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Studies of outdoor thermal comfort in northern China

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A B S T R A C T

Outdoor spaces play important roles in daily lives, and the use of these spaces is determined largely by outdoor thermal comfort. Few studies have been conducted on outdoor thermal comfort in northern China. Using microclimatic monitoring and subject interviews at a park in Tianjin, China, this investigation studied outdoor thermal comfort under different climate conditions. Although outdoor thermal environment varied greatly with air temperature from −5.0 to 34.5 °C, 83.3% of respondents consider it "acceptable". Preferences in solar radiation, wind speed, and relative humidity were related to air temperature. The higher the air temperature was, the higher the wind speed and the lower the solar radiation and relative humidity desired by the occupants, and vice versa. The data were also used to evaluate three indices. The Universal Thermal Climate Index (UTCI) satisfactorily predicted outdoor thermal comfort, while the Predicted Mean Vote (PMV) overestimated it. The neutral physiological equivalent temperature (PET) range found in this study was 11–24 °C, which was lower than the ranges in Europe and Taiwan. Our study indicated that residents of Tianjin were more adapted to cold environment.

1. Introduction

Over half of the world's population lives in cities [1]. Various outdoor or semi-outdoor spaces, including city parks, squares, pedestrian streets, residential areas, sports stadiums, etc., provide places for citizens to exercise and socialize. In addition, because recreational activities of considerable commercial value are conducted outdoors [2], the quality of these spaces directly affects the livability and vitality of a city. In addition, revitalizing outdoor spaces will lead to energy saving inside buildings. As people spend more time in outdoor spaces, the usage of air conditioners and other electronic equipment will be reduced. Among the many factors that influence outdoor space quality, outdoor microclimate or the concomitant outdoor thermal comfort is important [3]. Several studies investigated the correlations between thermal comfort and occupancy in outdoor spaces [4–9], most of them have identified that a strong correlation did exist.

Since the start of the new millennium, outdoor thermal comfort has received great attention. A growing number of thermal comfort studies have been conducted for various outdoor spaces in different climate regions. For example, Nikolopoulou et al. [10] investigated a wide variety of locations in seven cities across five European countries. Their findings confirmed a strong relationship between microclimate and comfort conditions. Spagnolo et al. [2] studied various outdoor and semi-outdoor locations in Sydney. They found that the outdoor environment had a wider "comfort zone" than the indoor environment. Lin [11] studied a public square in Taiwan, and the results showed that the thermal comfort range and neutral temperature for subjects in Taiwan were higher than those for people in a temperate region. Mahmoud [12] investigated a park in Cairo and observed changes in comfort level among different landscape zones. Lai et al. [13] surveyed a housing community in Wuhan and proposed a Thermal Sensation Vote (TSV) model and a space usage rate model for this area. These studies have provided valuable knowledge concerning the effect of microclimate on outdoor thermal comfort and space usage. Furthermore, the studies show differences in outdoor thermal comfort among various climatic zones. For instance, Kántor et al. [14] found that the neutral physiological equivalent temperature (PET) in Taiwan differed drastically, by 9 K, from that in Szeged, Hungry. These studies suggest the need for additional field surveys of subjective human perception in the outdoor context [15]. The existing surveys were conducted primarily in temperate or tropical climate regions where the winter is mild or warm. Although Stathopoulos et al. [16] investigated thermal comfort in a cold climate (Montreal,

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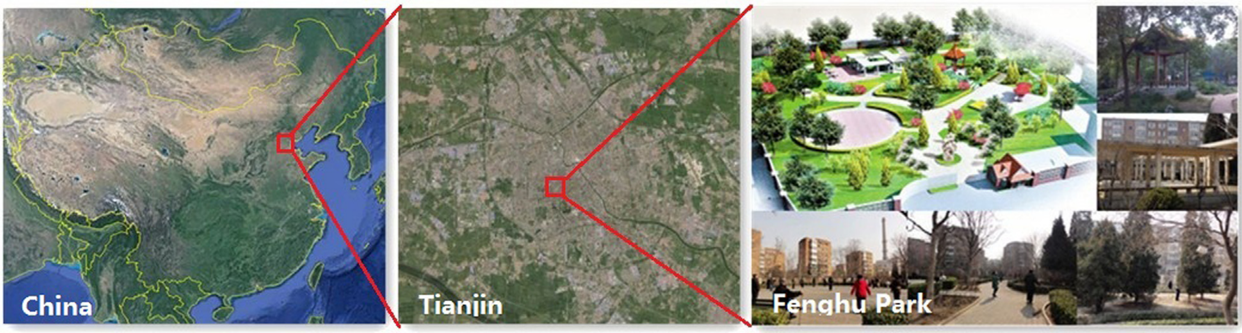

Fig. 1. Location and layout of the park investigated.

Canada), their survey was conducted at noontime in the spring and fall seasons, when the air temperature was not very low. Because no studies have been performed in the cold climate region of northern China, where the temperature can easily fall below 0 °C in winter, a better understanding of the outdoor thermal comfort in this region constitutes our main research objective.

In previous studies, various indices have been used to describe and evaluate the results. For example, Berkovic et al. [17] applied the Predicted Mean Vote (PMV) to investigate thermal comfort in courtyards in a hot, arid climate. Lin [11], Ng et al. [18], Kántor et al. [19], and Kruger et al. [20] used PET to determine the neutral temperature in the climate regions they studied. Because of the different thermal indices and thermal assessment procedures applied in these studies, the results may not be comparable. Meanwhile, the Universal Thermal Climate Index (UTCI) was developed by 45 scientists with multidisciplinary backgrounds from 23 countries in order to standardize applications across major fields of human biometeorology [21]. In addition to thermal indices, many studies of outdoor thermal comfort have used evaluation criteria developed for indoor thermal comfort. For example, Kariminia et al. [22] assessed the thermally acceptable range of an outdoor space by using the middle three thermal sensation votes (−1, 0, 1) as suggested by De Dear and Fountain [23] for an indoor study. However, because outdoor spaces have a broader thermal variation, direct use of an indoor thermal comfort model for outdoor spaces may not be appropriate. The broad thermal variation in outdoor settings also underscores the importance of other meteorological parameters such as radiation, wind and humidity. Since no single thermal environmental factor can explain the entire picture of outdoor thermal comfort [11], it is important to identify relative importance of different parameters. For example, a study in Taiwan [24] revealed that air temperature and mean radiant temperature (T_{mrt}) are most significantly related to outdoor thermal perceptions. In addition to objective weather parameters, subjective human parameters are significant. For instance, age may be a crucial factor because the physiological and psychological characteristics of different age groups may affect their outdoor thermal perception and comfort levels. Therefore, it is important to understand these differences.

Table 1
Sensors used for measurement of micrometeorological parameters.

Parameter	Sensor	Range	Accuracy
Air temperature	S-THB-M002	−40–75 °C	±0.2 K at 20 °C
Relative humidity	S-THB-M002	0–100%	±3%
Wind speed	S-WSET-A	0–45 m/s	±1.1 m/s
Global radiation	S-LIB-M003	0–1280 W/m^2	±10 W/m^2 or ±5%
Globe temperature	SPA 150	−50–250 °C	±0.3 K

This paper reports the findings of a nearly year-long study of outdoor thermal comfort in a cold climate in China, and our use of the data to evaluate the applicability of different thermal indices, including PMV, PET and UTCI, to an outdoor environment in this region.

2. Method

2.1. The site

Our investigation was conducted at Fenghu Park in Tianjin (near Beijing), in northern China. The park is located in the center of Tianjin and has an area of 6600 m^2, as shown in Fig. 1. It encompasses a variety of micro-environments, including two kiosks that provide abundant shade, an open square that receives direct sunlight, and a walking path that connects these micro-environments and is bordered by a significant amount of vegetation. The variety of micro-environments enables interactive physical adaptation [25]. In other words, the occupants can interact with the environment to improve their thermal comfort. People from the surrounding communities typically come to Fenghu Park to exercise, relax, chat, or attend to children.

2.2. Field survey

Outdoor microclimate has a direct impact on the thermal comfort of occupants and consequently affects their outdoor activity level. This investigation conducted 11 field surveys that involved microclimatic monitoring, questionnaires, and activity recording between 10:00 and 16:00. These surveys were completed between March 13, 2012, and January 8, 2013. Our study defined the period from November to March as the "cold season" with an average air temperature below 10 °C; the period from June to August as the "hot season" with an average air temperature above 20 °C; and the remaining months as "shoulder seasons." The 11 field surveys covered the three typical seasons (four surveys for the cold season, four for the shoulder seasons, and three for the hot season).

For microclimatic monitoring, two HOBO micro weather stations were deployed in an open space and under a pavilion to record the air temperature (T_a), relative humidity (RH), wind speed (V_a), and global solar radiation (G) every 10 min at a height of 2 m above the ground. The globe temperature, T_g, was manually recorded every 30 min with the use of two 70 mm global thermometers. Table 1 shows the specifications of the sensors used to measure the micrometeorological parameters in Fenghu Park. All instruments complied with ISO 7726 [26].