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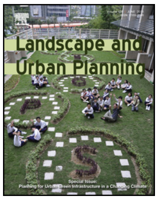

Research Paper

Thermal comfort of outdoor spaces in Lahore, Pakistan: Lessons for bioclimatic urban design in the context of global climate change

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HIGHLIGHTS

- We measured the microclimate in two contrasting outdoor environments in Lahore, Pakistan.
- The air temperature and humidity did not vary between or across sites.
- Shade from the sun was determined to be the most effective way to reduce the heat loads on people.

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ABSTRACT

Humans interact with urban microclimates through exchanges of energy. A surplus of energy can create thermal discomfort and be detrimental to human health. Many cities in warm regions all over the world are forecast to become very hot through global climate change. Some cities already experience extreme heat and have done so for centuries. We conducted a study of one such city in order to generate design guidelines for creating thermally comfortable outdoor places. In the hot, dry city of Lahore, Pakistan we compared the microclimates of two very different outdoor spaces. The first place was the 16th century Shalimar Garden, which contains much green infrastructure and water features. The other example was the hard-surfaced courtyard of the contemporary Alhamra Art Centre. In both places we measured the microclimatic characteristics and used those data to simulate thermal sensation through the energy-budget model COMFA. The measured air temperature and humidity in both spaces was similar. However, the solar radiation that would be received by a person in the Alhamra courtyard was much higher than in Shalimar Garden and was the main determinant of thermal discomfort. Results from this study can inform other cities in hot, dry climates about design responses that provide more outdoor thermal comfort and prevent health-threatening heat.

1. Introduction

There is compelling evidence that the global climate is warming and it is likely happening faster than is being generally reported (Brysse, Oreskes, O'Reilly, & Oppenheimer, 2013). Concurrently many cities are experiencing intensified urban heat islands (UHI) (e.g., Oke, 2010, Jim, 2015). Overheated conditions can have serious effects on the health and well-being of urban residents. The 2003 heat wave in Europe, for instance, was estimated to have killed 40,000 people (García-Herrera, Díaz, Trigo, Luterbacher, & Fischer, 2010).

The level of thermal discomfort that a person experiences during hot weather is generally understood as a surplus of energy (e.g., Brown & Gillespie, 1995, Mayer & Höppe, 1987, Parsons, 2003). Human bodies interact with their immediate environment through exchanges of energy (Brown, 2010). Energy is added to a body through metabolic heat and absorbed radiation while heat is lost from a body primarily through convection, evaporation, and emitted radiation. Several physics-based models have been developed to estimate the flows of energy to and from individuals under different conditions (Epstein & Moran, 2006). If the total amount of energy received is larger than the amount lost, a person will heat up over time. As a person overheats they might experience a wide range of symptoms including fatigue, headaches, nausea,

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and reduced capacity to work (Vanos, Warland, Gillespie, & Kenny, 2010) and if the surplus continues it can lead to hyperthermia and death.

Both global climate change and urban heat islands are often considered only in terms of air temperature (e.g., Grimmond & Oke, 1999; Houghton et al., 2001; Oke, 1987) but other parameters must also be considered (Vanos et al., 2010). There are seven parameters that affect the energy budget of a person in an outdoor environment: (1) air temperature, (2) air humidity, (3) wind, (4) solar radiation, (5) terrestrial radiation, (6) metabolic heat, and (7) clothing insulation (Brown & Gillespie, 1986). The first five parameters are affected by urban environments while the latter two relate to individual choice. Solar and terrestrial radiation and wind are strongly affected by the landscape at the local (microclimate) scale. Air temperature and humidity are known to be conservative at the microclimate scale (Brown & Gillespie, 1995, Mayer & Höppe, 1987) but can be affected by the landscape at the neighbourhood (mesoclimate) level (Oke, 1987). For example, air temperature measured at 1.5 m above the ground changes very little over short distances (metres to tens of metres), but it can be quite a bit cooler in the middle of a large green space than in a concrete and asphalt urban core.

The design of cities affects how the prevailing climate will be modified to create mesoclimates. For example, the orientation of streets affects how winds will flow through a city. And the width and orientation of streets affects how much solar radiation will be received by people and surfaces in the landscape. Climate-responsive urban design can create microclimates that people experience as feeling cooler than the prevailing climate, making urban areas both safer and more pleasant. These design principles have been discussed more generally in the older literature (Egli, 1951; Rudofsky, 1964, 1969; Sullivan, 2002), but recently more specific literature has focused on urban microclimates and climate responsive design (e.g., Brown, 2010, Brown, Vanos, Kenny, & Lenzholzer, 2015, Laue, 2009, Lenzholzer, 2013, Littlefair, 2000, Stuttgart, 2008). Still, there are many examples of urban design that do not consider the climate-modifying effects. Such urban design examples have the potential to create environments that people experience as much warmer, and in some cases uncomfortably hot conditions.

Climate change is not occurring at the same rate everywhere. Areas such as the Middle East are experiencing a disproportionally large increase in the frequency and intensity of hot weather conditions (Lelieveld et al., 2012). And cities that are already very hot, such as Lahore Pakistan, additionally experience urban heat islands (Sajjad, Shirazi, Khan, & Raza, 2009). Studying the relationship between urban form and microclimate in cities like Lahore can provide valuable lessons – both for keeping Lahore residents cool while the climate heats up, but also to inform temperate-climate cities that will be much warmer in future.

There is little that an individual can do to slow or stop global climate change (Brown, 2011). With billions of urban residents in the world the action of one person is miniscule. This issue requires global action. However, that doesn't mean that urban residents are destined to live in overheated conditions. Urban open spaces that are designed following the principles identified by this study have the potential to be places where people feel comfortably cool during hot weather, even in the face of a warming climate. And thermally comfortable microclimates have the potential to counteract the effects of urban heat islands.

The goal of this study was to identify urban landscape characteristics that increase or decrease thermal discomfort of residents in very hot conditions. This goal was addressed through: (1) measurement of the microclimate in two contrasting urban outdoor spaces in one city; (2) modeling of the thermal comfort conditions of the two spaces and comparing them with prevailing conditions; and (3) identifying climate-responsive urban design guidelines for reducing thermal discomfort in hot conditions.

2. Methods

The city of Lahore Pakistan was selected for our study, based on its extremely hot, semi-arid climate (Köppen BSh), and a wide range of different public outdoor open spaces. Two sites within Lahore that had contrasting site characteristics were selected for study. Based on energy budget theory (e.g., Oke, 1987) a site that has mostly hard, dry, unshaded surfaces would generate a substantially different microclimate from a site that consisted mostly of green, vegetated, shaded surfaces. There were many candidate sites but two places that met the criteria and also afforded public access were the courtyard of the Alhamra Art Centre and Shalimar Garden.

Shalimar Garden (Fig. 1) is a centuries-old open space consisting of 62% shade trees, 18% grass, 7% water ponds, and 13% brick pathways and brick boundary wall. The Alhamra Front Courtyard (Fig. 2), in contrast, is a contemporary open space consisting of 100% hard, unshaded surfaces (brick, steel, glass, asphalt, and concrete).

Two microclimate stations were established for the study: one that was placed each day in the full sun away from buildings and trees to provide a measure of prevailing conditions; and a mobile station that was moved around the site to measure different microclimatic conditions. The locations of the measurement sites are noted for Shalimar in Fig. 3 and Alhamra in Fig. 4. Each station was equipped with the following instruments: HC-S3 Rotronic HygroClip temperature and relative humidity probe; NRG#40C cup anemometer; NRG#200 wind vane; and a Li-Cor pyranometer (see Fig. 5).

Data were collected for a total of 5 days at the Alhamra front courtyard and 7 days at Shalimar Garden during November and December, 2010. For the first half hour of each test day the stations were set side-by-side in the open and the recorded measurements were used to test and calibrate the instruments each day. This ensured that any differences in readings were not due to instrument variation. Data were recorded by both stations once every minute and averaged over each hour. The mobile station was moved to new test locations on site after each one-hour interval.

Hourly air temperature, relative humidity, and wind speed data were acquired from the local weather station for the test days. Pakistan does not observe daylight savings time and Lahore is almost exactly in the middle of the time zone so there was no need to adjust any readings for variations in clock- versus sun-time. In addition, the local weather station in Lahore does not record solar radiation so this value was estimated using the process described in Brown and Gillespie (1995). Given the generally cloud-free skies during hot sunny weather these estimates would be expected to be very accurate.

The on-site measurements were compared with the measurements taken at the local weather station to establish the relationship between the two data sets.

After having collected on-site data, we used a human thermal comfort model to estimate energy budget surpluses or deficits in all of the test conditions. There are several human energy budget models available in the literature (Epstein & Moran, 2006). We wanted to be able to identify the relative magnitude of the streams of energy to and from a person so as to be able to suggest design guidelines that would address the main energy flows so we selected COMFA (Brown & Gillespie, 1986) for use in this study. This energy-budget model has been validated and used in a wide range of situations (e.g., Kenny, Warland, Brown, & Gillespie, 2009a, 2009b; Vanos et al., 2012) and allows direct input of meteorological measurements (Brown & Gillespie, 1995). It also provides quantitative estimates of each stream of energy allowing the identification of