

Subsurface heat island across the Chicago Loop district: analysis of localized drivers

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Abstract: The subsurface beneath many urban areas worldwide is warming up. This phenomenon, widely known as subsurface urban heat islands, has multiple detrimental impacts for urban areas, which span from environmental to public health and transportation infrastructure issues. Monitoring subsurface urban heat islands is crucial to study the mechanisms that govern their development across urban areas and inform urban planning strategies to mitigate this pervasive phenomenon. This paper presents an unprecedented Internet of Things facility to measure the intensity of localized drivers of the subsurface urban heat island across the Chicago Loop district. This facility consists of a wireless network of more than 150 sensors deployed to measure temperature in parks, surface and subsurface streets, building basements, underground parking garages, train lines, pedways, tunnels, and the ground. This work unravels a subsurface urban heat island in the hearth of the Loop. Specifically, the work highlights that localized drivers of subsurface urban heat islands, such as building basements and parking garages, are characterized by significant and markedly different temperatures. On the one hand, the temperatures of the localized drivers characterizing the monitored subsurface heat island can exceed by more than 20°C the ground temperature, involving a continuous heat transfer towards this medium. On the other hand, the temperatures of such drivers can differ by more than 10°C across the studied district, not only when diverse drivers are examined, but also when different locations within the same driver are considered. In summary, this study highlights a significant spatial heterogeneity in the temperature of localized drivers of the studied subsurface urban heat island, which arguably characterizes the underground climate change of many other cities worldwide.

Keywords: Sensing network, temperature, subsurface urban heat islands, underground climate change, Chicago Loop

1 Introduction

Urban areas across the world are facing the dire impacts of subsurface urban heat islands (SUHIs) – an underground climate change associated with warming temperatures in the subsurface. SUHIs are caused by two classes of heat sources for the underground (Ferguson and Woodbury 2007, Visser et al. 2020): large-scale drivers at the surface and localized drivers in the subsurface. Large-scale drivers, which are linked to surface urban heat islands (UHIs), are primarily the envelopes of buildings and other urban infrastructure that maintain heat in the atmosphere which then diffuses in the subsurface (Visser et al. 2020; Menberg et

al. 2013). Localized drivers can be heated basements, underground parking garages, subway and train tunnels, subterranean metro and train stations, sewers, district heating networks, or any other facilities that reject waste heat in the subsurface (Visser et al. 2020). Due to the slower rate of heat conduction in the subsurface compared to heat convection in the air at the ground surface, SUHIs tend to be more persistent and pronounced than their surface-level counterparts represented by UHIs (Huang et al. 2009, Menberg et al. 2013). Therefore, it is critical to investigate the mechanisms and impacts of SUHIs, especially considering that they are detrimental to the environment, public health, and transportation infrastructure for several reasons detailed hereafter.

The impacts of SUHIs on the environment derive from the fact that temperature crucially influences the biological, biochemical, and hydrological states of the subsurface. Temperature rises can affect organic matter formation in the ground, fertilizer efficiency, seed germination, plant development and root growth, plant winter survival and disease, and insect occurrence (Jacobs et al. 2011). Higher subsurface temperatures can also reduce the biodiversity of wildlife (Robinson et al. 2018) and impair drinking water quality by increasing the growth and propagation of harmful bacteria therein (Müller et al. 2014).

The impacts of SUHIs on public health result from the fact that excessive temperatures can reduce thermal comfort conditions and cause health issues for people traveling in underground environments (e.g., with public transport). Heat, heat stroke, and related health issues including asthma, dehydration, and heart attacks, are an increasing concern for underground mass transit operations (Jacob et al. 2008.) and there is evidence that environmental conditions affect stress levels and job performance (Chinazzo 2021). The oldest deep subway lines across the world, such as the London Underground (1863), Paris Métro (1900), New York Metro (1902) and Berlin U-Bahn (1902) were not designed to handle the high numbers of passengers and train traffic that are currently observed, and commonly experience overheating problems with temperatures as high as 47°C and numerous recorded cases of health issues (Griffiths 2006; Fertig 2009; Stephen 2016; Temperton 2018; ICBSE 2018; Zuccala 2019; Railway International 2020; Musaddique 2018; “Berlin” 2019; Barley 2010).

The impacts of SUHIs on transportation infrastructure result from the fact that high ambient temperatures can create damage and delays to underground rail networks. Higher temperatures can cause over-heated switch gears, along with expansion and buckling of steel rails. Subway trains can thus be forced to stop or decrease their traveling speed to avoid incidents (Brodwin 2014), with delays and economic costs that for the London Underground achieve the stellar amount of around \$1M per year (Arnell and Darch 2006). The increased stress on air conditioning systems in vehicles, stations, and operational facilities can further result in air conditioning and circulation outages, which can lead to medical risks to both passengers and workers in a deleterious feedback process (Greenham et al. 2020).

Monitoring SUHIs is paramount from multiple perspectives. From a scientific perspective, this endeavor can inform on the key variables and fundamental mechanisms that govern the development of such phenomena, with the promise to develop models and tools that can predict their temporal evolution and effects. From an engineering perspective, this endeavor can serve the development of urban planning strategies to mitigate the intensity and presence of SUHIs across the world. Examples of such strategies include the structured deployment of geothermal solutions for harvesting part of the waste heat rejected in the subsurface by distributed and localized SUHI drivers (Bayer et al. 2019; Cassina et al. 2022; Luo and Asproudi 2015a; Rivera et al. 2017a; Zhu et al. 2010).

To date, most studies about SUHIs have customarily focused on the intensity of such phenomena and thus on the effects of their drivers (i.e., heat sources). As a result of these studies, it is widely acknowledged that subsurface temperatures are highly heterogeneous – more than surface temperatures. Experimental evidence showed local hotspots in the subsurface of up to +20°C relative to the undisturbed ground temperature (Menberg et al. 2013). Various numerical studies also highlighted significant heterogeneities in the temperature field around localized SUHI drivers (Bidarmaghz et al. 2019a; Ferguson and Woodbury 2004; Krcmar et al. 2020b; Kreitmair et al. 2020; Menberg et al. 2013b). The heterogeneity of the temperature field in the subsurface is certainly linked to the non-uniformity of the heat diffusion and the superposition of the temperature field around heat sources, but it is also inherently caused by the highly heterogeneous intensity of the heat sources themselves. Constant temperatures are rationally assumed in numerical models to simulate specific classes of drivers of SUHIs (building basements, tunnels, etc.) (Bidarmaghz et al. 2019b, 2020). However, in reality, SUHI drivers are arguably characterized by different temperatures within each environment of the same class (e.g., lower level 1 of basement A vs. lower level 2 of basement A), as well as across different environments of the same class (e.g., basement A vs. basement B) or belonging to different classes (e.g., basement A vs. parking A). Despite significant advances in the characterization of subsurface urban heat islands, very limited, if any, information is available about the spatial variability that characterizes the intensity SUHI drivers (e.g., localized) – an aspect of crucial importance to advance the current understanding of changes in the underground climate of urban areas.

To develop a robust understanding of the inherent characteristics and impacts of subsurface urban heat islands, this paper presents the features and measurements of a novel sensing network that has been deployed across the Chicago Loop district to quantify the temperature (i.e., intensity) of SUHI drivers. In other words, rather than focusing on the *effects* of SUHIs, this work focuses on the *sources* of SUHIs, with an emphasis on the localized drivers for such an investigated form of urban climate change. Composed of more than 150 wireless sensors deployed to measure temperature in parks, surface and subsurface streets, building basements, underground parking garages, train lines, pedways, tunnels, and the ground, this Internet of Things solution enables to unravel a subsurface heat island for the Chicago Loop and to identify a heterogeneity in the localized drivers for the monitored phenomenon.

In the following, the features of the sensing network are presented first. Next, preliminary monitoring results are reported. Then, a discussion of such results is proposed. Finally, concluding remarks and an outlook deriving from this work are presented.

2 Subsurface sensing network

2.1 State-of-the art

Table 1 provides a list of journal articles that have investigated to date SUHI-related topics to the knowledge and accessibility of the authors. Contributions that do not explicitly reference ‘urban heat islands’ in the subsurface are not included. Each study is classified according to four categories, which describe their source of subsurface temperature data: (1) borehole or station data for ground temperatures, (2) monitoring well data for groundwater temperatures, (3) satellite imagery, and (4) derived temperature values from past literature. Category 4 (‘Values from previous studies/reports’) specifically refers to articles that use a mean or characteristic temperature values from a previous study/report to model subsurface temperatures. This classification includes articles that model basement temperatures with a fixed value

range, based on a regulation or recommendation from a technical report. It also includes articles that use archived temperature data for which certain pieces of metadata are missing or are not available. This classification does not include articles that analyze raw temperature data from previous studies; in this case, the source of the raw data is classified under categories 1-3.

The table considers both temperature data that were directly used to measure SUHI intensity and temperature data used to predict, validate, and/or compare the modelled results of a given study. Based on this review, the majority of SUHI studies thus far have used boreholes and/or monitoring wells for their subsurface temperature data. A few other studies have used satellite imagery or past literature values to make predictions about subsurface temperatures using heat transfer models. To our knowledge, the recent contribution by Tissen et al. (2021) is the only SUHI-related study that uses temperatures from basements, underground parking garages, and subway tunnels in their analysis. All other SUHI-related journal articles thus far have used temperature data that can be classified into the four source categories.

2.2 The Chicago Loop subsurface sensing network

The urban area analyzed in this study consists of the Chicago Loop district, the densest American district after Manhattan in New York City, which is bounded by the Chicago River in the north and west sides, Lake Michigan in the east side, and West Roosevelt Road on the south side. A specificity of this urban area is that it includes a myriad of underground environments and facilities, which may contribute to and undergo the effects of a subsurface urban heat island in a feedback loop (Figure 1). These include building basements, underground parking garages, train lines, pedways, and various underground tunnels that were used before the Chicago flood in 1992 for mailing and commerce activities (i.e., freight tunnels).

For this study, a network comprising more than 150 wireless temperature sensors was deployed across the Loop district to assess the intensity of a SUHI. This network has two specific features compared to those used so far to investigate SUHI's. On the one hand, while including several sensors deployed in surface green spaces, surface and subsurface streets, and the ground for data comparison, this network is mostly deployed in underground built environments. On the other hand, this network is also unique because it is comprised of wireless temperature sensors that are commercially available to the public and are deployed at a district-scale. Recent energy studies have reviewed the use, diversity, and potential of commercially-viable sensors for environmental monitoring in buildings (Ahmad et al. 2016, Hayat et al. 2019). Such technologies can play a significant role in helping achieve climate and energy efficiency targets due to their low cost, availability, and ease of deployment and data communication (Ahmad et al. 2016). Commercially viable temperature sensors thus present an accessible solution to dense urban areas, like the Chicago Loop district, which do not have existing borehole or monitoring well temperature data to study SUHIs.

Therefore, the sensing network developed as a part of this work presents a unique opportunity to comprehensively study the intensity of localized drivers of SUHIs and identify areas of SUHI vulnerability in the Loop district. Currently, there are 60 sensors installed in the subsurface and 11 sensors installed in the surface, and another 79 sensors that are being deployed. This results in a sensing network totaling 150 sensors. Figure 2 shows a map of the sensor locations in the surface and subsurface of the Loop.

2.3 Sensor features

The sensing network is comprised of two types of sensors (Figure 3). All the sensors are wireless and record one temperature measurement per hour, resulting in an approximate lifetime of their AC batteries of 10 years. Figure 4 shows examples of sensor deployments across the Loop.

The first type of sensor is used to record the ambient air temperatures in surface and subsurface locations. These sensors are HOBO MX2305 Wireless Temperature Data Loggers with dimensions of $10.8 \times 5.08 \times 2.24$ cm and a weight of 75.5 g. The MX2305 sensors are wireless, weatherproof, and can be attached to pipes via zip-ties or to surfaces via screws. The compact size of the sensors allows for their installation in small, hard-to-reach spaces, which further enables to minimize potential interactions with people and help maintain the integrity of recorded data. Both past and real-time data from each sensor can be accessed and shared through a mobile device with the HOBO connect app. Table 2 provides further specifications for the HOBO MX2305 Wireless Temperature Data Logger.

The second type of sensor is used to record ground temperatures around local underground thermal hotspots or in undisturbed underground conditions. Each ground temperature sensor is a system of a HOBO UX120 4-Channel Thermocouple Logger, a Type J Subminiature Connector Adapter, and a 24 AWG Type J Thermocouple wire that is inserted into the subsurface. The HOBO UX120 4-Channel Thermocouple Logger has dimensions of $10.8 \times 5.41 \times 2.54$ cm and a weight of 107.5 g. Table 3 provides further specifications of the HOBO UX120 4-Channel Thermocouple Logger, 24 AWG Type J Thermocouple. The Type J Thermocouple wire (HOBO TCW100-J) is characterized by a range of 0 to 250°C (32 to 482°F), a probe accuracy of $\pm 0.6^\circ\text{C}$, and a Type J TEFLON® insulation.

3 Monitoring data and observations

3.1 Temperature in green spaces, surface streets and subsurface streets

Figure 5 presents the daily average ambient air temperatures for green spaces, surface streets, and subsurface streets. These average temperatures result from the multiple sensor measurements in the referenced environments. The temperature trends for each type of surface and subsurface locations follow similar trends, tending to decrease through the winter (bottoming in February) and increase through the summer (peaking in June). This result indicates that seasonal air temperature variations affect to a comparable extent the temperature field in the surface and subsurface locations, implying that environmental conditions in the considered subsurface streets are not particularly protected by surface conditions. During the colder months, underground streets are almost always warmer than the surface streets and the surface green spaces. However, even during the warmer months, underground streets continue to be warmer with lower temperature differences with surface streets and surface green spaces as compared to the colder months. The amplitude of temperature fluctuations for underground streets is comparatively lower than green spaces and surface streets and the higher amplitude variations in the latter two environments is possibly a reflection of the effects of synoptic events.

3.2 Temperature in the ground

Figure 6 presents the monthly average ground temperatures for sensors deployed in Grant Park at a depth of 4 m and in the hearth of the Loop at a depth of 12 m (data in the Loop specifically derive from

measurements at the interface between the non-operational freight tunnels and the ground). Figure 6(a) compares the considered values of ground temperature with the monthly average surface air temperature. Figure 6(b) highlights the spatial variation of ground temperature in the Loop as a function of the distance from the operational blue line of the metro system run by the Chicago Transit Authority (CTA).

The annual mean ground temperature derived from the measurements in Grant Park is 11.18°C while the annual mean surface air temperature is 8.37°C (Figure 6(a)). The temperature in the ground does not significantly vary throughout the year compared to the surface air temperature measurements. This result implies that the seasonal surface air temperature variations do not penetrate in the ground down to the considered depth and hence the thermal penetration depth for which notable temperature variations appear in the ground at the considered location is smaller than 4 m. Accordingly, the temperature at measured at depth in Grant Park can be considered relatively undisturbed due to a damping and thermal insulation effect provided by the ground from the surface thermal conditions.

The ground temperature in the hearth of the Loop is significantly higher than the ground temperature in Grant Park (Figure 6(a)). Recorded data specifically show that ground temperatures in the hearth of the Loop can exhibit temperature anomalies ranging between 5.67°C to 9.54°C with respect to the ground temperature recorded in Grant Park. While no localized drivers of waste heat appear to be present in the vicinity of the sensor deployed in Grant Park, multiple buildings and the blue line of the metro system run by the CTA are present in the vicinity of the sensors located in the Loop. This result provides evidence of the influence of localized sources of waste heat on the ground temperature of an urban environment and quantify the local intensity of the subsurface heat island for the Loop district.

It is important to note that there seems to be a correlation between the magnitude of the ground temperatures measured in the core of the Loop and the distance from the CTA blue line that runs from North to South (Figure 6(b)). Gradually decreasing ground temperature are particularly observed as the distance from the blue line is increased, indicating that the subway system likely acts as a major source of waste heat. No specific trend is observed when considering the distance of the deployed sensors from the portion of the blue line that runs from East to West.

3.3 Temperature in underground parking garages

Figure 7 presents the daily average air temperatures for selected parking garages. Temperatures recorded by multiple sensors are shown to inform on the variability of environmental conditions within the same levels of the chosen parking garages, across different levels of such garages, as well as across different parking garages. At any level, the temperature trends follow a sinusoidal pattern, with differences in temperatures that can be as high as 11.41°C within each level and up to 10.65°C across different levels of the same parking garage. Air temperatures as high as 32°C can characterize the selected parking garages throughout the year. Temperatures in Grant Park North and South garages become warmer and cooler with depth during cooler and warmer months, respectively – evidence that is generally expected in view of the more significant thermal inertia of underground built environments with depth. However, this fact does not characterize Millennium Park and Lakeside garages, where temperatures decrease with an increase in depth during cooler months and increase with depth during warmer months. This difference between the results may be attributed to different features characterizing individual measuring sites, starting from the presence and power of ventilation systems to technological features of the envelope of such sites.

Figure 8 shows the relationship between subsurface and surface air temperatures for different parking garages. Such a relationship is presented for each of the levels constituting the chosen parking garages. The relationship between subsurface and surface air temperatures is linear, with a flatter slope for greater depths in the parking garages. The latter result indicates that air temperature in parking garages is less sensitive to surface air temperature fluctuations for an increase in depth, which is an expected result due to the increase in the thermal inertia of such built environments with depth. The difference between surface air temperature and subsurface air temperature is estimated to be 20°C when the surface air temperature is the coldest and 12°C when the surface air temperature is the warmest.

Figure 9 shows the temperatures during the peak winter and summer months of February and June 2021, respectively, and compares such temperatures with the surface air temperature. The subsurface temperature trends are always more stable than the surface temperature trends. The subsurface temperatures are warmer in comparison to the surface air temperature during February (i.e., winter), while they are cooler than the surface air temperatures during June (i.e., summer). The difference in temperature between the subsurface air temperature and surface air temperature is significantly higher at deeper levels in comparison to the shallower levels, as seen in the parking garage Grant Park South, the deepest level 3 sensors recorded the highest temperatures in peak winter and lowest temperatures in peak summer among all the sensors in different levels of the garage. From this observation, it can be noted that the subsurface acts as a heat source during the colder months and as a heat sink during the warmer months. During the month of June there is a prominent rise in temperature of approximately 1°C during the mid-month date range, with no discernable effects derived from the surface air temperature.

Figure 10 shows the hourly average temperatures for each month of the year in the parking garages considered so far. Such temperatures allow analyzing the subsurface temperature variability throughout the day. Temperatures rise during the daytime hours in parking garages and are more pronounced at shallower levels compared to deeper levels. The commented temperature rises start to appear during the month of March 2021 and continue throughout June 2021, most likely due to the end of various COVID-19 restrictions in spring 2021 and the increased human activity across the city of Chicago. Consequently, this result suggests that rises in human and vehicular traffic correspond to a direct increase in the air temperature of parking garages. As the depth of each parking level increases, the surge in the parking air temperature during the day becomes more gradual. The diminishing surge in temperatures with depth might be attributed to the greater usage of parking spaces at shallower levels compared to the lower levels. Air temperatures fall back down after sunset and continue into the night hours because of low human activity.

Figure 11 shows the annual average temperature measured in different levels of selected parking garages. The subsurface air temperatures show a clear increasing trend with depth, with values that can be up to 9°C warmer than the average annual undisturbed ground temperature of about 11°C for Chicago. This result highlights that air temperatures in underground parking garages across the Chicago Loop can be markedly higher than the undisturbed ground temperature not only during isolated days over the year, but also on average throughout the year.

3.4 Temperature in building basements

Figure 12 shows the daily average temperatures for each level of selected building basements. Temperature fluctuations markedly characterize some basements but not others. The air temperature in the basements of

La Quinta, Lakewells, and Hotel Julian is relatively constant with time, while the air temperature of the Union league and Blackstone basements markedly fluctuates with time. Air temperatures as high as 33°C are recorded. At any level, differences in temperatures can be as high as 9.86°C across different building basements. Temperature fluctuations can derive from environmental control and thermal insulation of the specific underground environments, human activity in such environments, and other specific technological, architectural, and environmental attributes. For example, a sensor installed in the hallway of La Quinta (Sensor ID: 254) shows steadily increasing temperatures with time, presumably due to increased human activity after the lessening of the COVID-19 pandemic. This evidence does not characterize the readings collected from a sensor installed in the maintenance room (Sensor ID: 249), where human activity is low compared to the hallway and thus involve an approximately constant temperature of 22°C over time. The temperature in the lower level of the Union League building is about 5°C warmer than the other levels due to the presence of heavy utility equipment.

Figure 13 shows the relationship between subsurface air temperature and surface air temperature for different building basement levels. A linear relationship characterizes the subsurface air temperature of building basements and the surface air temperature, consistently with the results collected for parking garages. Nevertheless, the slope of the regression line obtained for building basements is comparatively flatter compared to that referring to parking garages. The air temperatures of basements are generally warmer than surface air temperatures when these are lower than 25°C, while they are cooler when these temperatures are above 25°C. The difference between surface air temperature and subsurface air temperature is estimated to be 32°C when the surface air temperature is the coldest and 13°C when the surface air temperature is the warmest.

Figure 14 shows the air temperatures of the selected building basements during the peak summer month of June 2021 and compares them with the surface air temperature. The subsurface temperature trends are always more stable than the surface temperature trends, similar to the observations reported for underground parking garages. The subsurface temperatures are cooler than the surface air temperatures for La Quinta and Hotel Julian, while they are warmer than the surface air temperature for LakeWells, Union League and Blackstone. The temperature in level 3 of Union league is drastically higher compared to the surface air temperature and the other upper levels. This evidence is attributed to the presence of remarkable sources of waste heat that were identified for such basement level during the installation of the sensors.

Figure 15 shows the hourly average temperature for each month of the year in the building basements considered so far. Temperatures are generally stable during the day. The basements of the Blackstone and Hotel Julian show a surge during the midst of working hours, a phenomenon that is associated to the influence of human activity over such hours and does not appear to characterize the other building basements.

4 Closure

This paper presented an unprecedented sensing network deployed in subsurface and surface environments across the Chicago Loop district to monitor the intensity of localized drivers of the subsurface heat island for such urban area. In this context, the work reported temperature measurements recorded since October 2020 to discuss key features characterizing the *sources* of subsurface urban heat islands. The main outcomes of this work can be summarized as follows:

- This work reports a large set of temperature data for multiple subsurface and surface environments across a city district, with a focus on parking garages, building basements, surface and subsurface streets, parks, and the ground. Measurements of ground temperatures currently available for the hearth of the considered city district and an undisturbed location in a park show a significant subsurface urban heat island intensity, with a maximum temperature anomaly of 9.54°C. This subsurface urban heat island is greatly fueled by localized sources of waste heat, such as underground built environments.
- The temperature field in underground built environments is markedly heterogeneous. Differences in temperature as high as 11.41°C can characterize the same level of a given underground environment (e.g., lower level x of environment X) and comparable differences are also measured in different underground environments (e.g., lower level x of environments X and Y). Differences in temperatures as high as 10.65°C are further observed for different levels of the same underground environment (e.g., lower levels x and y of environment X). This heterogeneity in the temperature of localized drivers of subsurface urban heat islands arguably characterizes Chicago and many other urban areas, making the modeling of subsurface urban heat islands difficult. Based on this result, the accuracy of simulations that consider the same temperature for equal classes of localized drivers of subsurface heat islands (e.g., basements, parking garages, etc.) might be questioned. Nevertheless, such a modeling approach appears the most reasonable at the time of writing. Simulations accounting for the heterogeneous nature in the temperatures of the same class of drivers would require large experimental datasets for validation purposes that are often unavailable. One approach to encompass the possible impacts of the heterogeneous temperatures of localized drivers of subsurface urban heat islands more comprehensively may consist in the consideration of temperature ranges, instead of individual temperatures, for given classes of drivers. The data presented in this paper for building basements and parking garages provide useful quantitative guidance for these simulations efforts.
- Temperatures as high as 33°C characterize underground built environments in the Loop, involving a difference in temperature higher than 20°C compared to the average undisturbed temperature of 11°C characterizing the ground at locations where surface temperature effects are negligible and localized sources of heat are seemingly absent. This evidence highlights the presence of tremendous sources of waste heat for the underground of the considered urban area, which will be monitored in the years to come.
- In many situations, the temperature in underground parking garages has been shown to increase with depth, but not in all of them. Oftentimes, temperatures in parking garages and building basements have shown to be more stable for an increase in depth, but not always. These results can be attributed to different technological and environmental features of underground built spaces (e.g., presence and power of ventilation systems, proximity to exits, etc.). Such features are hard to identify a priori and even more difficult to reproduce through large-scale computer simulations.
- Air temperatures in parking garages and building basements are characterized by a linear relationship with surface air temperatures, whose magnitude can significantly vary depending on the presence of sources of waste heat (e.g., human activity for both parking spaces and basements, car activities for parking garages, furnaces for basements, etc.). Air temperatures in parking garages are typically more susceptible to changes in surface air temperature compared to building basements. In some building basements, the air temperature is approximately constant over time, irrespective of the surface air temperature.

- The availability of temperature data for underground built environments during periods in which local business was hit with varying severity by the spread of COVID-19 across the city of Chicago, and consequently human activity had varying intensity, have highlighted clear surges in air temperature during working hours. The intensity of such temperature surges differs for different underground environments, but also for different levels of the same underground built environment. Greater air temperature surges associated with human activity can be observed in spaces that are more easily accessible to people during the day (e.g., shallower compared to deeper parking floors).

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Table 1: Classification of SUHI-related journal articles by source of subsurface temperature data.

Author(s)	Year	Title	Primary area of investigation	Subsurface temperature data source				Depths of observations (m.b.g.l)
				Borehole or station data for ground temperatures	Monitoring wells for groundwater temperatures	Satellite Imagery	Values from previous studies/reports	
Changnon	1999	A Rare Long Record of Deep Soil Temperatures Defines Temporal Temperature Changes and an Urban Heat Island	Long-term temperature trends, SUHI/Subsurface monitoring	+				0.91
Ferguson and Woodbury	2004	Subsurface heat flow in an urban environment	Subsurface thermal processes	+	+			~ 0 - 150
Taniguchi, Uemura, and Sakura*	2005	Effects of urbanization and groundwater flow on subsurface temperature in three megacities in Japan	Subsurface thermal processes		+			0.08 - 465
Taniguchi and Uemura*	2005	Effects of urbanization and groundwater flow on the subsurface temperature in Osaka, Japan	Subsurface thermal processes		+			0.1 - 465
Ferguson and Woodbury	2007	Urban Heat Island in the Subsurface	SUHI/Subsurface monitoring		+			20 - 150
Taniguchi et al.*	(2007)	Combined Effects of Urbanization and Global	SUHI/Subsurface monitoring, Subsurface		+			~0 - 465

		Warming on Subsurface Temperature in Four Asian Cities	thermal processes					
Huang et al.	2009	Detecting urbanization effects on surface and subsurface thermal environment - A case study of Osaka	Subsurface thermal processes	+				6 - 57
Yalcin and Yetemen	2009	Local warming of groundwaters caused by the urban heat island effect in Istanbul, Turkey	SUHI/Subsurface monitoring	+	+			0.1 – 20 m
Taniguchi et al.*	2009	Anthropogenic effects on the subsurface thermal and groundwater environments in Osaka, Japan and Bangkok, Thailand	Subsurface thermal processes		+			47 - 465
Banks et al.	(2009)	Anthropogenic thermogeological 'anomaly' in Gateshead, Tyne and Wear, UK	SUHI/Subsurface monitoring, Subsurface thermal processes	+			+	~0 - 80
Yasukawa et al.	(2009)	Groundwater Temperature Survey for Geothermal Heat Pump Application in Tropical Asia	SUHI/Subsurface monitoring, Geothermal potential		+			~0 - ~240
Zhu et al.	2010	The geothermal potential of urban heat islands	Geothermal potential		+			20 - 150
Turkoglu	(2010)	Analysis of urban effects on soil temperature in Ankara	SUHI/Subsurface monitoring	+				0.05 - 0.5
Liu et al.	2011	A numerical and field investigation of underground temperatures	Subsurface temperature estimation, Subsurface thermal processes	+				0.1 - 3

		under Urban Heat Island						
Shi et al.	2012	Observation and analysis of the urban heat island effect on soil in Nanjing, China	SUHI/Subsurface monitoring	+				0 - 3
Gunawardhana and Kazama	(2012)	Using subsurface temperatures to derive the spatial extent of the land use change effect	SUHI/Subsurface monitoring, Subsurface thermal processes		+			~0 - 600
Shi et al.	(2012)	Observation and analysis of the urban heat island effect on soil in Nanjing, China	SUHI/Subsurface monitoring	+				0.1 - 1.5
Menberg et al.	2013a	Subsurface urban heat islands in German cities	SUHI/Subsurface monitoring		+			2 - 25
Menberg et al.	2013b	Long-Term Evolution of Anthropogenic Heat Fluxes into a Subsurface Urban Heat Island	Subsurface thermal processes, Long-term temperature trends		+			At water level for 1977 data and 3-4 m below water level for 2011 data
Epting and Huggenberger	2013	Unraveling the heat island effect observed in urban groundwater bodies – Definition of a potential natural state	Groundwater resource management, Subsurface thermal processes	+	+			Unspecified total range, includes ~0 - ~22
Epting, Händel, and Huggenberger	2013	Thermal management of an unconsolidated shallow urban groundwater body	Groundwater resource management, Subsurface thermal processes		+			Unspecified total range, includes ~0 - ~25
Liu et al.	(2013)	Investigation on potential applicability of	Subsurface cooling solutions				+	-

		subsurface cooling in Singapore						
Müller et al.	2014	Analysis of the subsurface urban heat island in Oberhausen, Germany	SUHI/Subsurface monitoring, Groundwater resource management	+				1-1.95
García-Gil et al.	2014	The thermal consequences of river-level variations in an urban groundwater body highly affected by groundwater heat pumps	Subsurface thermal processes, Groundwater resource management		+			5 - 65 m
Arola and Korkka-Niemi	2014	The effect of urban heat islands on geothermal potential: examples from Quaternary aquifers in Finland	Geothermal potential		+			6 – 57 m
Wu et al.	2014	Effect of Ground Covers on Soil Temperature in Urban and Rural Areas	Subsurface cooling solutions	+				~ 0 - 3
Zhan et al.	2014	Satellite-derived subsurface urban heat island	Subsurface temperature estimation	+		+		0.05 - 3.20
Abe et al.	(2014)	Effect of Urban Aquifer Exploitation on Subsurface Temperature and Water Quality	Subsurface thermal processes, Long-term temperature trends		+			18
Saito et al.	(2014)	Thermal properties of boring core samples from the Kanto area, Japan: Development of predictive models for thermal conductivity and diffusivity	Subsurface thermal processes, Subsurface temperature estimation		+			5.16 - 49.16

Luo and Asproudi	2015	Subsurface urban heat island and its effects on horizontal ground-source heat pump potential under climate change	SUHI/Subsurface monitoring, Geothermal potential	+				0.1 - 1
Zhu et al.	2015	Groundwater temperature evolution in the subsurface urban heat island of Cologne, Germany	SUHI/Subsurface monitoring, Subsurface thermal processes		+			20 - 44
Lokoshchenko and Korneva	2015	Underground urban heat island below Moscow city	SUHI/Subsurface monitoring, Long-term temperature trends	+				0.2 - 3.20
Benz et al.	2015	Spatial resolution of anthropogenic heat fluxes into urban aquifers	Subsurface thermal processes		+		+	~3 - ~21
Westaway et al.	(2015)	Subsurface absorption of anthropogenic warming of the land surface: The case of the world's largest brickworks (Stewartby, Bedfordshire, UK)	SUHI/Subsurface monitoring		+			~20 - ~40
Busby	(2015)	UK shallow ground temperatures for ground coupled heat exchangers	SUHI/Subsurface monitoring	+				0.05 - 1
Benz et al.	2016	Linking Surface Urban Heat Islands with Groundwater Temperatures	Subsurface temperature estimation		+	+	+	1 - 23 m
Bayer et al.	2016	Extracting past atmospheric warming and urban heating effects from borehole temperature profiles	Subsurface thermal processes	+			+	~0 - 540

Rivera et al.	2016	Increased temperature in urban ground as source of sustainable energy	Geothermal potential		+			9 - 20
Hein et al.	(2016)	Quantification of exploitable shallow geothermal energy by using Borehole Heat Exchanger coupled Ground Source Heat Pump systems	Geothermal potential				+	-
Salem and Osman	(2016)	Shallow subsurface temperature in the environs of El-Nubaria canal, northwestern Nile Delta of Egypt: implications for monitoring groundwater flow system	SUHI/Subsurface monitoring		+			0 - 200
Westaway and Younger	2016	Unravelling the relative contributions of climate change and ground disturbance to subsurface temperature perturbations: Case studies from Tyneside, UK	SUHI/Subsurface monitoring, Subsurface thermal processes	+				Unspecified total range
Benz et al.	2017	Identifying anthropogenic anomalies in air, surface and groundwater temperatures in Germany	Subsurface thermal processes		+			≤ 30
Epting et al.	2017	The thermal impact of subsurface building structures on urban groundwater resources – A paradigmatic	Subsurface thermal processes, Groundwater resource management		+			Unspecified total range

		example						
Rivera, Blum, and Bayer	2017	Increased ground temperatures in urban areas: Estimation of the technical geothermal potential	Geothermal potential				+	-
Farr et al.*	(2017)	Mapping shallow urban groundwater temperatures, a case study from Cardiff, UK	SUHI/Subsurface monitoring	+	+			~0 - 130
Agudelo-Vera et al.	(2017)	Identifying (subsurface) anthropogenic heat sources that influence temperature in the drinking water distribution system	Subsurface thermal processes, Groundwater resource management	+	+			1
Bucci et al.	(2017)	Shallow groundwater temperature in the Turin area (NW Italy): vertical distribution and anthropogenic effects	SUHI/Subsurface monitoring		+			~0 - 50
Epting et al.	(2017 a)	Development of concepts for the management of thermal resources in urban areas – Assessment of transferability from the Basel (Switzerland) and Zaragoza (Spain) case studies	Groundwater resource management	+	+			Unspecified total range, includes 0 - 65
Ichinose and Liu	2018	Modeling the relationship between the urban development and subsurface warming in seven Asian	Long-term temperature trends				+	-

		megacities						
Benz et al.	2018	Comparing anthropogenic heat input and heat accumulation in the subsurface of Osaka, Japan	Subsurface thermal processes		+			20
Epting et al.	2018	Relating groundwater heat-potential to city-scale heat-demand: A theoretical consideration for urban groundwater resource management					+	-
Mueller et al.	(2018)	Combining monitoring and modelling tools as a basis for city-scale concepts for a sustainable thermal management of urban groundwater resources	Subsurface thermal processes, Groundwater resource management, Geothermal potential		+			Unspecified total range, includes ~0 - ~25
Bidargmaghz et al.	2019	Influence of geology and hydrogeology on heat rejection from residential basements in urban areas	Subsurface thermal processes	+			+	~0 - ~100
Buday et al.	2019	Subsurface urban heat island investigation in Debrecen, Hungary based on archive and recently measured data	SUHI/Subsurface monitoring	+			+	0.02 - 100
Boon et al.	(2019)	Groundwater heat pump feasibility in shallow urban aquifers: Experience from Cardiff, UK.	Geothermal potential		+			~2 - ~22

Vienken et al.	(2019)	Monitoring the impact of intensive shallow geothermal energy use on groundwater temperatures in a residential neighborhood	SUHI/Subsurface monitoring	+	+			~0 - ~30
Tissen et al.	(2019)	Groundwater temperature anomalies in central Europe	SUHI/Subsurface monitoring, Subsurface thermal processes		+			~0 - 60
Hemmerle et al.	(2019)	Estimation of Groundwater Temperatures in Paris, France	SUHI/Subsurface monitoring, Subsurface temperature estimation		+	+	+	~0 - ~150
Riedel	(2019)	Temperature-associated changes in groundwater quality	SUHI/Subsurface monitoring, Groundwater resource management	+	+			Unspecified total range, includes 0 - ~40
Visser et al.	2020	Impacts of progressive urban expansion on subsurface temperatures in the city of Amsterdam (The Netherlands)	Subsurface temperature estimation, Subsurface thermal processes, Long-term temperature trends		+			~0 - 115
Bidargmaghz et al.	2020	Large-scale urban underground hydro-thermal modelling – A case study of the Royal Borough of Kensington and Chelsea, London	Subsurface thermal processes	+			+	~0 - ~100
Huang et al.	2020	Satellite identification of atmospheric-surface-subsurface urban heat islands under clear sky	Subsurface thermal processes	+		+		0.2 - 3.20
Kremer et al.	2020	Assessing the Impact of a Heated Basement on Groundwater Temperatures	Subsurface thermal processes		+			5 - 20

		in Bratislava, Slovakia						
Epting et al.	2020	City-scale solutions for the energy use of shallow urban subsurface resources – Bridging the gap between theoretical and technical potentials	Geothermal potential				+	Unspecified total range
Patton et al.*	(2020)	Establishing an urban geo-observatory to support sustainable development of shallow subsurface heat recovery and storage	SUHI/Subsurface monitoring		+			1.5 - 120
García-Gil et al.	(2020)	Defining the exploitation patterns of groundwater heat pump systems	Groundwater resource management		+			Unspecified total range
Bryś et al.	(2020)	Characteristics of heat fluxes in subsurface shallow depth soil layer as a renewable thermal source for ground coupled heat pumps	Subsurface thermal processes, Geothermal potential	+				0.05 - 0.5
Watson and Westaway	(2016)	Borehole temperature log from the Glasgow Geothermal Energy Research Field Site: a record of past changes to ground surface temperature caused by urban development	SUHI/Subsurface monitoring, Subsurface temperature estimation, Long-term temperature trends	+				~0 - 197
Schweighofer et al.	2021	Calculating Energy and Its Spatial Distribution for	Geothermal potential		+			5 - 20

		a Subsurface Urban Heat Island Using a GIS-Approach						
Previanti and Crosta	(2021)	Characterization of the subsurface urban heat island and its sources in the Milan city area, Italy	SUHI/Subsurface monitoring, Subsurface thermal processes		+			~0 - 100
Schweighofer et al.	(2021 b)	Detecting Groundwater Temperature Shifts of a Subsurface Urban Heat Island in SE Germany	SUHI/Subsurface monitoring		+			10 - 30
Makasis et al.	(2021)	Impact of simplifications on numerical modelling of the shallow subsurface at city-scale and implications for shallow geothermal potential	Subsurface thermal processes, Geothermal potential				+	-
Tissen et al.	(2021)	Identifying key locations for shallow geothermal use in Vienna	Geothermal potential		+			Unspecified total range, includes ~0 - 30
Previanti et al.	(2022)	The subsurface urban heat island in Milan (Italy) - A modeling approach covering present and future thermal effects on groundwater regimes	Subsurface thermal processes, Groundwater resource management, Geothermal potential		+			~0 - 100
Böttcher and Zosseder	(2022)	Thermal influences on groundwater in urban environments – A multivariate statistical analysis of the subsurface heat island effect in Munich	Subsurface thermal processes	+	+			~0 - 20

Miocic and Krecher	(2022)	Estimation of shallow geothermal potential to meet building heating demand on a regional scale	Geothermal potential			+		-
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* Although this article primarily used the term ‘boreholes’ to describe their temperature source, the source was used to measure groundwater temperatures. Therefore, the source is classified under “Monitoring wells for groundwater temperatures” as opposed to “Station or borehole data for soil temperatures” for this table.

Table 2: Sensor specifications for the HOBO MX2305 Wireless Temperature Data Logger.

Range	-40 to 70°C (-40 to 158°F)
Accuracy	±0.25°C from -40 to 0°C (±0.45 from -40 to 32°F) ±0.2°C from 0 to 70°C (±0.36 from 32 to 158°F)
Resolution	0.04°C (0.072°F)
Drift	<0.02°C (0.018°F) per year
Logging rate	1 second to 18 hours
Battery type	2/3 AA 3.6 Volt lithium, user replaceable
Memory	128 KB (84,650 measurements, maximum)
Full memory download time	Approximately 60 seconds

Table 3: Sensor specifications for the HOBO UX120 4-Channel Thermocouple Logger.

Range	-20 to 70°C (-4 to 158°F)
Accuracy	$\pm 0.6^{\circ}\text{C}$ ($\pm 1.08^{\circ}\text{F}$) $\pm$ thermocouple probe accuracy
Resolution	0.03°C (0.06°F)
Logging rate	1 second to 18 hours, 12 minutes, 15 seconds
Battery type	Two AAA 1.5V alkaline batteries, user replaceable
Memory	4 MB (1.6 million measurements, maximum)
Full memory download time	Approximately 1.5 minutes

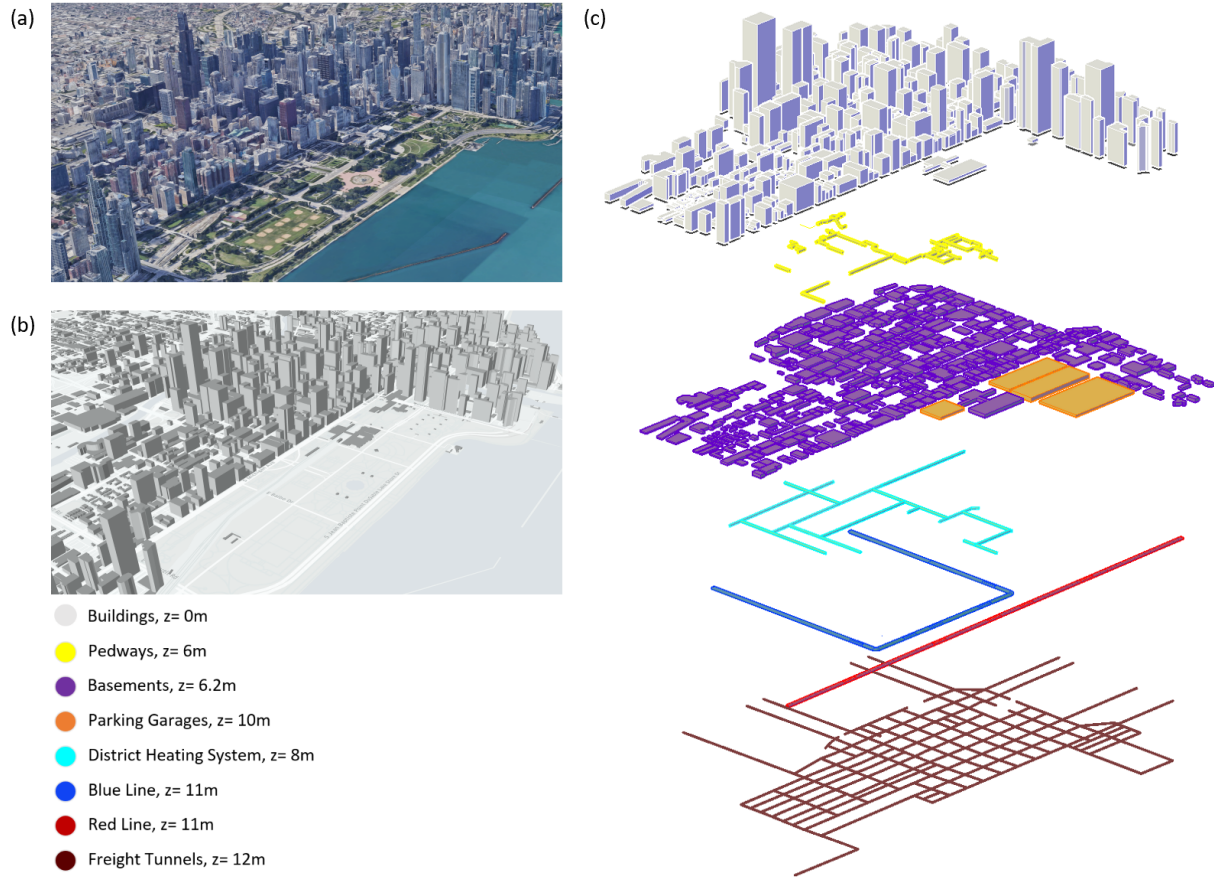


Figure 1: (a) 3D view of the loop using Google earth; (b) 3D rendering of the Loop area; and (c) 3D model of the subsurface, showing the different layers of the subsurface infrastructure. The provided depths are average values at which the considered environments can be found across the Loop.

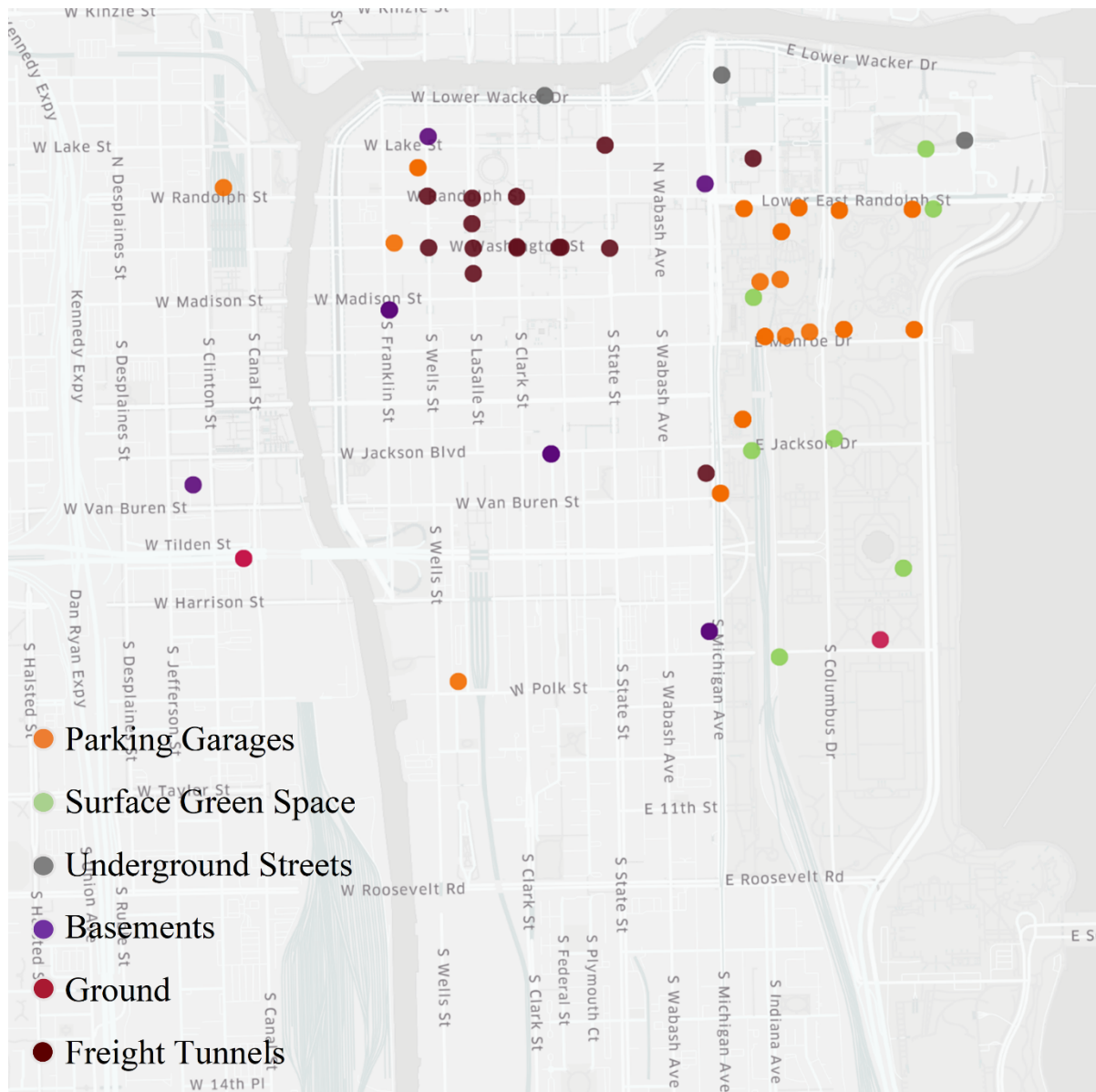


Figure 2: Locations of the temperature sensors installed in subsurface and surface environments across the Chicago Loop district.



Figure 3: (Top panel) The HOBOMX2300 Wireless Temperature Data Logger and cable ties/screws for mounting. (Bottom panel) The HOBUX120 4-Channel Thermocouple Logger and Thermocouple case and screws for mounting.

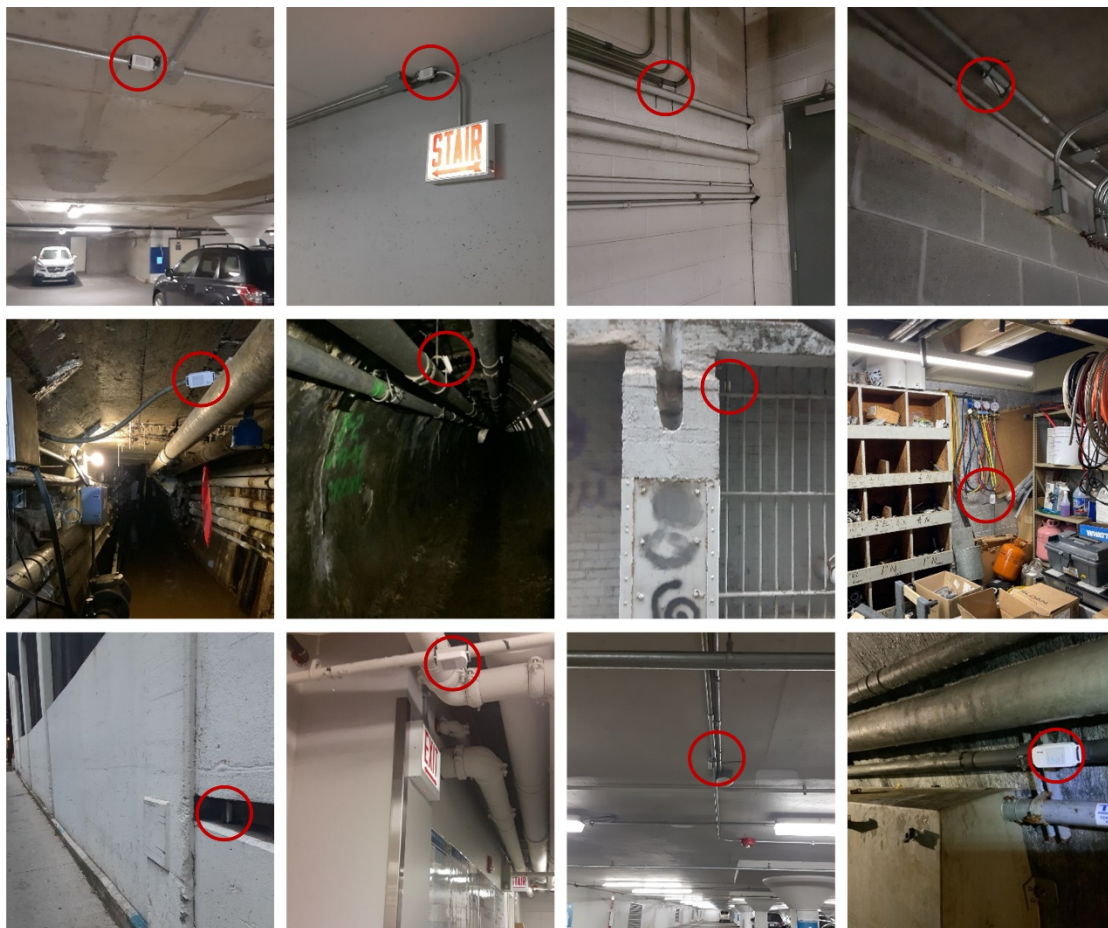


Figure 4: Installation of sensors in underground environments, with sensors circled in red.

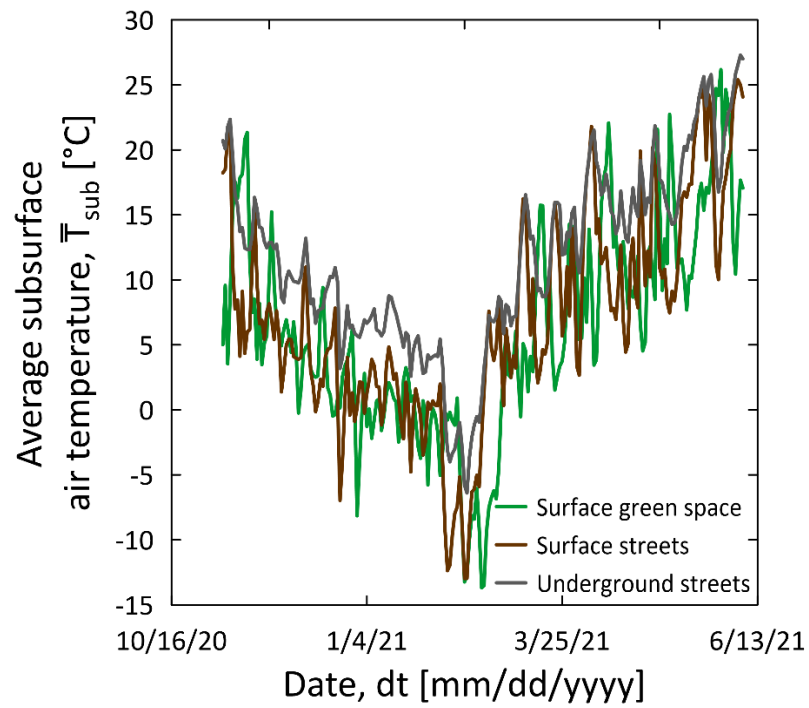


Figure 5: Daily average temperatures for surface green spaces, surface streets, and underground streets.

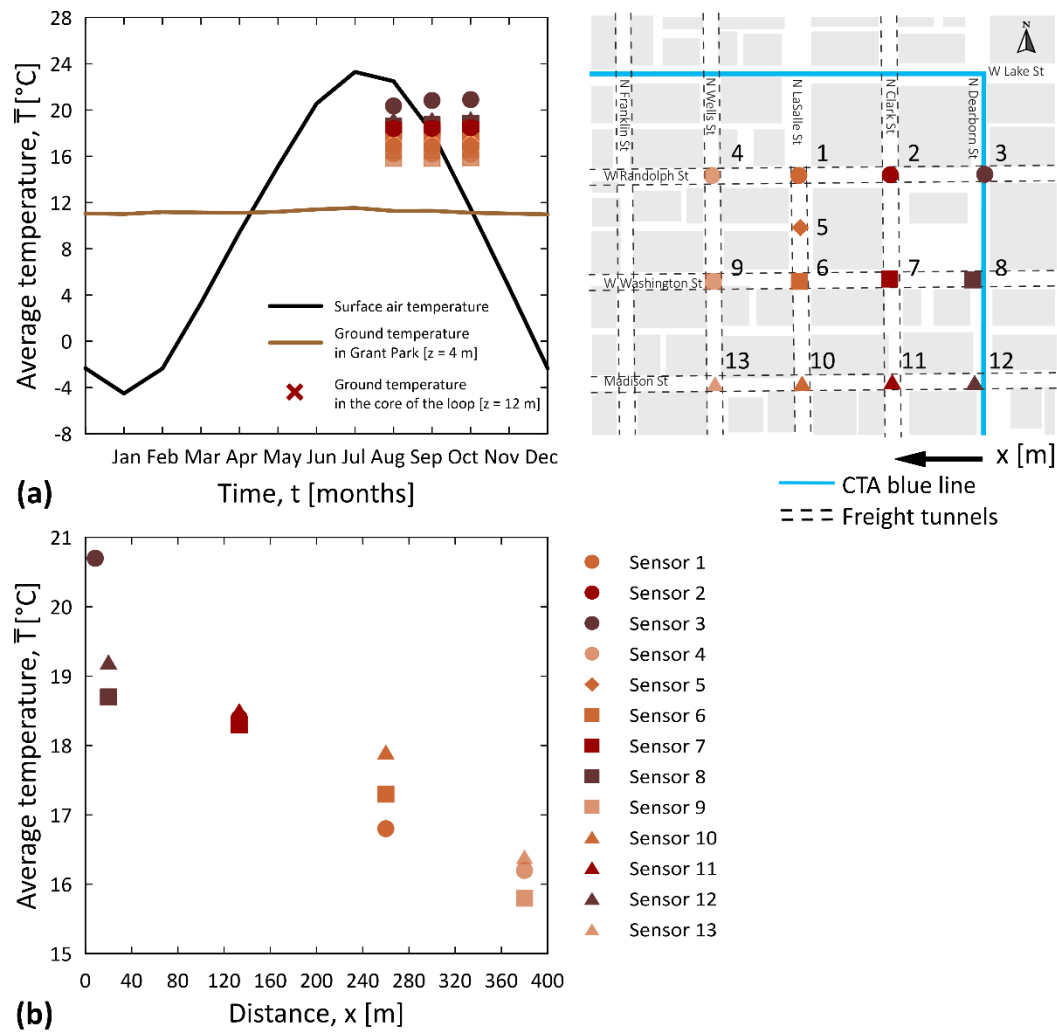


Figure 6: Monthly average temperatures for sensors installed in the ground: (a) comparison with surface air temperature and (b) spatial variation of temperature with respect to the distance from the CTA blue line.

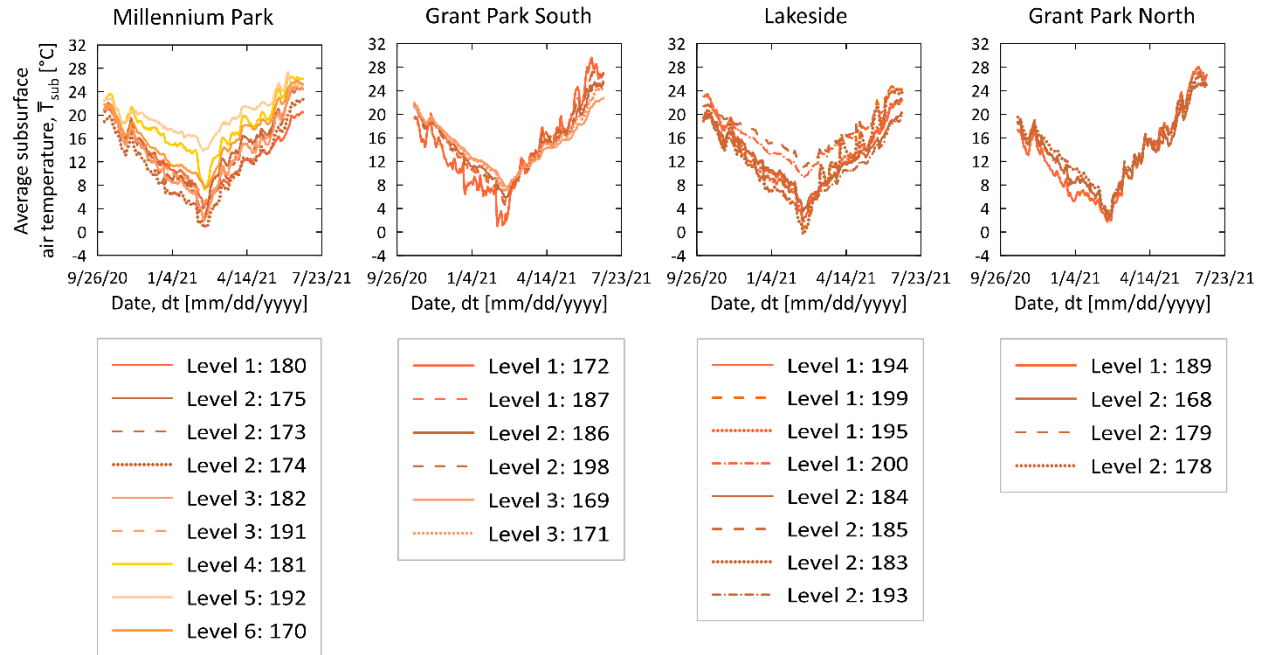


Figure 7: Daily average temperatures for selected parking garages.

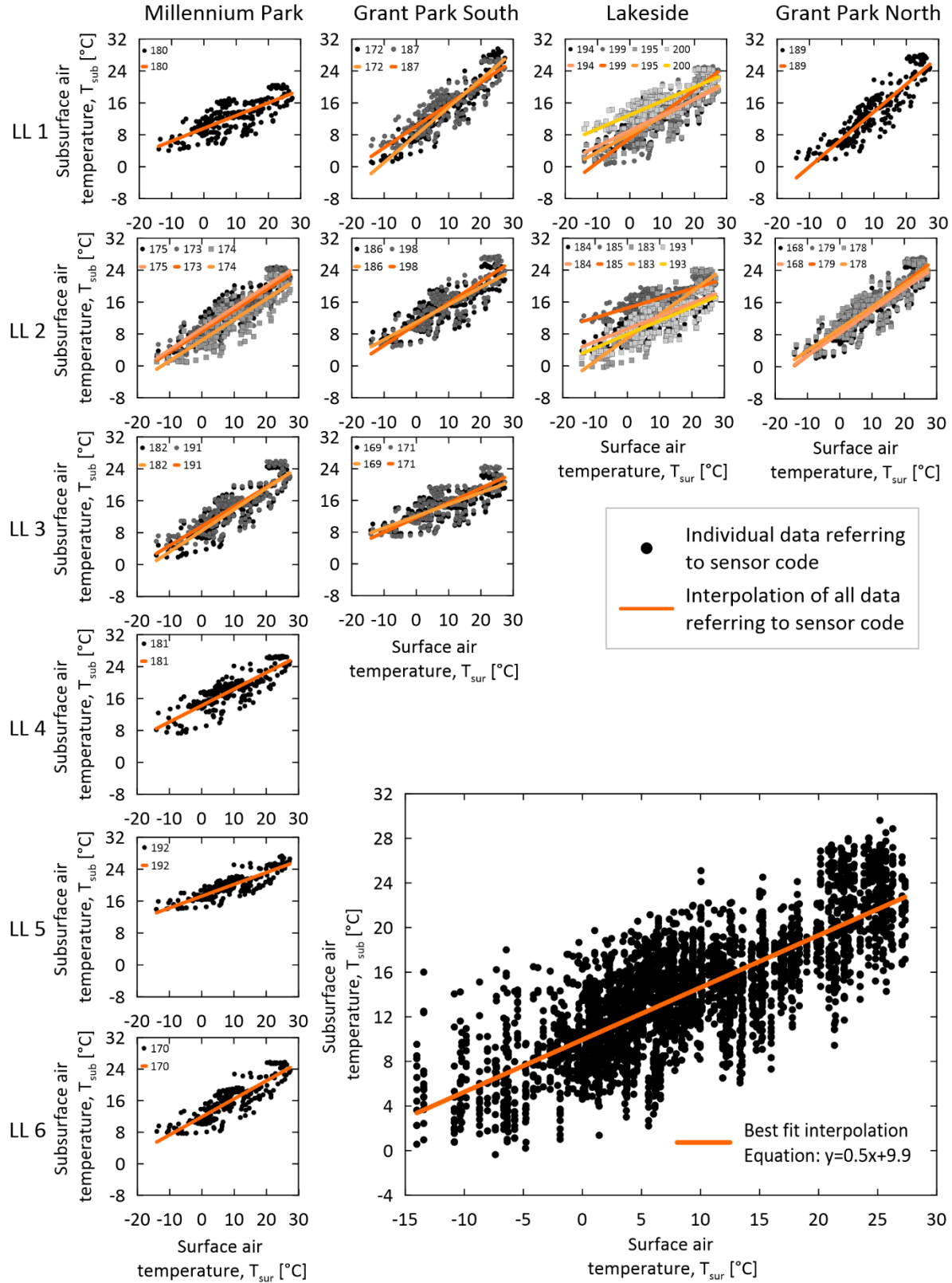


Figure 8: Subsurface air temperature for corresponding surface air temperatures for each lower level (LL) of selected parking garages.

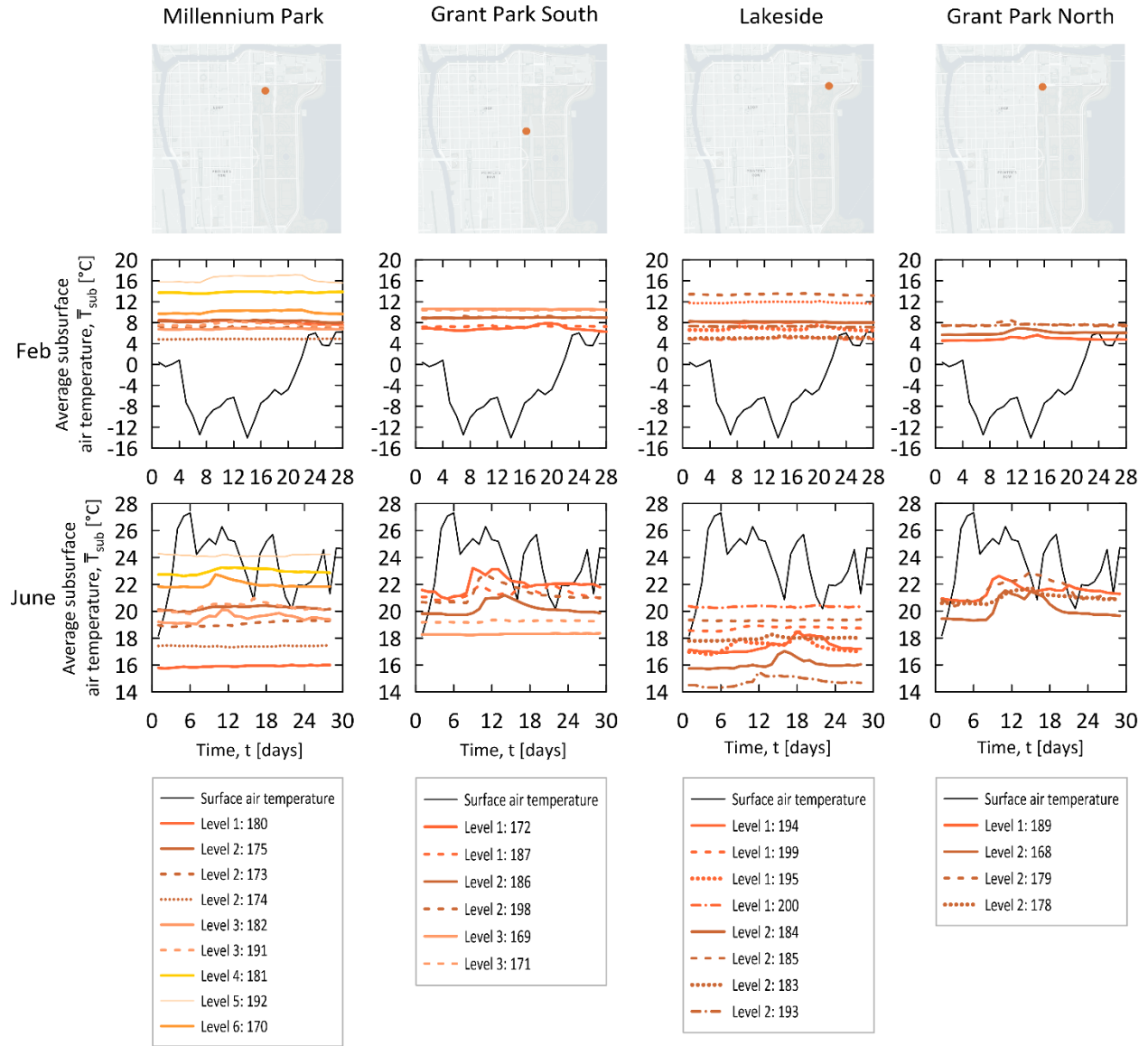


Figure 9. Daily average temperature for the peak winter and summer months of February and June 2021 for each lower level (LL) of selected parking garages.

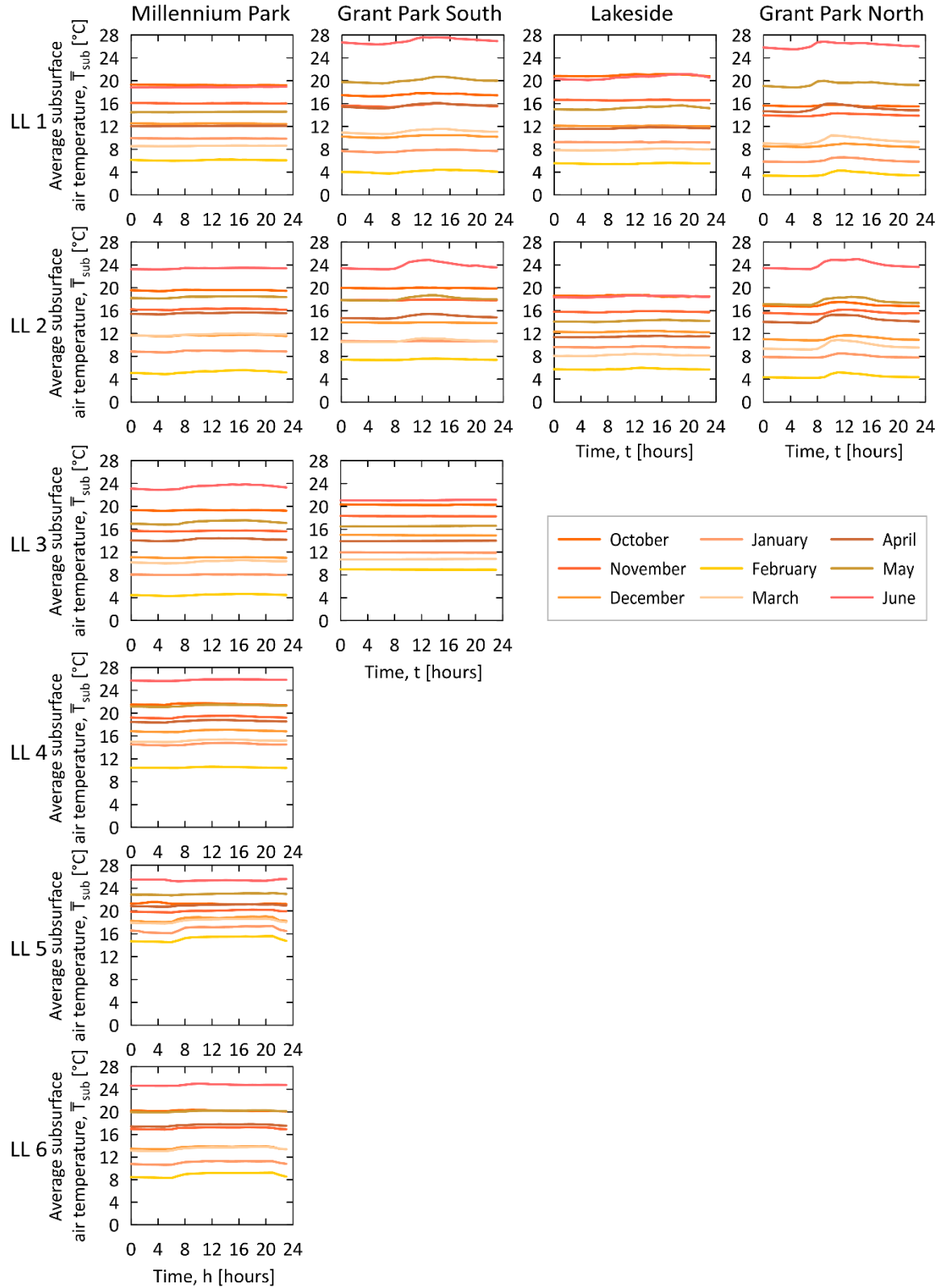


Figure 10: Hourly average temperature for each lower level (LL) of selected parking garages for the months of October 2020 to June 2021.

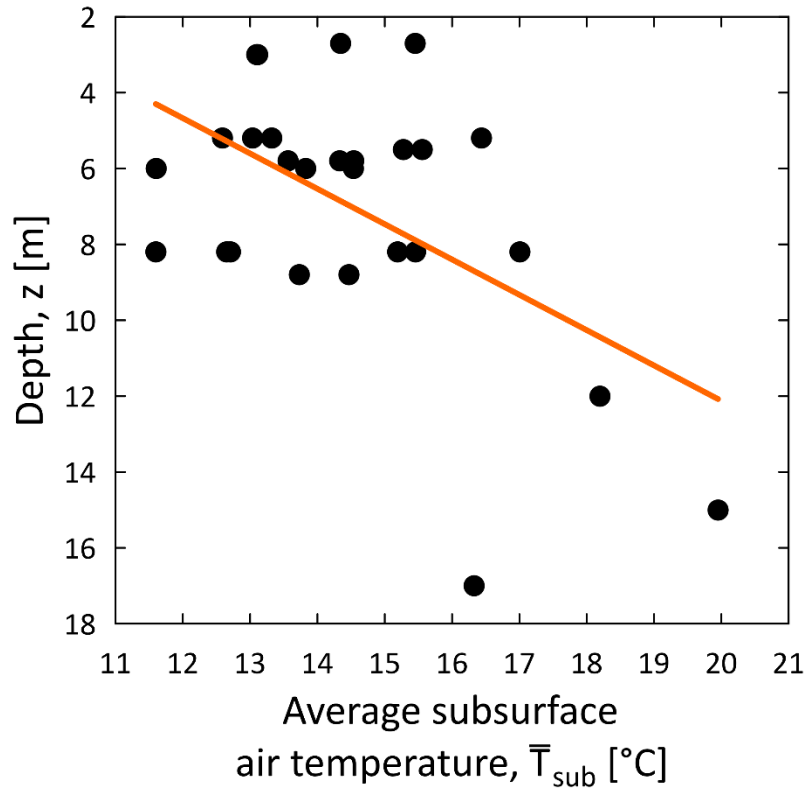


Figure 11: Annual average temperature values for selected parking garages in the depth zone of 2.7 to 17 m.

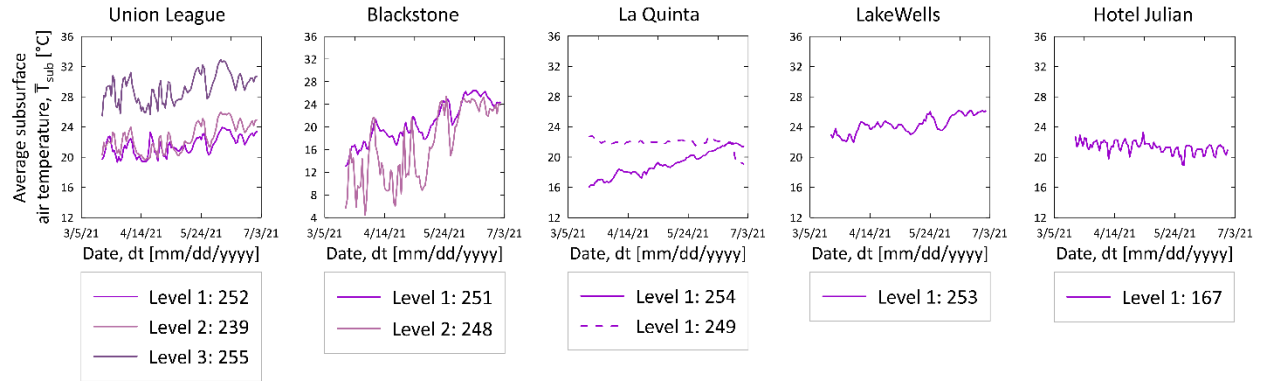


Figure 12: Daily average temperatures for selected buildings basements.

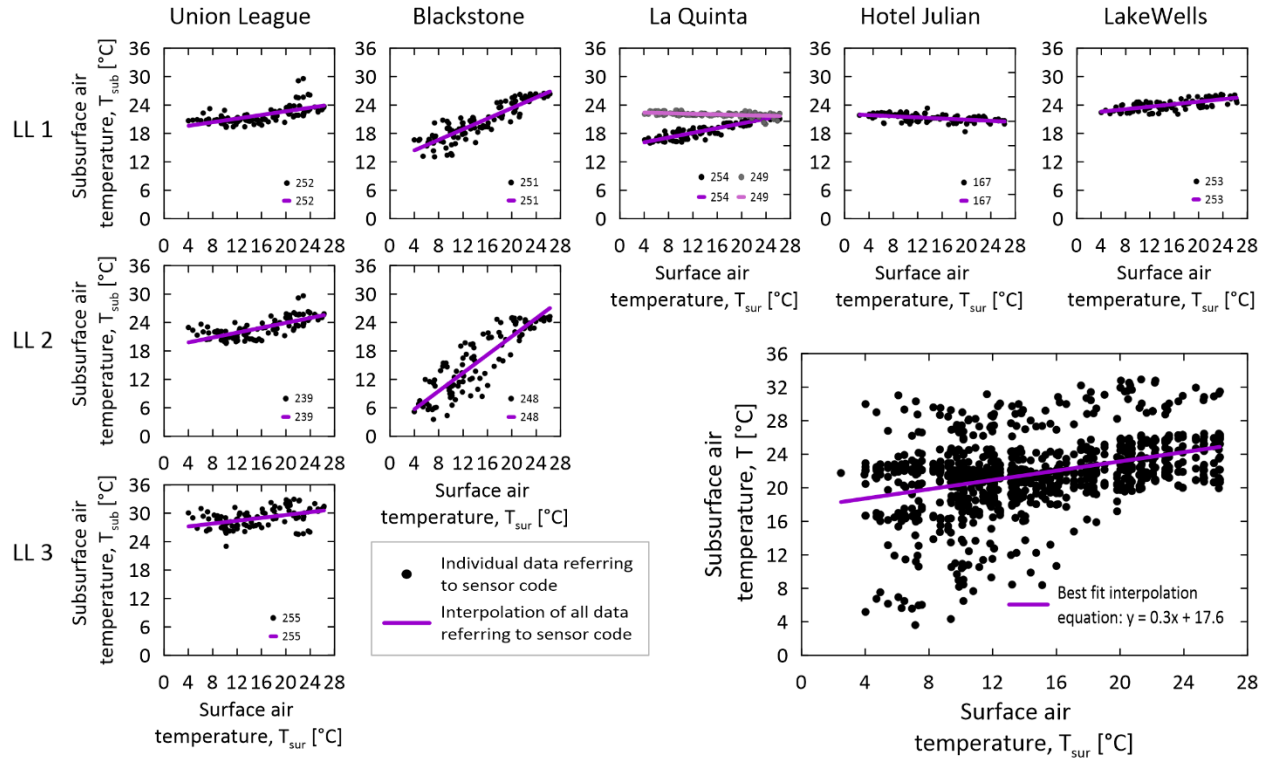


Figure 13: Subsurface air temperature for corresponding surface air temperatures for each lower level (LL) of selected buildings basements.

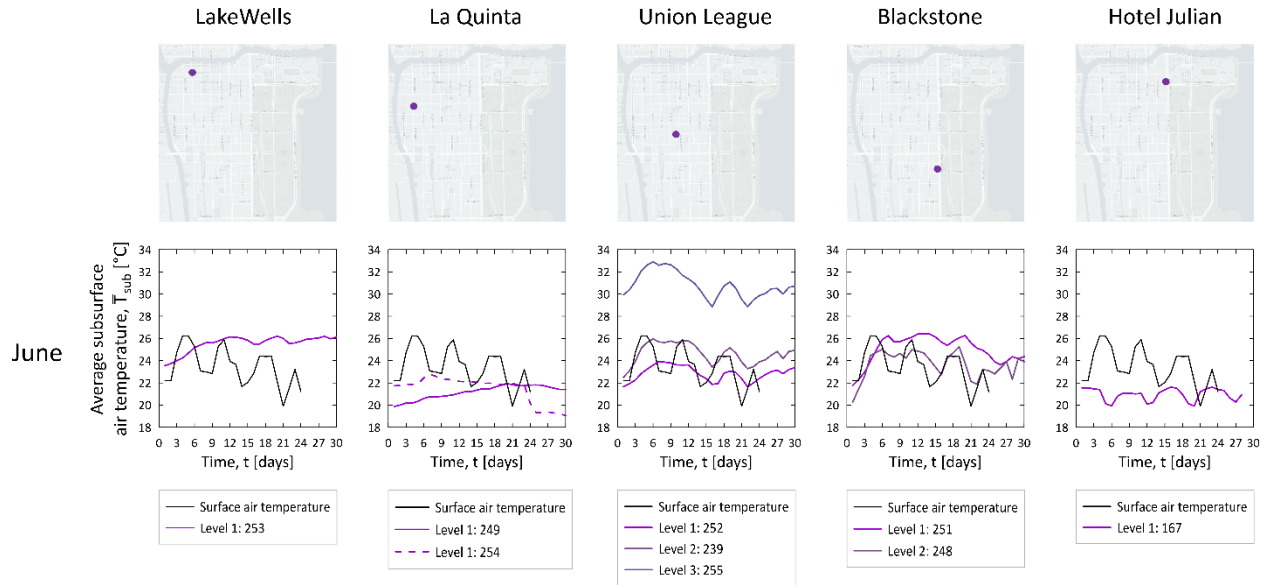


Figure 14: Daily average temperature for the peak summer month of June 2021 for each lower level (LL) of selected building basements.

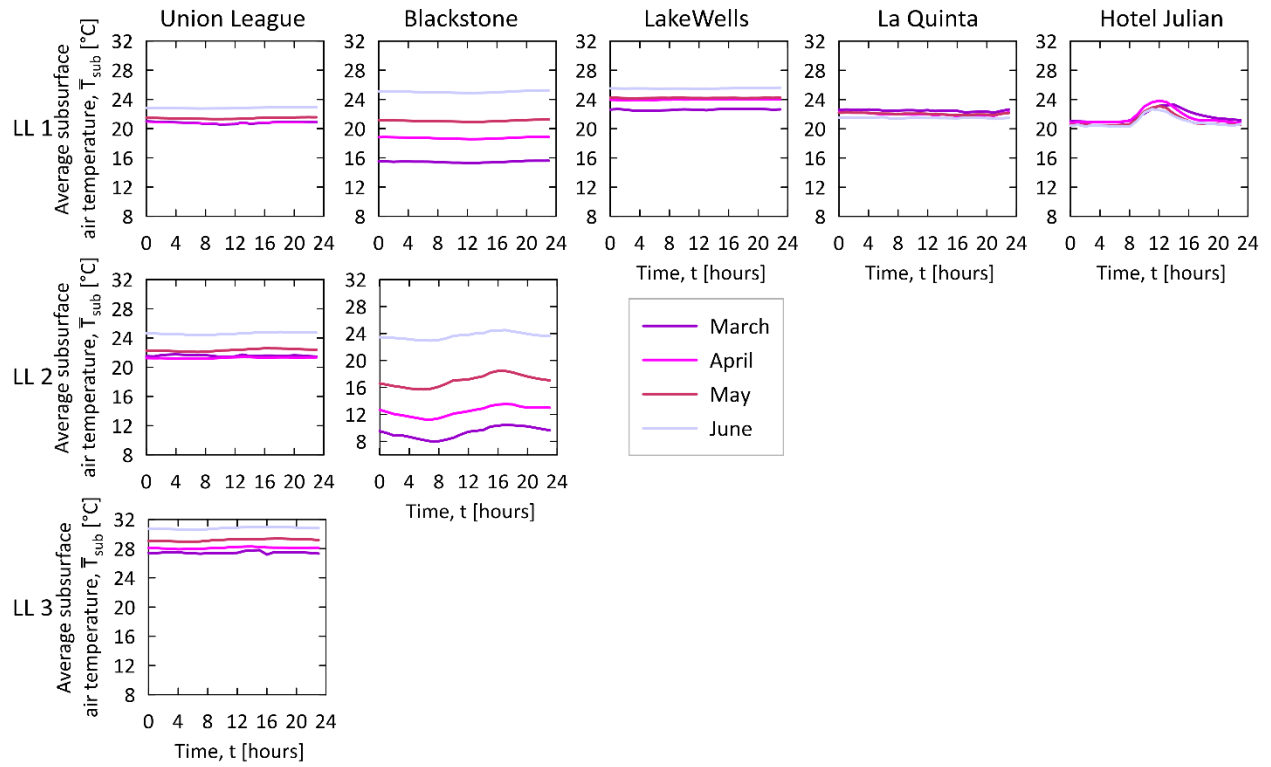


Figure 15: Hourly average temperature for each lower level (LL) of selected building basements for the months of March 2021 to June 2021.