

Surface and ambient air temperatures associated with different ground material: a case study at the University of California, Berkeley

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ABSTRACT

The urban heat island (UHI) phenomenon rises as urbanization increases. A key characteristic of urban areas is artificial surfaces, which can absorb and store great amounts of heat throughout the day. While standard pavements like asphalt and concrete have been extensively studied, newly introduced pervious pavements have not been intensively analyzed. My study examined the surface temperatures of impervious, pervious, and natural ground materials and their association to ambient air temperatures in the urban microclimate. As a case study, I investigated an area on the University of California, Berkeley campus exhibiting open areas of asphalt, concrete, brick pavers, and grass lawns. I conducted field work mid- to late-winter and collected temperatures during the warmest time of day, between 2 p.m. to 4 p.m., using an infrared thermometer for surface temperatures and digital thermometer for air temperatures. Using ANOVA, I found differences in surface temperatures of each material, but air temperatures showed no significant difference. However, a correlation test showed strong and positive correlation between the surface temperature and air temperature of each material. An ANCOVA revealed that there was no significance between the rates of heating among materials. In conclusion, I determined that the UHI effect may be minimal during the winter in Berkeley.

KEYWORDS

urban heat island, pavement, brick pavers, urban microclimate, ground study

INTRODUCTION

As urbanization increases over time, managing the urban microclimate becomes crucial. The urban microclimate is influenced by surface materials, city structure, introduction of heat, air pollution, disposition of precipitation and urban vegetation (Lowry, 1967). Furthermore, urban microclimates are often characterized by urban heat islands (UHIs), phenomena that cause city atmospheres to be consistently warmer than surrounding non-urbanized areas (Voogt & Oke, 2003). UHI intensities are affected by wind speeds, cloud cover, season, city and population size, and time of day (Arnfield, 2003). With higher temperatures, energy consumption increases and air quality worsens, affecting people's health and comfort (Svensson & Eliasson, 2002). As a result, UHIs can create a positive feedback loop that increases temperatures while emitting air particulates that reflect incoming solar radiation and trapping more heat produced by cities (Lowry, 1967).

Generally, the UHI can be divided into the urban canopy layer (UCL) and the urban boundary layer (UBL). The UCL consists of the air between the ground and roof level and is influenced by its immediate surroundings such as materials used and geometry of the area. The UBL consists of the layer above the UCL and exists on a local scale. The UBL is more affected by wind since nothing deters airflow whereas at the UCL, "urban roughness" elements from buildings and tree canopy shelter the surface from winds (Arnfield, 2003; Oke, 1976). This study focused on the UCL. Surface temperatures are affected by the thermodynamic properties of the surface materials, which incorporates surface moisture, thermal absorption and emission and radiative input from the sun and atmosphere (Voogt & Oke, 2003). Surface temperatures are thus largely affected by the type of material used on the surface.

Cities are largely characterized by impervious surfaces where water cannot percolate into the soil, including streets, sidewalks and parking lots. These surfaces are generally composed of cement, asphalt, brick, pebbles or aggregates, which absorb and store radiation throughout the day and slowly release heat through the night (Buyantuyev & Wu, 2009). Planners and architects typically focus on day-time conditions, since people are most active during daylight hours (Svensson & Eliasson, 2002). Yet, the UHI effect was shown to be strongest during calm nights when stored heat from the built environment is released into the atmosphere (Doulos, Santamouris, & Livada, 2004). Thus, it is crucial to carefully consider the type of material used

in urban design or planning to create and manipulate spaces that are beneficial to the environment, as well as human health and comfort.

Since the urban environment is predominantly covered by artificial pavement, it is important to decide what types of materials to use based on their individual characteristics. Impervious surfaces absorb high heat loads, which increase air temperatures through heat convection (Doulos et al., 2004) and also increase the rate and temperature of runoff during storms (Barnes, Morgan, & Roberge, 2000). The albedo of a material must also be considered as it determines how much light is reflected. Materials with high albedo, generally lighter-colored materials, are cooler as they reflect more solar radiation. Darker materials generally absorb more heat than lighter materials, and rougher surfaces also tend to absorb more heat as their surface area increases (Doulos et al., 2004). Still, additional factors such as heat storage capacity must be considered. As Asaeda, Ca and Wake (1996) showed, during the day, the surface temperature of black-top concrete was less than asphalt, but at night it was reversed due to the amount of heat stored by the concrete material. While there have been many studies on how pavement affect the microclimate, few ground studies investigate how pervious pavement compare to standard pavement or natural cover.

My study aimed to determine how surface temperatures affect ambient air temperatures in an urban environment. My research questions were: How do the surface temperatures of impervious, pervious, and natural materials compare with each other? And how do surface temperatures correlate with ambient air temperatures? I expected to find that surface and air temperatures of impervious materials will generally be warmest since they absorb and store large amounts of heat. I also expected to find that air temperatures above artificial pavement will be warmer than over natural cover as heat convection occurs over artificial pavement and evaporation occurs over natural cover.

METHODS

Study system

My study system was the University of California, Berkeley (UCB) campus in Northern California. The campus is directly surrounded by urban landscape to the north, south, and west,

and by parks and hills to the east. The San Francisco Bay is 4 km west of the campus. Due to its geographical location and physical topography, both Berkeley and the surrounding San Francisco Bay Area have a Mediterranean climate, characterized by warm, dry summers and mild, wet winters. I chose to analyze the UCB because it uses a few types of pervious pavement throughout the campus. The types of land cover assessed for this study were impervious pavement (asphalt and concrete), pervious pavement (brick pavers) and natural cover (grass) (Figure 1). These types of cover allow different rates of permeability for water to infiltrate underlying soil, affecting the temperature of the ground.

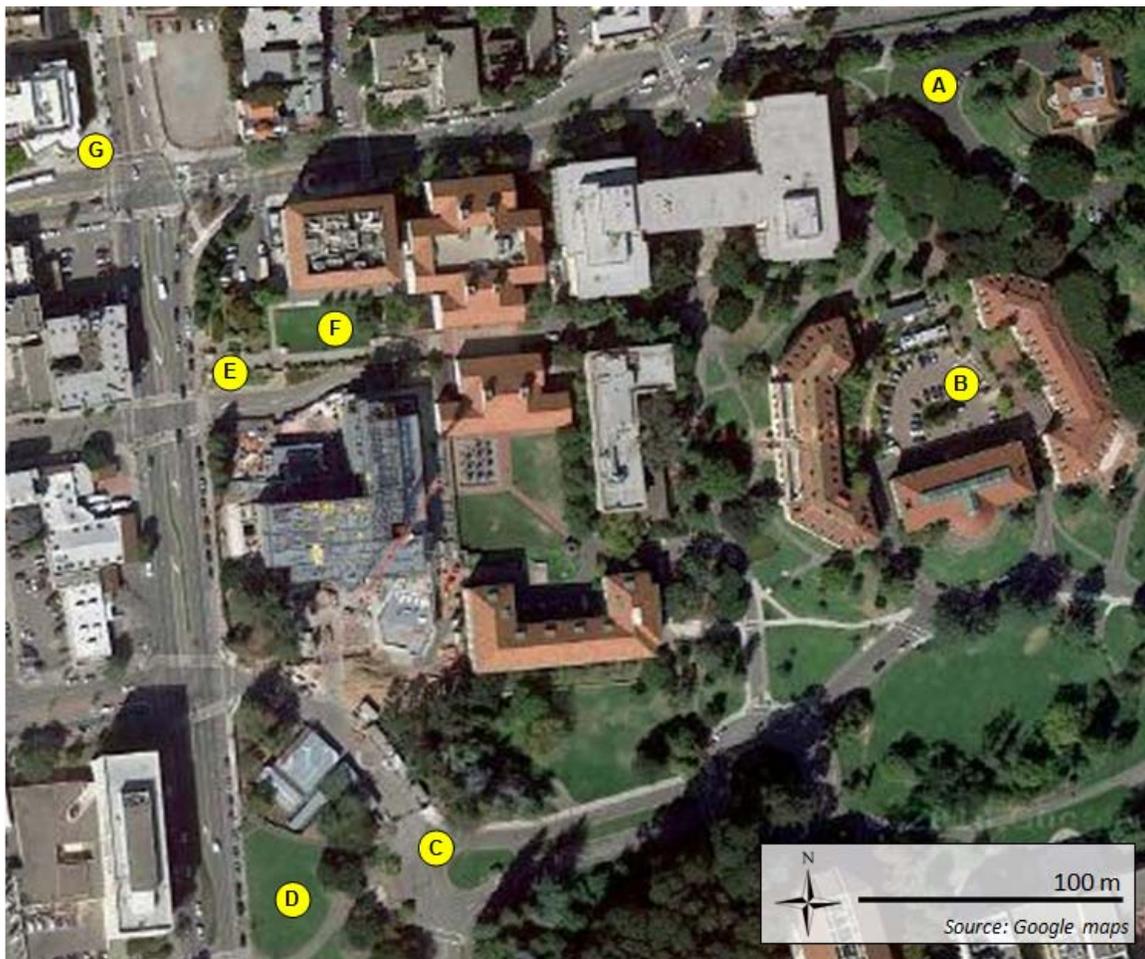


Figure 1. Map of study sites on UCB campus. My study sites were on the northwest corner of campus, bounded by Hearst Avenue to the north and Oxford Street to the west. A – asphalt (University House), B – brick pavers (Wellman Courtyard parking lot), C – asphalt (West Circle), D – grass (West Circle), E – concrete (Barker Hall), F – grass (Barker Hall), G – concrete (Earl Warren Hall).

Site criteria

To determine the study sites, I used a digital orthophoto to find areas that had multiple types of cover relatively close to each other yet large enough that neighboring materials did not affect temperature readings. Sites were located in open and mostly flat areas with no shade to reduce variables and to allow surfaces to be exposed to maximum sunlight throughout the day. Sites were also not heavily irrigated to affect surface temperatures. Surfaces per material were uniform in color or texture. Asphalt surfaces were mostly black, concrete surfaces were generally smooth, and grass sites had similar maintenance schedules.

Field days were mostly clear to clear, sunny days with forecasted temperatures to be at least 18.5°C for surfaces to have maximum exposure to solar radiation. Days were also calm with minimal winds for accurate air temperature readings. Data were collected in winter months from January to April 2011.

Data collection

I used a Raytek Raynger ST IR thermometer to collect surface temperatures and a thermo-hygro digital thermometer to collect air temperatures. I measured both types of temperature readings 1.5 m above the surface and at least 1.5 m from the material's perimeter (Asaeda, Ca, & Wake, 1996). I collected temperature measurements for each material during the warmest time of day, generally between 2 p.m. to 4 p.m. and took the average of 4 surface temperature readings. In order to collect stable air temperature readings, I took measurements when there were no winds.

Statistical analysis

Differences between surface temperatures in materials

I used the statistics software R and R commander (R Development Core Team, 2009; Fox et al., 2009) to run an ANOVA test to assess differences in mean surface temperatures across all materials and used a Tukey-Kramer test to determine how the materials compared to each other (Doulos et al., 2004).

Surface temperatures versus air temperatures

Using R and R commander (R Development Core Team, 2009; Fox et al., 2009), I ran an ANOVA test to assess if mean air temperatures above different types of materials were different, then used a linear regression test to determine if a correlation exists between surface and air temperatures. I used an ANCOVA test to determine if there were differences between the rates of heating between different materials.

RESULTS

Weather characteristics

I collected measurements on days forecasted to be between 17°C to 21°C. During these collection periods, there were minimal to no winds. While most of my observation days had clear skies, some collection days were mostly clear with some clouds or slight haze. I collected data late January to early February and late March to early April of 2011 when weather permitted.

Analysis of differences between surface temperatures in materials

Average surface temperatures varied between all of the materials. Asphalt (40.0°C) and brick pavers (37.3°C) were the warmest materials and grass (25.4°C) was the coolest material (Table 1). An ANOVA produced significant results ($F(3,45) = 9.77, p << .01$). Further analysis using a Tukey-Kramer test revealed differences among individual materials (Figure 2).

The results showed no significant difference between asphalt vs. concrete, asphalt vs. pavers, and concrete vs. pavers. However, there was a significant difference between all artificial materials and grass.

Analysis of the effect of surface temperatures on air temperatures

The air temperature above the different materials did not mimic the trend shown in surface temperatures (Figure 3). All average air temperatures were between 24°C to 25°C (Table 2). An ANOVA showed that there was no significance between air temperatures ($F(3,45) = 0.05, p = 0.99$). However, surface temperatures showed positive and moderately strong correlation to air temperatures as surface temperatures rose (Figure 4; Table 3). An ANCOVA did not produce significant results between the slopes of each material.

Table 1. Average of surface temperatures. Asphalt depicted warmest surface temperatures, followed by the pavers, concrete, and grass.

Material	Average surface temperature (°C)
Asphalt	40.04583
Concrete	33.62333
Grass	25.37214
Pavers	37.27909

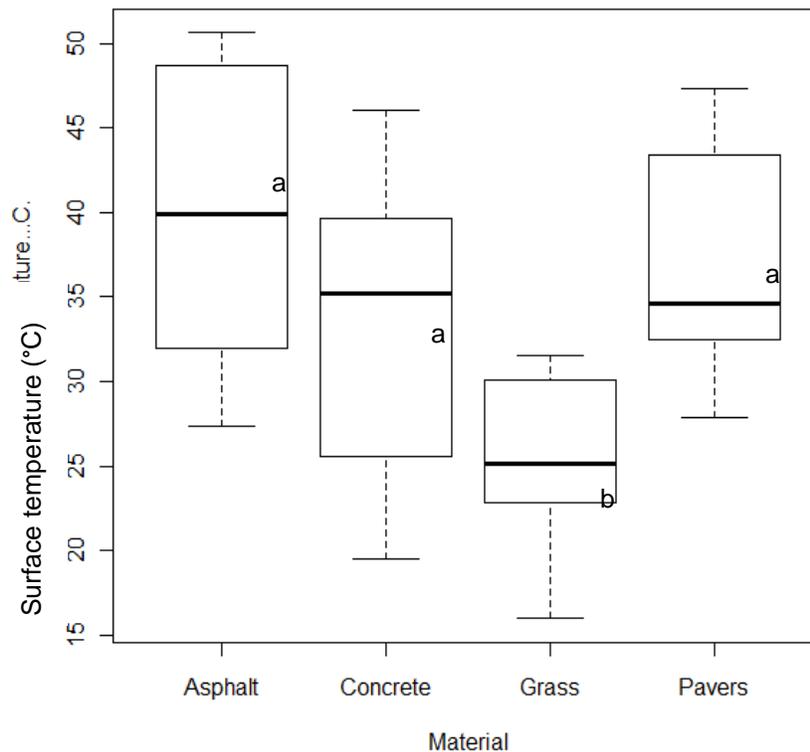


Table 2. Average of air temperatures. The mean air temperatures above all materials were very similar. They were all around between 24°C to 25°C.

Material	Average air temperature (°C)
Asphalt	24.92500
Concrete	24.83333
Grass	24.67143
Pavers	24.25455

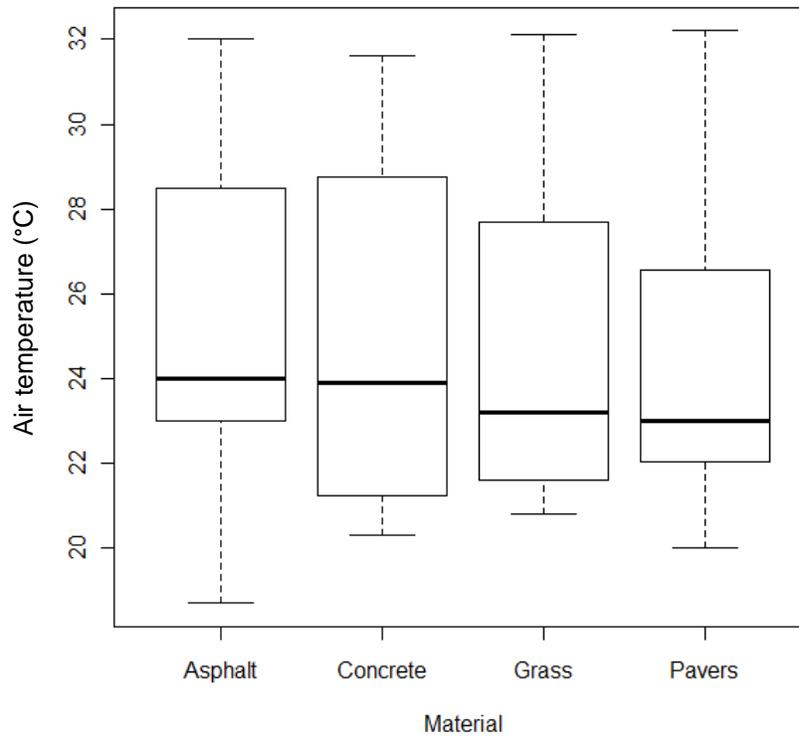


Figure 3. Distribution of air temperatures above ground surface. The boxplot shows the distribution of air temperatures with the bold lines depicting the median temperature of each material. Air temperatures were similar above each material most likely due to cooler winter temperatures. There was no significant difference in air temperatures.

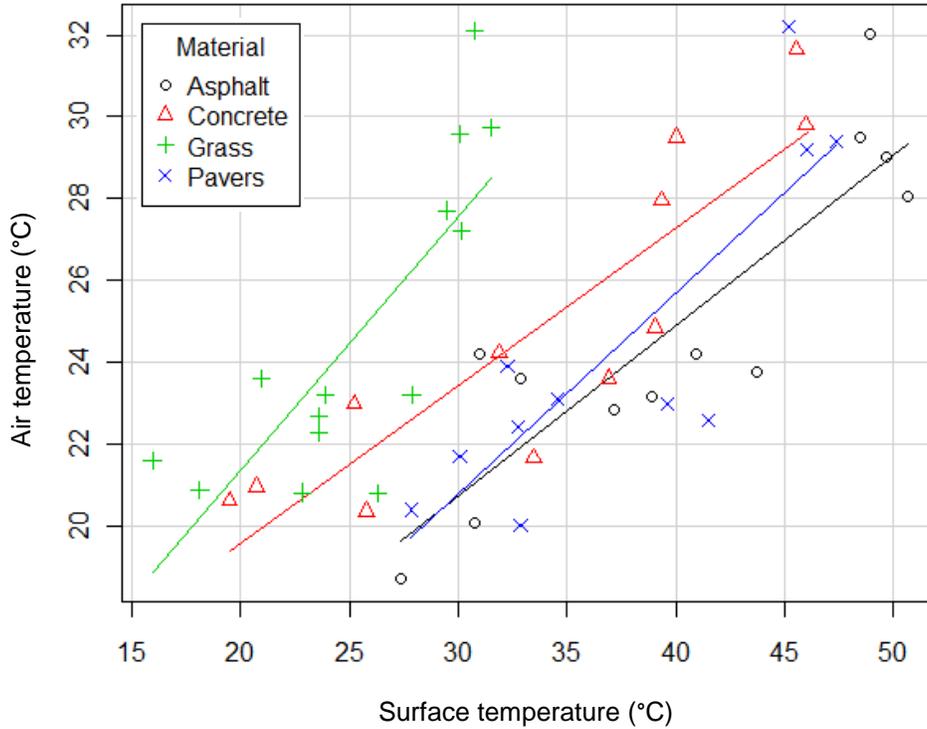


Figure 4. Surface temperatures vs. air temperatures. All materials showed moderately strong and positive correlation between surface temperatures and air temperatures.

Table 3. Correlation of materials. All materials showed moderately strong correlation between surface temperatures and air temperatures. All materials also show significant values.

	Asphalt	Concrete	Pavers	Grass
R²	.7722	.704	.7103	.627
p-value	.0001678	.0003363	.001124	.0007377

DISCUSSION

Differences in surface temperatures

The objectives of my study were to determine if there were differences in surface temperatures of various ground material and if these surface temperatures affect the ambient air temperature above the corresponding material. Based on my results, different ground materials have distinctly different surface temperatures. These differences are determined by pavement composition, thermal properties, color, and texture. Depending on material composition, each

type of pavement has its own heat storage capacity, which is affected by solar absorption, reflectivity, and surface emissivity (Tan & Fwa, 1992). The color of surfaces also affects surface temperatures by affecting the albedo of a material. Darker surfaces absorb more solar radiation and have low albedo, while lighter surfaces reflect more light and have higher albedo (Sailor, 1995). Generally, asphalt is black and absorbs a high heat load, however, the albedo of asphalt increases with age as the surface becomes lighter over time (Pomerantz, Akbari, & Chang, 2000). Furthermore, the texture of a surface affected the direct absorption of solar radiation. Smoother surfaces were cooler while rougher surfaces were warmer due to having more surface area exposed to direct sunlight over the course of a day (Doulos et al., 2004). As all materials absorb solar radiation during the day, they reradiate the stored heat during cooler nights, warming ambient air temperatures (Svensson & Eliasson, 2002).

Comparable ambient air temperatures

While there were major differences within surface temperatures, variations within air temperatures were not apparent. Similarly, while there were moderately strong correlations between surface and air temperatures, there were no differences between the rates of heating. Due to seasonal and climatic effects, air temperatures were not largely affected since materials were not exposed to enough sunlight. During warmer summer months, ground materials are exposed to more intense radiation from the sun and absorb more heat. As solar radiation is absorbed, surface temperatures increase until ambient air temperatures also increase through convection from the materials. However, temperatures remain relatively cooler over natural cover due to evapotranspiration (Lin, Ho, & Huang, 2007). Generally, air temperature variations above different materials are not as readily apparent during cooler winter months since net differences between the ground and air temperatures are not as large as during the summer (Klyzik & Fortuniak, 1999).

Similar studies were conducted during the winter, however, they compared winter results to summer results. Interestingly, Sofer and Potchter (2006) found that the intensity of the urban heat island was stronger in the summer than the winter in Eilat, Israel, a hot, arid region. However, Yang, Lau, and Qian (2011) found that the urban heat island effect was strongest in

late autumn and winter months in Shanghai, China, largely due to the dense and tall urban design of the area, reaffirming that city structure affects city temperatures.

Site variability

While I created a set of criteria to reduce the amount of variability during site selection, other considerations on the site level may influence temperature readings. I found sites that were big enough so that neighboring surfaces would not affect my data, I did not quantify for a specific surface area or depth of material. Depending on the volume of the material, it can store more heat with greater depth while releasing more total heat over greater surface areas as compared to materials with thinner or smaller surface areas (Tan & Fwa, 1992).

Furthermore, since my study system was on the UCB campus, test sites were prone to changing each day. The site with the brick pavers was located at the Wellman Courtyard parking lot (B). It was surrounded by buildings and often occupied by parked vehicles. Depending on the time of day or the day of the week, the lot varied from being full to almost empty. Though I took temperatures away from cars, the presence of parked vehicles could have affected air temperatures to be warmer. Further investigation to examine the material underneath the brick pavers could also reveal miscellaneous factors that may influence both surface and air temperatures (Scott, Simpson, & McPherson, 1999). On the other hand, the grass lawn in front of Barker Hall (F) is located above an underground parking lot, which may interfere with natural processes and affect temperature readings. Grass lawns were also difficult to control for as their growth and length varies. Longer grasses keep soils moist and cooler than short grass (Blaylock & Davis, 1994). Other times, there was heavy pedestrian traffic as I collected air temperatures, which may have also affected air temperature readings. Sites (C), (D), (E), and (F) may have also been affected by construction between them (Figure 1).

Limitations

Because of the timeline of my project, I was only able to collect data during winter months. My study period was not ideal as it was mostly cold and wet, with rare warm days that were suitable for field work. I collected minimal measurements resulting in non-normal data and

transforming the data did not normalize them. The possible sites for pervious pavement study were also limited due to my site criteria. Other locations with pervious pavement on campus were covered in shade, thus I collected temperatures at the Wellman parking lot twice to substitute a second site. Finally, using more standardized instruments to collect continuous data would have shown broader trends in temperatures, but the campus is very lively and would have been liable to be tampered with by people or animals.

Future directions

Future studies should investigate temperature variations in hotter climates at a seasonal level. Research may reveal how land cover surface and air temperatures differ seasonally, allowing planners and designers to use appropriate materials to account for changing weather. It is also worth investigating how both surface and air temperatures differ between standard artificial pavements and recently introduced permeable pavements. Since there are several forms of permeable pavements, research can reveal the characteristics of each type. Initial investigations can use created samples to compare materials strictly on their thermal properties. A more extensive study can also consider how these materials interact in the environment with surrounding vegetation and buildings.

Broader implications and conclusions

In conclusion, I found significant surface temperature variations between different urban ground materials but was unable to show that the absorbed heat affected the ambient air temperature above. This implies that Berkeley may not have an intense UCL to passively mitigate during the winter. However, hotter locations may benefit from such studies to cool down their cities, even during the winter. Using this passive mode of cooling temperatures would benefit air quality and reduce energy use since air conditioning and other artificial means of cooling would be reduced.

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