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Micro-scale thermal performance of tropical urban parks in Singapore

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ABSTRACT

As Singapore is near the equator, heat is a concern, especially given the increasing yearly average temperatures and significant urban heat island effects. National greening policies propose increasing the number of parks; this may indirectly benefit thermal conditions at a macro level, but there has been little consideration of the thermal environment within these spaces. This study examined micro-scale thermal conditions within 10 urban parks at the hottest period of the year, assessing operative temperature with three measurement variables: air temperature (t_a), globe temperature (t_g), and wind velocity (v). It found that 1) thermal performances between and within parks range widely, and 2) critical thermal points in the respective parks highlight the value of shade, especially in terms of volume and continuity over a length of path. The findings suggest the need for a quantitative study of design factors to guide the future planning and design of climatically adapted parks in the tropics.

1. Introduction

The equatorial climate of Singapore ensures high temperatures year round, with a diurnal maximum temperature of 31 °C–34 °C and a minimum of 23 °C–26 °C [28]. On top of this, the heat has been intensifying in the city-state, with an observed increase of 0.25 °C in the average temperature every decade since the 1970s [18]. Singapore also experiences the urban heat island effect because of its urban development [31,36,45], with an overall average temperature difference of up to 4 °C island-wide [48]. Air-conditioning, used throughout Singapore to mitigate high temperatures, not only increases energy consumption, but worsens the urban heat island effect [25]. In the face of such conditions, the land use planning and conservation authority of Singapore is conducting island-wide studies in a bid to manage the urban heat at the macro level [46]. Discrepancies in temperatures measured on sites and by official weather stations highlight the inadequacy of relying on general regional measurements taken by fixed weather stations [12] suggesting the need to calibrate the value of the 'urban' temperature [19] and to use local macro-scale thermal measurements to verify the thermal experience of park users.

Many studies demonstrate the effect of vegetation and green spaces in generating thermal benefits for their urban surroundings [1,9,15,17,22,24,35,37–39,49,53]. Such spaces are found to intercept radiation, facilitate evapotranspiration, and even reduce energy consumption [2,3,5,8]. In the same vein, several studies of the local Singaporean context reach the following conclusions: the locations of large and dense green areas in Singapore correspond with lower measurements of temperature, indicating the function of vegetation quantity in reducing temperatures at the macro level [23,48,51]; temperature measurements are lower not only within parks compared to an external reference point but also in the parks' adjacent built-up environments, highlighting the ability of parks to cool their surroundings [13]; vegetation, especially mature trees, can improve microclimatic conditions within pedestrian canyons through shading [50].

Singapore has been called a "City in a Garden". Vegetation and vegetated settings are a common sight, with almost half of the city covered in green (as cited in Refs. [44]; pp. 14–15), including man-made spaces such as parks, park connectors, and roadside greenery, and natural areas such as nature reserves. Public urban parks currently constitute about 40% of all man-made green space in the city [29]. There are large-scale plans to boost recreation and biodiversity in these spaces [30] and to ensure an increased quantity of, and accessibility to, key outdoor gathering and activity nodes up to 900ha by 2020 [27]. While green policies may increase functional opportunities and indirectly benefit city-scale thermal conditions, it is believed that the park users' overall experience can be further enhanced with the concurrent consideration of micro-scale thermal aspects during the implementation of these plans.

Accordingly, this paper considers heat at the micro level and

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how it may be moderated or exacerbated by immediate park surroundings. It hypothesizes that quantifying localized thermal conditions in parks will shed light on of the experience of heat for the park user. Comparing these conditions across park settings may reveal important relationships between design and thermal aspects, setting the stage to generate guidelines useful for park design and management to regulate thermal performance. The specific objectives are:

1. To investigate the range of micro-scale thermal performance of existing parks in Singapore through on-site measurements, and
2. To identify related design parameters and examine their influence on thermal performance by identifying extreme thermal points.

The first part of the paper explains the methods employed during a field study of 10 parks in Singapore. It analyzes data gathered during the observation exercise to understand the thermal performance of these particular parks. It then assesses the different park settings by setting them against the thermal analysis, creating the basis for further quantitative study. The paper concludes by noting the limitations of the research and briefly discussing the potential for future studies.

2. Method

2.1. Defining thermal performance

In quantifying the experience of heat, the assessment of thermal performance in this study references the concept of “thermal comfort”. The concept was originally developed for indoor building spaces [34] but has been gaining recognition in the outdoor environment. Thermal comfort is defined as “the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation”. Its analysis relies on four microclimatic parameters – air temperature, radiant temperature, air velocity and relative humidity – and two human factors – metabolic rate and clothing insulation [4]. Of the microclimatic factors, air temperature, is the most relevant for the study of thermal performance in parks as it is one of the most commonly available and easily measured thermal variables [10].

The high humidity in Singapore, with a diurnal range of about 60%–90% all year round [28], cannot be easily decreased but can be offset with lower air and radiant temperature; similarly, wind cannot be easily increased through landscape approaches and requires manipulation at a larger scale of the city [10,14]. Therefore, the present study limits itself to air and radiant temperatures.

While human factors are not immediately relevant to an examination of relationships between design and thermal conditions, it is possible to examine human acceptance of the thermal performance of parks. A local study by [52] used the thermal comfort model Predicted Mean Vote (PMV) to determine the neutral and acceptable ranges of operative temperatures in the outdoor urban context of Singapore, described as thermal conditions able to satisfy 100% and 80% of people respectively [4]. The neutral operative temperature was found to be 28.7 °C, with the acceptable range between 26.3 °C and 31.7 °C [52]. The present study uses these numbers as a gauge to assess how the actual thermal performance within the parks measures up to an identified acceptable range of outdoor thermal conditions.

Parks' thermal performances can be determined by calculating operative temperatures. Commonly used in the assessment of thermal comfort, operative temperature is the “weighted average of mean radiant temperature and dry-bulb air temperature” [47]. In other words, it combines the effects of convective and radiant heat. To obtain the operative temperatures (Spirn) of the parks, we use Equation (1), requiring air temperature. We calculate mean radiant temperature (t_{mrt}) from Equation (2), an equation from ISO 7726:1998 [21] that was calibrated based on a Singaporean study; simply stated, it increases the accuracy of the measurements taken with a flat grey globe thermometer in a tropical outdoors setting [43]. In all, the measurement variables used to assess the thermal performance of parks in this study are air temperature (t_a), globe temperature (t_g), and wind velocity (v).

$$t_o = \frac{\left(t_{mrt} + \left(t_a \times \sqrt{10v}\right)\right)}{1 + \sqrt{10v}} \tag{1}$$

t_o = Operative temperature (°C)
t_{mrt} = Mean radiant temperature (°C)
v = Wind velocity (m/s)

$$t_{mrt} = \left[\left(t_g + 273.15\right)^4 + \frac{3.42 \times 10^9 v^{0.119}}{\varepsilon D^{0.4}} \times \left(t_g - t_a\right)\right]^{0.25} - 273.15 \tag{2}$$

t_{mrt} = Mean radiant temperature (°C)
t_g = Globe temperature (°C)
v = Wind velocity (m/s)
t_a = Air temperature (°C)
D = Globe diameter (mm)
ε = Globe emissivity

2.2. Site selection and observation period

In order to assess the influence of different design parameters on thermal performance, it is important to include a variety of park settings. Therefore, we conducted a separate study before the observation period to determine suitable parks. Parks located within or near to coastal and forested areas and the high-density city core were disregarded to minimize unfavourable macro-climatic influences on subsequent measurements. Ten regional urban parks distributed evenly across the island were selected (Fig. 1), and a representative path of about 500–600 m in each park was demarcated for observation at the end of the preliminary study. Measurements and mappings were to be taken at short and regular intervals of 10 m along the paths, resulting in about 50–60 points of measurements for each park.

The observation exercise was done during the warmest and driest period of the year, from March to May in 2015, and during the hottest part of the day, between 1pm and 3pm, to determine thermal performances under conditions of extreme heat and see how various park settings may augment or aggravate these. To account for slight daily weather variations, we visited each park on three different days for repeated measurements of t_a, t_g and v at each point. Measurements were made only on sufficiently sunny days, avoiding the occasional cloudy or rainy day; the entire observation period took about eight weeks.

2.3. Field measurement equipment and procedure

As measurements for several thermal parameters had to be