their daily trips and activities in the PMA (MAG, 2013; Parsons Brinckerhoff, 2010). Despite covering only 6% of the land area of the PMA, the study region (Figure 2) accommodates 53% of the ABM population and 979,970 workers living and working in the region. The ABM was generated based on the 2010 household travel survey;

the demographics, travel behaviors, and activity patterns reflect a typical working day in the surveyed year. Consequently, the total population count is lower than the reported 2023 PMA population.

The 2018 Maricopa County land parcel data (Maricopa County Assessor's Office, 2018) is introduced to assist in downscaling the ABM event locations from Metropolitan Analysis Zones (MAZs) to land parcels. MAZs are commonly employed for transportation planning purposes, but they lack the granularity necessary to analyze heat exposure at the street and building levels. Parcel data, which contains the building category, land use type, and the location of the building, are obtained for the study area to assist in refining the location of the events to more specific building areas instead of MAZs in the city. The analysis involves spawning the events to parcels within the event's MAZ. As such, the location of events, which are also the origins and destinations of trips, can be refined to land parcels. The roadway network for the Phoenix metropolitan area, which is used for trips to route on, was retrieved from OSM (OpenStreetMap Contributors, 2015).

### 2.2.7 *Temperature data*

MRT is used to estimate event heat exposure. The MRT refers to the total heat load of all surrounding surfaces an individual perceives (Middel & Krayenhoff, 2019). MRT values are presumed to be equivalent to the Air Temperature ( $T_{\text{air}}$ ) before sunrise and after sunset (Thornton et al., 2021).  $T_{\text{air}}$ , refers to the hot/cold of the surrounding air, and is used to estimate the temperature when MRT is unavailable. This study uses simulated hourly MRT raster layers at a 1-meter resolution for June 27, 2012, spanning from 7:00 to 20:00 (Buo et al., 2023). The simulated MRT ranges from 29°C (84°F) to 85°C (185°F). The  $T_{\text{air}}$  on the same simulation date, with a 1-km spatial resolution, is extracted from Daymet data (Thornton et al., 2016) to complement the MRT before 7:00 and after 20:00. The minimum  $T_{\text{air}}$  for the study date was between 16°C (61°F) to 28°C (82°F), while the maximum  $T_{\text{air}}$  was between 27°C (81°F) to 45°C (113°F). Hourly  $T_{\text{air}}$  is calculated using the minimum and maximum  $T_{\text{air}}$  to match the temporal resolution of MRT (Li, Chester, Hondula, et al., 2023).

## 3 RESULTS

We first look at the outdoor frequency estimated from ORS across various industries in the ABM to gain insight into the overall outdoor working frequency and duration of the subjects under study. Then, we dive into the work and travel patterns, such as the start and end of work time, the number of shifts scheduled, and the ratio of people commuting by biking or walking. These factors influence the time and duration workers spend outdoors affecting their exposure to heat. The MAHE is then discussed to identify the ratio of workers who experience high MAHE, and the industries with long-duration and high MAHE exposure. Lastly, we present the job locations of workers with high MAHE to demonstrate the heat vulnerability spatial distribution in the study region.

### 3.1 *Outdoor Working*

Workers in industries reliant on physical labor and direct interaction with physical environments or materials are more likely to experience heat exposure. These industries include extraction, construction, transportation industries, and agriculture. About a quarter of the workforce is in these industries. Overall, 80% to 93% of the workers in these industries have outdoor work

responsibilities (Table 2). Besides the high ratio of outdoor tasks, construction, extraction, and agriculture also have 30% to 43% of workers constantly working outdoors. Meanwhile, service and knowledge-focused industries are less likely to have workers operating outdoors. Industries like medical, administrative, information, postal service, and finance have only 3% to 6% of outdoor workers (Table 2). About one-third of the population in the study region works in these industries. Manufacturing, wholesaling, retailing, utility, and entertainment industries have 23% to 34% of outdoor workers (Table 2).

Table 2. Industry work conditions in the study area, focusing on outdoor exposure, work schedules, and the ratio of workers with high moving average hourly exposure (MAHE)

NAICS Code	Industry	work schedule from ABM <sup>1</sup>			outdoor exposure frequency from ORS <sup>2</sup>						Ratio of workers MAHE pass 38°C at least once
		median continuous working hours	more than two shifts scheduled	walk/bike commute ratio	constant	frequent	occasional	seldom	exposed	not exposed	
23	Construction	7.2	18%	4%	43%	18%	31%	1%		7%	89%
21	Extraction	6.8	25%	5%	43%	18%	31%	1%		7%	88%
48	Transportation	7.1	20%	4%	3%	5%	73%	11%		9%	77%
11	Agriculture	7.3	17%	3%	30%	12%	39%			19%	73%
71	Arts, Entertainment, and Recreation	6.5	18%	6%	20%	9%	25%			38%	53%
72	Entertainment, Accommodation and Food Services	6.4	16%	5%	20%	9%	25%			38%	53%
61	Education	6.8	19%	5%			31%	14%		55%	30%
22	Utility	7.1	22%	4%	4%	4%	15%	10%		67%	23%
92	Administrative/Military	7.4	20%	5%	4%	4%	15%	10%		67%	23%
55	Professional II	6.9	21%	5%	1%	2%	13%	8%		76%	17%
45	Retail II	6.5	17%	6%		3%	9%	23%		66%	13%
44	Retail I	6.8	18%	6%		3%	9%	23%		66%	13%
81	Services	6.6	18%	5%					45%	55%	2%
54	Professional I	7.0	21%	5%					73%	27%	2%
42	Wholesale	7.0	20%	5%					23%	77%	2%
52	Finance I	7.2	21%	5%					3%	97%	1%
53	Finance II	7.0	20%	5%					3%	97%	1%
56	Professional III	7.1	18%	5%					3%	97%	1%
51	Information	7.2	20%	5%					1%	99%	1%
62	Medical, Health Care and Social Assistance	6.9	20%	4%					4%	96%	1%
49	Transportation - Postal/Warehousing	7.1	20%	4%					6%	94%	1%
32	Manufacturing II	7.2	20%	4%					23%	77%	1%
33	Manufacturing III	7.3	20%	4%					23%	77%	1%
31	Manufacturing I	7.0	18%	3%					23%	77%	1%

1. the data are obtained from MAG ABM.

2. the outdoor exposure frequency is estimated using ORS and ABM industries.

3. the ratio is calculated as the number of workers with over 38°C MAHE divided by the total number of workers in the corresponding sector.

### 3.2 Work schedule, occupation, outdoor time, and frequency

Work schedules, such as start/end times and the number of daily shifts, differ across diverse industries. The median work starting time is 8:14. However, entertainment, retail, and SCA workers start their jobs 20 to 48 minutes later. In contrast, management, extraction, and utility workers tend to start their jobs 20 to 25 minutes earlier than the populational median work starting time. The median end working time for the workforce is 16:12, and workers leave work around the same time regardless of the industries. As the outdoor temperature is lower in the mornings, workers may benefit from starting work early, as the heat exposure is lower during commuting and performing outdoor work in the early mornings. Most of the workers in the study region have only one shift in a day (Table 2). The number of shifts per person in a day is counted as the number of working activities tagged in ABM. On average, 81% of the workers have one shift in the simulation day, and 19% have two or more shifts. Extraction industry employers have a higher ratio (25%) of multiple shifts in their working day, while only 16% of entertainment and retail industry workers have multiple shifts in their working day. Commuting patterns in the study region are predominantly characterized by car driving. On average, 5% of workers commute by walking or biking (Table 2). A greater proportion (6%) of individuals in the entertainment and retail sector opt for active transportation for their commute. In contrast, those in the agriculture and manufacturing industries exhibit the lowest ratio (3%) of active trip commuting.

Work schedules impact the time and duration of heat exposure. An early start time, multiple job shifts, and short duration of continuous work can each provide reprieve. Industries such as the construction sector already use strategies like rescheduling the working hours from the daytime to cooler times, such as early morning or midnight, to mitigate heat exposure (Lewis, 2022).

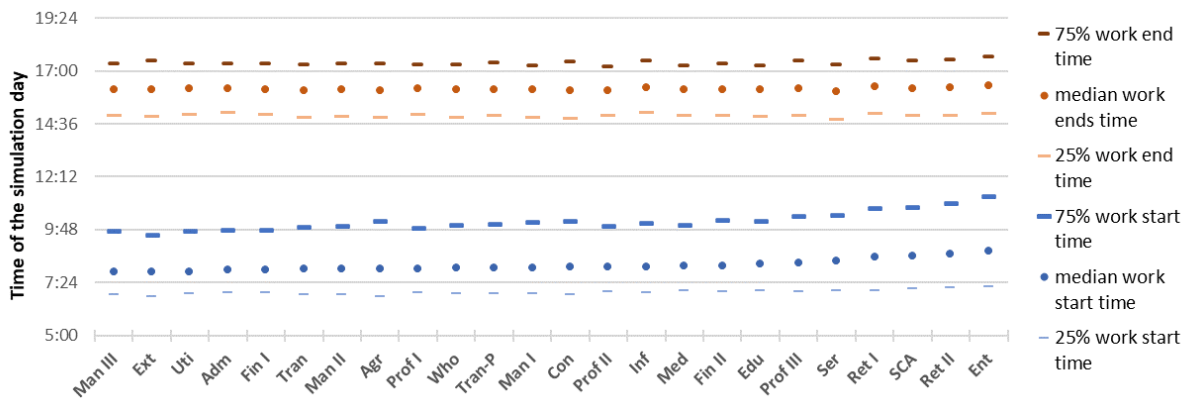


Figure 3. Work start/end times distribution across industries (ranked by median start time), with the manufacturing III sector having the earliest start time and the entertainment sector having the latest work start time. X-axis represents the industries.

### 3.3 Moving Average Hourly Exposure (MAHE)

Most workers experience MAHE below 38°C, with a subset facing elevated MAHE. Figure 4 illustrates the cumulative distribution of the highest MAHE encountered by individuals. During the simulation day, 70% of workers maintained a MAHE under 27°C, while 18% encountered their peak MAHE in the range of 27°C to 37°C. Approximately 12% of workers experienced MAHE exceeding

38°C. The simulation identified the maximum MAHE at 66.8°C between 16:00 and 17:00. Conversely, the minimum MAHE estimated was 20.8°C between 5:00 and 6:00 in the early hours. Here MAHE is calculated with the MRT, which represents the average temperature and radiation of all surrounding surfaces emitted on a person. The value of MAHE could be significantly higher than the ambient air temperature.

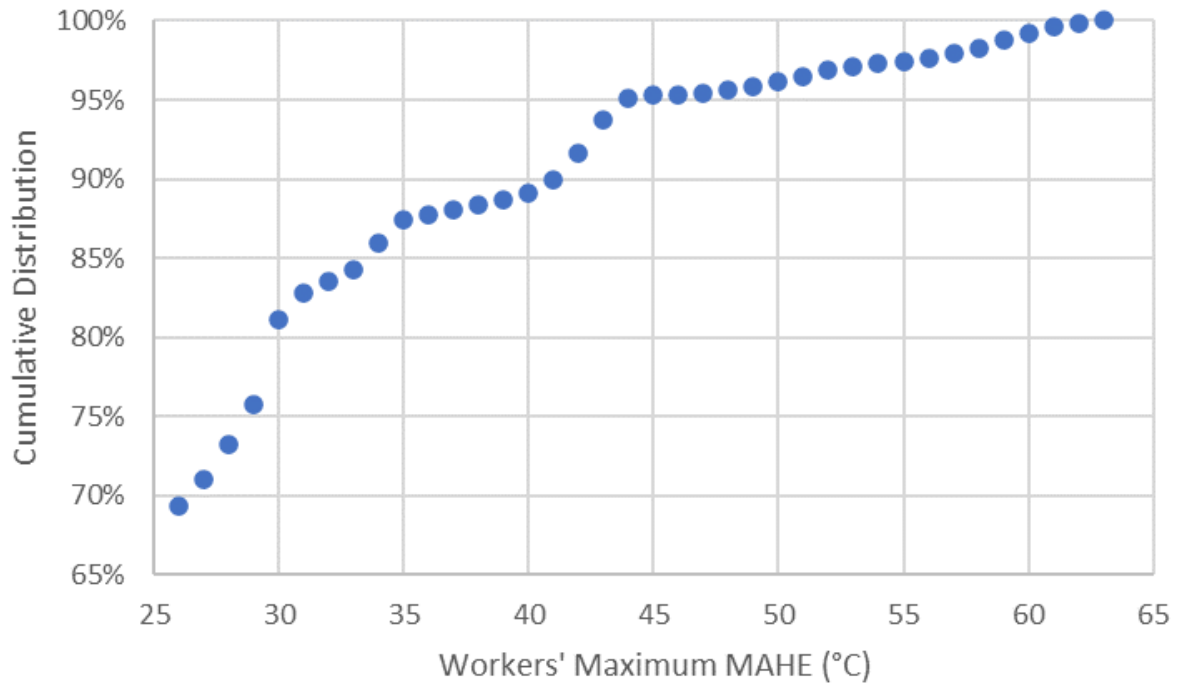


Figure 4. Cumulative distribution of individual maximum MAHE calculated with MRT.

Using the 38°C (100°F) benchmark we identify workers with MAHE over the threshold at least once in the day (Table 2). Industries with a large ratio of outdoor workers are likely to have high MAHE values. 73% to 89% of construction, extraction, transportation, and agriculture workers are exposed to high MAHE for at least one hour of the day (Table 2). Previous studies have consistently highlighted these sectors heightened health risks associated with environmental heat exposure (Calkins et al., 2019; Karthick et al., 2021; Petitti et al., 2013; Spector et al., 2014). Over half of workers in the entertainment, recreation, and food service industries (NAICS 71, 72) have their MAHE over 38°C at least one hour on the simulation day. While the literature has traditionally paid less attention to excessive heat concerns within the entertainment sector, recent reports underscore the pressing need to address heat exposure in the entertainment and service sector, such as music venues (Masley, 2023) and food trucks (Mackovich-Rodriguez, 2023). 23-30 % of the military, utility workers, and educators (NAICS 61, 92, 22) and 13% of the retail sector have their MAHE over the threshold. These industries are traditionally out of the spotlight of excessive heat exposure studies. The other sectors, including the top two employees, medical and professional III, have less than 2% of workers with MAHE over the threshold.

Extended exposure to extreme heat poses substantial health risks for outdoor workers. Industries with a high proportion of workers experiencing MAHE over 38°C also exhibit a high ratio of individuals enduring several hours of continuous high MAHE (over 38°C). Figure 5 highlights the proportion of workers enduring continuous exposure to high MAHE across various industries. It details the range of exposure durations from ‘one hour’ to ‘thirteen hours straight,’ showcasing the continuous period workers face with high MAHE.

Industries such as transportation, extraction, agriculture, and construction exhibit higher percentages of their workforce that are subjected to extended work periods over 38°C MAHE conditions. 11.4% of transportation workers are likely to experience high MAHE over 7 hours straight. 34% of construction workers have MAHE above 38°C for over 7 hours straight. 31% of extraction workers are estimated to have long-duration high MAHE over 7 hours straight. And 20.4% of agricultural workers have long-duration high MAHE over 7 hours.

Service-Commercial and Administrative, Entertainment, Education, Administrative (Adm), Utilities (Uti), and Retail present a different pattern, with lower percentages and shorter continuous working hours under high MAHE (Figure 5). The rest of the industries show the lowest percentages of workers exposed to high heat for extended periods, likely reflecting indoor work environments or jobs with greater control over work schedules and conditions. Less than 1% of their workers experienced one hour of high MAHE, and less than 0.5% had 2 hours of continuous high MAHE exposure (Figure 5).

Multiple reasons, such as job locations, work schedules, and occupation outdoor frequency, impact the long duration and high MAHE profile. Being outdoors frequently is not the only reason for people with several hours of high MAHE. For instance, Construction (Con) and Extraction (Ext) have the same outdoor profile (Table 2). Still, extraction workers (maroon solid line in Figure 5) are more likely to experience longer hours of high MAHE than their construction industry peers (brown dashed line in Figure 5). A complex combination of work schedules, job locations, and travel modes impacts this exposure profile.

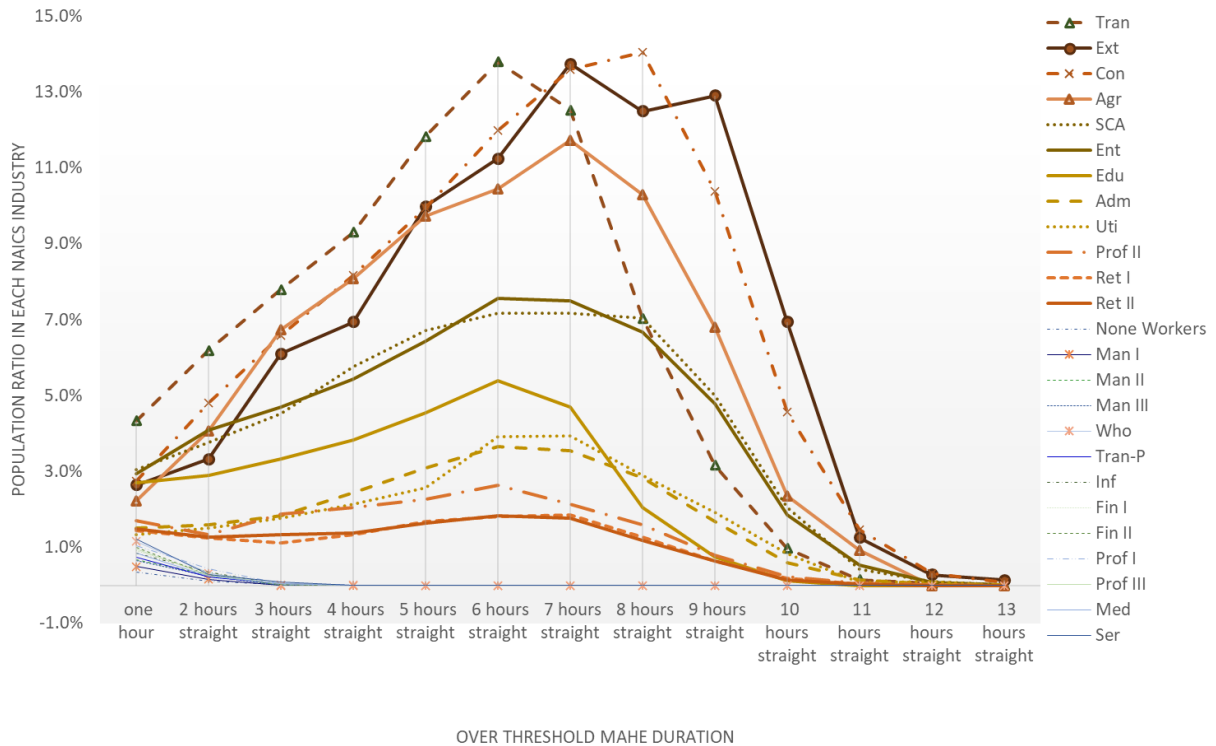


Figure 5. The ratio of workers with continuous over 38°C MAHE in each industry. The x-axis shows the constant high MAHE exposure duration, from only one hour to 13 hours straight. The y-axis shows the ratio of people in each industry exposed to the constant high MAHE.

Worker residential and employment locations differ significantly which impacts MAHE. The simulation indicates that most workers reside in the northern Phoenix and the Tempe to Chandler area (as shown in Figure 6.a), with a population density ranging from 800 to 2,000 people per square kilometer. Conversely, their places of employment are predominantly located in downtown Phoenix and Tempe (illustrated in Figure 6.b), where the density increases to between 1,000 and 6,000 people per square kilometer. These workers spend their daytime hours at their places of employment, which coincides with peak temperature periods, and return to their homes in the cooler evening hours. The necessity of outdoor work in certain job roles increases worker susceptibility to extreme heat at their places of employment.

Analysis of the geographic distribution of workers facing high MAHE reveals a pattern consistent with the broader workforce distribution, focusing on downtown Phoenix and Tempe. By isolating the locations of individuals who experience over one hour of MAHE above 38°C, it becomes apparent that high heat exposure areas coincide with the greatest density of work locations, particularly around downtown Phoenix and Tempe, where density is noted between 51 to 668 people per square kilometer (Figure 6.c). Further examination of locations with high MAHE exposure identifies a pronounced risk in the west and southwest regions of the study area (Figure 6.d), where 25 to 60% of workers in areas with fewer than 100 workers per square kilometer face high MAHE. This contrasts with downtown Phoenix and Tempe, where despite higher worker densities of 2,000 to 6,000 people per square kilometer, only 10 to 25% might experience high MAHE. The areas with a low density of

workers but a high percentage facing significant MAHE overlap with agricultural and industrial zones, indicating a specific vulnerability profile in these regions.

Traditional metrics for assessing heat vulnerability typically focus on demographic (such as race, age, and education) and socioeconomic (such as living alone, economic status, and rates of poverty) factors based on residential locations (Niu et al., 2021). Yet, these assessments may overlook the significant high MAHE that many individuals face outdoors at their work, separate from their living areas. This gap highlights the critical need to include residential and workplace data in vulnerability evaluations, recognizing that high MAHE often occurs away from home, necessitating targeted intervention and adaptation strategies for heat risk mitigation.

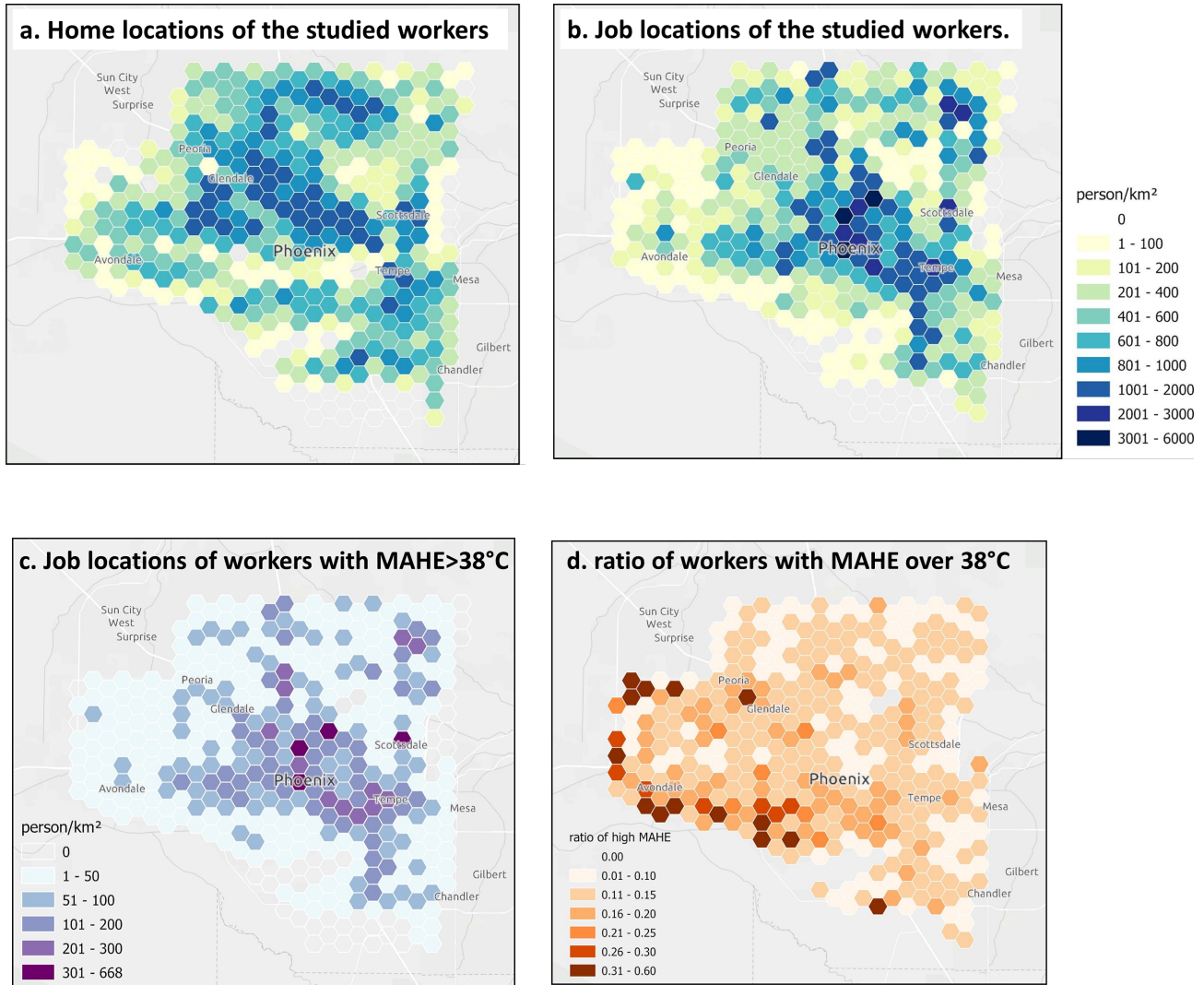


Figure 6. Geospatial analysis of workers' home and job locations relative to high MAHE exposure. a. home location of studied workers. b. Job location of studied workers. c. job locations of workers with MAHE over 38°C at least once. d. ratio of workers with MAHE over 38°C at different

## 4 CONCLUSION AND DISCUSSION

By integrating personal heat exposure simulation with considerations for indoor/outdoor occupation and daily travel/activity patterns, this research provides valuable insights into the personal and industrial level of high heat exposure and the geographical distribution of individuals with heat exposure. MAHE was introduced as a surrogate measure for assessing personal heat exposure, considering both the effects of heat exposure and opportunities for reprieve. By balancing out the short-duration but high-temperature exposure events, the incorporation of MAHE identifies workers susceptible to prolonged heat exposure and allows for considering heat reprieve mechanisms.

The findings reveal significant disparities in heat exposure among workers across different industries, with construction, extraction, transportation, and agriculture sectors facing the highest risks due to their predominantly outdoor nature. Additionally, the entertainment, recreation, and food service industries (e.g., food truck vendors) exhibit a concerning trend, with over half of their employees experiencing MAHE exceeding 38°C for at least one hour. While previous studies have consistently emphasized worker elevated heat health risks in construction, extraction, transportation, and agriculture (Calkins et al., 2019; Varghese et al., 2018), there has been comparatively less attention given to excessive heat concerns within the entertainment, recreation, and food sectors. Identifying high MAHE levels in the entertainment sector aligns with recent reports on the heat risk for these sectors and underscores the urgency to address heat exposure and bolster resilience efforts in these industries (Mackovich-Rodriguez, 2023; Masley, 2023). Moreover, the case study conducted in the Phoenix Metropolitan Area underscores the importance of considering both residential and workplace locations in heat vulnerability assessments. Conventional methods used to evaluate heat stress commonly center on demographic and socioeconomic indicators tied to residential areas (Niu et al., 2021). The analysis reveals distinct geographic patterns in heat exposure at work and residential locations, which would further support adding the occupation-related matrix into future heat stress assessment. The job location of high MAHE workers highlights areas where the workforce faces heightened heat risks and necessitates targeted intervention and adaptation strategies for heat risk mitigation.

Overall, this research contributes to the ongoing efforts to address the health and safety challenges posed by extreme heat events in occupational settings. By incorporating insights from personal heat exposure simulation and MAHE analysis, policymakers, employers, and public health officials can develop proactive measures to protect workers from the adverse effects of heat exposure and enhance resilience to climate-related hazards.

Study limitations are largely from the scoping of the analysis and model capabilities. First, only work-related activities outside were considered and the study excluded nonwork-related outdoor activities. Previous studies have found that nonwork-related activities, such as garden care and sports (Hoehne et al., 2018), are suspected of high heat exposure. The current ABM data does not provide details on non-work-related activities, such as whether they are related to sports or gardening, and are therefore not considered in the exposure analysis. However, future studies can expand to more outdoor activity types when the data are available. Additionally, this study assumes that all indoor environments, including those within vehicles, have a uniform temperature of 26.6°C in the simulation, which oversimplifies the real-world variability of indoor temperatures. In reality, indoor environments vary significantly depending on building insulation, HVAC systems, occupancy levels, and local climate conditions (Zuurbier et al., 2021). By assuming a fixed indoor temperature for all indoor

settings, the simulation fails to accurately represent the range of thermal conditions that individuals may encounter indoors. This oversimplification could lead to inaccurate estimations of heat exposure. To account for the variability in indoor temperatures, future studies could adopt more sophisticated modeling approaches, such as building energy simulation models (Lu et al., 2015) and the indoor air-conditioning availability (Ahn & Uejio, 2022), to capture the indoor temperature (Nahlik et al., 2017). Furthermore, this study relies on synthetic agents generated from activity-based travel models, which may not fully capture the diversity of real-world occupational behaviors and characteristics.

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## **6 AUTHOR CONTRIBUTIONS**

The authors confirm contribution to the paper as follows: Conceptualization: RL, MC, JV. Methodology: RL, MC. Data collection: RL, AM, MC. Analysis: RL. Writing-original draft: RL. Writing-review and editing: RL, MC, JV, DH, AM.

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## APPENDIX I. ABM INDUSTRY CODE AND THE CORRESPONDING OCCUPATIONS IN ORS

ABM Industry	NACIS code	Occupations in ORS
<b>Agriculture</b>	11	Farming, fishing, and forestry occupations
<b>Extraction</b>	21	Construction and extraction occupations
<b>Utility, Administrative</b>	22, 92	All workers
<b>Construction</b>	23	Construction managers, First line supervisors of construction trades and extraction workers, Operating engineers and other construction equipment operators
<b>Wholesale, Manufactureing I, Manufactureing II, Manufactureing III</b>	42,31,32,33	Sales representatives, wholesale and manufacturing, except technical and scientific products, Sales representatives, wholesale and manufacturing, technical and scientific products
<b>Retail I, Retail II</b>	44,45	Retail salespersons
<b>Transportation</b>	48	Heavy and tractor-trailer truck drivers, Light truck drivers
<b>Transportation - Postal/Warehousing</b>	49	Mail clerks and mail machine operators, except postal service
<b>Information</b>	51	Computer and information systems managers, Information and record clerks, all other, Information security analysts, Receptionists and information clerks
<b>Finance I (Finance and Insurance), Finance II (Real Estate and Rental and Leasing)</b>	52,53	Business and financial operations occupations, Financial and investment analysts, Financial managers, Financial specialists, all other, Personal financial advisors
<b>Professional I (Professional, Scientific, and Technical Services)</b>	54	Aircraft mechanics and service technicians, Automotive service technicians and mechanics
<b>Professional II (Management of Companies and Enterprises)</b>	55	Management occupations
<b>Professional III (Administrative and Support and Waste Management and Remediation Services )</b>	56	Administrative services managers
<b>Education</b>	61	Adult basic education, adult secondary education, and english as a second language instructors, Career/technical education teachers, secondary school, Education administrators, kindergarten through secondary, Educational instruction and library occupations, Elementary school teachers, except special education, Middle school teachers, except special and career/technical education, Preschool teachers, except special education, Secondary school teachers, except special and career/technical education, Teaching assistants, preschool, elementary, middle, and secondary school, except special education, Teaching assistants, special education
<b>Medical</b>	62	Medical and clinical laboratory technicians, Medical and clinical laboratory technologists, Medical and health services managers, Medical assistants, Medical equipment preparers, Medical records specialists, Medical secretaries and administrative assistants, Medical transcriptionists
<b>SCA, Entertainment</b>	71,72	Lifeguards, ski patrol, and other recreational protective service workers, Recreation and fitness studies teachers, postsecondary, Recreation workers
<b>Services</b>	81	Community and social service occupations, Community and social service specialists, all other, Protective service occupations, Social and community service managers, Social and human service assistants