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RESEARCH ARTICLE

Effects of thermal environment and air quality on outdoor thermal comfort in urban parks of Tianjin, China

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Abstract

The comfort level of outdoor thermal environments is affected by several factors. Previous studies of thermal comfort have generally investigated the main microclimatic factors as dependent variables, such as the temperature, wind speed, humidity, and thermal radiation, but the influence of the air quality has rarely been explored. In this study, we acquired meteorological element observations and conducted questionnaire surveys in Peach Blossom Park, Hebei University of Technology, and Xigu Park in Tianjin. We analyzed the effects of the outdoor air quality and thermal environment on the thermal comfort in order to provide a theoretical basis for comprehensive evaluations of the outdoor environment and the mechanism. The results showed that thermal resistance of clothing and ambient temperature followed a negative step change, where people generally reduced the minimum amount of clothing when the temperature exceeded 28 °C. One unit change in the thermal sensation vote (TSV) occurred for every 11 °C rise in the physiological equivalent temperature (PET). The neutral PET was 21.68 °C, and the comfortable PET was about 23 °C. The air quality index (AQI) and air satisfaction were negatively correlated, and satisfaction decreased by 1 unit for every change of 230 AQI. The transitional season was most comfortable when the temperature felt slightly cool ($TSV = -0.70$). The neutral TSV was 0.507 in the summer and −0.334 in the winter. Air quality had a significant effect on the thermal comfort vote (TCV) ($p = 0.0485 < 0.05$). The effect of PET on TCV was highly significant ($p < 0.01$).

Keywords Air quality · Cold zone · Outdoor thermal comfort · Physiological equivalent temperature · Thermal environment

Introduction

Outdoor thermal comfort is an important factor affecting the urban development and the life quality of urban spaces. For instance, thermal comfort level of outdoor spaces directly affects the reputation and vitality of cities (Lai et al. 2014). Improving outdoor thermal environments can also effectively prolong outdoor activities to reduce the energy consumed by buildings (Chen and Ng 2012). In addition, a good outdoor thermal environment encourages residents to become active outside of their houses and to participate in outdoor activities, which is beneficial for physical and mental development (Hao 2014).

In recent years, outdoor thermal comfort has received much attention and several outdoor thermal comfort models have been developed. Most of the main thermal comfort indexes, such as the physiological equivalent temperature (PET), standard effective temperature (SET*), and universal thermal climate index (UTCI), are based on the human body heat balance equation and they are widely recognized (Jianlei et al. 2015), (Matzarakis and Fröhlich 2018), (Matzarakis et al. 2021), (Matzarakis et al. 2007), (Matzarakis et al. 2010). Lai et al. fitted a dynamic prediction model for outdoor thermal environment voting and thermal comfort voting based on the PET by using real thermal environment

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measurements acquired in West Lafayette, Indiana, USA, and Tianjin, China (Lai et al., 2017). Feng (2018) modified and adapted the PET, predicted mean vote (PMV), SET*, and UTCI to Guangzhou and developed a thermal comfort model for this area. (Kunming et al. 2017), (Li et al. 2017) analyzed human thermal sensory voting and microclimate parameters in outdoor spaces in eight typical cities, and compared the outdoor thermal sensory predictive performance of various index models using statistical and qualitative indicators. They found that the empirical index comprising the thermal sensation vote (TSV) model obtained the highest correct prediction rate and it was recommended as an outdoor thermal comfort evaluation index for use in humid regions. Tianyu et al. compared and analyzed various indicator models for the Harbin campus in winter and found that PET obtained the best predictions, where its overall prediction and classification prediction accuracy were higher, and analysis based on Spearman's correlation coefficients showed that the predicted PET values correlated strongly with the real thermal sensation values given by respondents (Xi et al. 2021). Wuxing found seasonal and regional differences in the human heat sensation, heat acceptability, wet sensation, behavioral regulation, and psychological expectations among local people and foreigners (Zheng 2017).

In contrast to indoor spaces where the state of the thermal environment is stable and controllable, the level of thermal comfort in outdoor spaces is influenced by many factors, such as meteorological parameters, behavioral regulation, and adaptation, and it can fluctuate greatly (Nikolopoulou and Lykoudis, 2006), (Li et al. 2016b). Meteorological parameters have important effects on outdoor thermal comfort, but the main factors vary among regions (Hu et al. 2020). In Montreal, Canada, Stathopoulos et al. found that temperature was the most important factor that affected thermal comfort, followed by the wind speed, solar radiation, and relative humidity (Fröhlich et al. 2019), (Stathopoulos 2006). In New Zealand, Walton et al. found that the wind speed was the main microclimatic parameter for people when evaluating the outdoor thermal environment. The main microclimate parameter for people when evaluating the outdoor thermal environment was the wind speed, whereas the air temperature was the least important factor when conducting outdoor activities (Walton et al. 2007). Chen et al. analyzed the thermal comfort of people in Harbin university campus and found that reducing the wind speed or increasing the solar radiation energy in the winter could effectively improve the thermal comfort level in outdoor spaces (Chen et al. 2018). Tianyu et al. studied the thermal comfort of people in Harbin Park during the winter and summer, and found that the neutral PET values in the summer were significantly higher than those in the winter (Xi et al. 2021). Studies conducted in Cambridge, UK (Nikolopoulou et al. 2001), Gothenburg in Sweden (Thorsson et al. 2004), and Matsudo in Japan (Thorsson et al. 2007) detected positive correlations between the air temperature, mean radiation, and outdoor space utilization, whereas studies performed in the summer in subtropical regions such as Taiwan (Lin 2009a), (Lin et al. 2012), Guangzhou (Li et al. 2016a), and Hong Kong (Ng et al. 2012) found the opposite.

In addition to the meteorological environment, psychological factors, age, gender, and the noise environment can have important effects on thermal comfort (Xi et al. 2021). Katzschner et al. (2006) and Knez and Thorsson (2008) demonstrated that thermal experiences in typical seasons and typical spaces directly affect the thermal sensory experience, and that people actively adjust their psychological expectations in different seasons, thereby resulting in different thermal comfort evaluations. Jin et al. found that higher traffic noise led to lower outdoor thermal comfort (Jin et al. 2020). Clausen et al. investigated the relative importance of air pollution, temperature, noise, and odor for thermal comfort under controlled indoor conditions (Clausen et al. 1993).

Much mature research has been done on the role of air quality on the indoor thermal comfort. Nonetheless, scarce research has been conducted on the influence of the air quality of the outdoor environment. As to the indoor environment, Babich et al. (2023), by verifying the indoor air quality level of schools under different standards, pointed out that the prevailing standards lacked comprehensive consideration to such factors as heat and air quality. Lin et al. (2022) conducted a survey on the air quality and thermal comfort at the subway stations and found that CO_2 and solid particulate matters were primary factors influencing air quality and high pollutant concentration would remarkably lower the thermal comfort of the passengers. As to the outdoor environment, Miao et al. (2023) chose to research the relations between air quality and thermal comfort at the streets and found that different air pollutants had different functional rules at different heights. Li et al. (2020), through modeling analysis, found that air quality and thermal comfort could reach the optimal building density under natural atmospheric conditions. Previous studies have conducted in-depth studies on thermal and air quality, but there are still two aspects that need further research: (1) most of the studies have analyzed the thermal comfort and air quality separated, and the coupling mechanism of the two aspects is still unclear. (2) Urban parks are rarely chosen to be the study object, especially in coastal cities. Parks are important places to regulate urban climate and improve environment quality and sound park environment can help reduce people's fatigue and pressure and improve their health level so that people have higher expectations for the air quality in parks; meanwhile, parks provide the space of strolling and rest. Compared with such spaces as office buildings, factories, and business streets, the thermal environment of parks is more comfortable and other comfort levels of sound, light and vision are higher. Therefore, this paper takes urban parks in Tianjin, a coastal city, as the research object, and applies questionnaire survey combined with microclimate field test to study outdoor thermal comfort under the coupling effect of outdoor thermal environment and air quality (PM2.5), in order to clarify the thermal comfort level of human body under the interaction effect of outdoor thermal environment and haze. So as to provide experimental support for the construction of multi-environment coupling outdoor thermal comfort research system. We investigated the comprehensive influence of air quality and thermal environment on outdoor thermal comfort in order to determine how air quality might affect thermal comfort and to provide a reference for optimizing outdoor environments.

Methods

Location

Tianjin was selected as the research area for this study. Tianjin (Fig. 1) is located in the northern part of the North China Plain, east of the Bohai Sea, and north of the Yanshan Mountains, between 116°43′E and 118°04′E longitude and 38°34′N and 40°15′N latitude. Tianjin is a typical representative city in the cold region of China due to its unique climatic conditions. Tianjin has four distinct seasons comprising a windy spring with a short drought, a hot summer with concentrated rainfall, a cool autumn with moderate cold and warmth, and a cold winter with abundant precipitation and snow. The average annual temperature is about 14 °C and the hottest month is July with an average monthly temperature of 28 °C. The highest historical temperature is 41.6 °C. The coldest month is January with an average monthly temperature of −2 °C. The lowest historical temperature is −17.8 °C (Fig. 2).

Three representative measurement sites were selected in Peach Blossom Park, Xigu Park, and Hebei University of Technology (HEBUT), as shown in Fig. 3. Peach Blossom Park is located along the North Canal. Xigu Park is characterized by the original plant landscape and it was transformed from a farm. HEBUT is also located along the canal and it mainly has a hard substrate. The temperature and air quality in the year when this study was conducted are shown in Fig. 2. In this survey, we conducted questionnaire survey and field test in 6 typical test sites A to F as shown in Fig. 3. Physical parameters of the test included temperature, relative humidity, wind speed, black bulb temperature, solar radiation, PM2.5, and other air quality parameters.

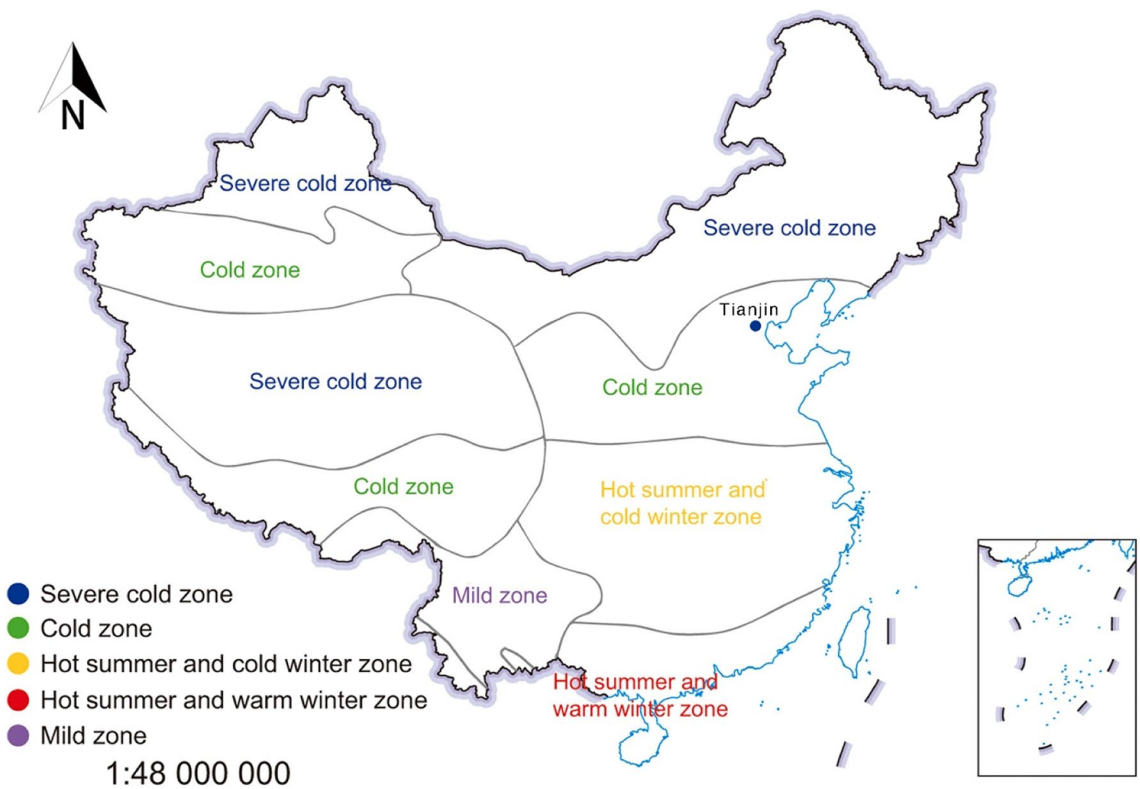


Fig. 1 Location of Tianjin and climatic zones in China

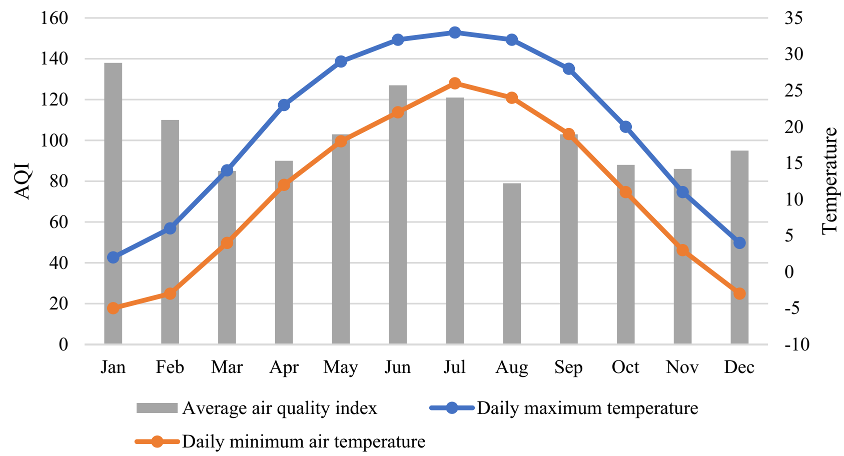


Fig. 2 Monthly mean temperature and air quality index (AQI) in Tianjin

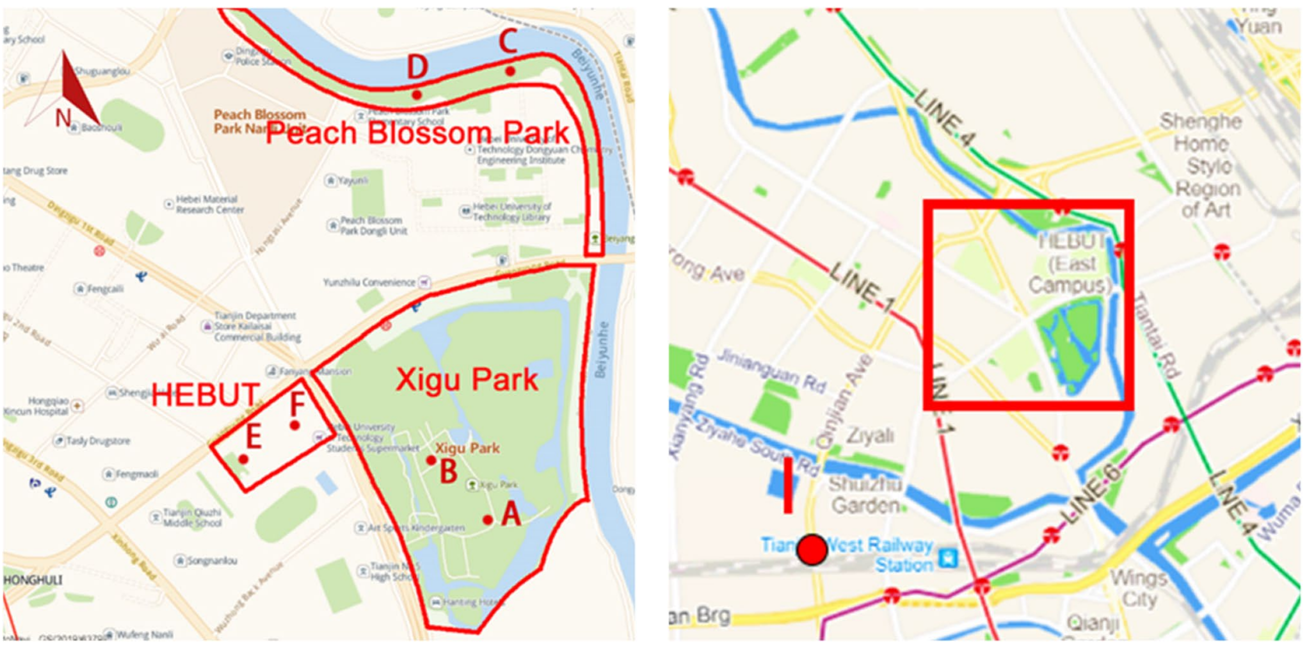


Fig. 3 Study sites in Tianjin

Fig. 4 Questionnaire surveys

Questionnaire surveys

A questionnaire was used to obtain evaluation data from randomly selected respondents at the three study sites (Fig. 4). The questionnaire comprised two parts. The first part collected basic information from the respondents, such as their gender, age, activity status, and amount of clothing. Clothing and activity status data were quantitatively converted into the clothing thermal resistance and metabolic rate, respectively (Standard 2013). The second part mainly collected judgments and evaluations of the current environment by the outdoor space users, including TSV, air satisfaction vote (ASV), and thermal comfort vote (TCV), and the voting scale was designed according to ASHRAE standards (Standard 2013), as shown in Fig. 5. An electronic questionnaire was used to record the data (Fig. 6), and questionnaires were completed on an equal and voluntary basis. Questionnaires completed by respondents who were sick, lived locally for less than 3 months, and when rainfall occurred at the time were removed to ensure the reliability of the findings.

Measurements

Microclimate parameters were measured at each site when the questionnaire survey was conducted. Each climatic factor was automatically recorded by the instruments, i.e., air temperature, relative humidity, wind speed, and black bulb temperature. The range and accuracy of the instruments used to collect the measurements conformed to the relevant provisions in the ISO 7726 standard (Standard et al. 2013) and they were fixed on a tripod at a height of 1.2 m from the ground (Standard 2002). The specific parameters and instruments are shown in Table 1. The globe temperature was measured using a standard matte black painted sphere (diameter = 50 mm, emissivity > 0.95). Air quality related parameters were obtained in real time from the nearest national environmental monitoring station, which was located less than 1 km from the survey site (Site I in Fig. 3). The environmental monitoring station was built in 1990s, which has the ability to monitor 6 conventional

Fig. 6 Digital questionnaire used in this study

Fig. 5 Subjective evaluations in questionnaire surveys

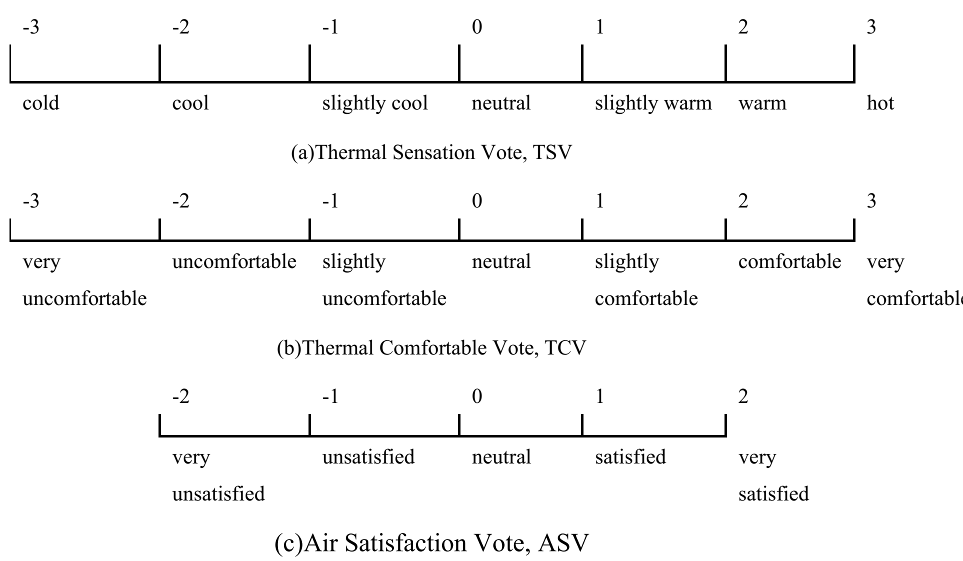


Table 1 Parameters collected and instruments employed

Meteorological parameter	Units	Type	Range	Precision
Air temperature	°C	JT2020 multifunctional tester (temperature and humidity sensor)	–20 to 125 °C	±0.5 °C
Relative humidity	%		0–100%	±3%
Wind speed	m/s	JT2020 Omnidirectional wind speed sensor	0.05–5 m/s	±0.05 m/s
Globe temperature	°C	JT2020 globe temperature sensor	–20 to 85 °C	±0.5 °C
Solar radiation	W/m^2	TES solar power meter	0–2000 W/m^2	±10 W/m^2

Table 2 Air quality and AQI classifications

O^3 (ppb)	O^3 (ppb)	PM$_{2.5}$ (μg/m^3)	PM$_{10}$ (μg/m^3)	CO (ppm)	SO$_2$ (ppb)	NO$_2$ (ppb)	AQI value	AQI category	AQI level
0–54 (8-h)	-	0.0–12.0 (24-h)	0–54 (24-h)	0.0–4.4 (8-h)	0–35 (1-h)	0–53 (1-h)	0–50	Good	I
55–70 (8-h)	-	12.1–35.4 (24-h)	55–154 (24-h)	4.5–9.4 (8-h)	36–75 (1-h)	54–100 (1-h)	51–100	Moderate	II
71–85 (8-h)	125–164 (1-h)	35.5–55.4 (24-h)	155–254 (24-h)	9.5–12.4 (8-h)	76–185 (1-h)	101–360 (1-h)	101–150	Unhealthy for sensitive groups	III
86–105 (8-h)	165–204 (1-h)	55.5–150.4 (24-h)	255–354 (24-h)	12.5–15.4 (8-h)	186–304 (24-h)	361–649 (1-h)	151–200	Unhealthy	IV
106–200 (8-h)	205–404 (1-h)	150.5–250.4 (24-h)	355–424 (24-h)	15.5–30.4 (8-h)	305–604 (24-h)	650–1249 (1-h)	201–300	Very unhealthy	V
-	405–504 (1-h)	250.5–350.4 (24-h)	425–504 (24-h)	30.5–40.4 (8-h)	605–804 (24-h)	1250–1649 (1-h)	301–400	Hazardous	VI
-	505–604 (1-h)	350.5–500.4 (24-h)	505–604 (24-h)	40.5–50.4 (8-h)	805–1004 (24-h)	1650–2049 (1-h)	401–500		

air pollutants, namely PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and O_3. All data were recorded at hourly concentrations as specified in Table 2.

According to the ISO 7726 standard (Standard 2013), the average radiation temperature (Tmrt) was calculated from the globe temperature (Tg), wind speed (V), and air temperature (Ta) through the Eq. (1), where ε is the reflectance of the black globe ($\varepsilon = 0.95$ in this study) and D is the diameter ($D = 0.05$ m in this study).

$$T_{mrt} = \left[\left(T_g + 273.15 \right)^4 + \frac{1.10 \times 10^8 V^{0.6}}{\varepsilon D^{0.4}} \times \left(T_g - T_a \right) \right]^{0.25} - 273.15 \quad (1)$$

Index

The level of thermal comfort is influenced by the climatic conditions and behavioral adjustments, and a single meteorological parameter cannot directly characterize the thermal comfort state of the environment. Thus, thermal comfort indicators are commonly used for evaluating the outdoor thermal environment, such as UTCI (Jendritzky et al. 2012), PET (Hoppe 1999), new SET* (Gagge et al. 1986), and PMV (Fanger, et al. 1972). PMV is mostly used for relatively controlled indoor thermal comfort evaluations, and UTCI and SET* are generally used for outdoor thermal environment evaluations in the tropics and subtropics. PET provides the equivalence of a complex outdoor thermal environment to a specific indoor environment and the results are easy to understand, and it is more suitable for use in cold regions (Xi and Lei 2021a) and humid hot regions (Li, et al. 2016a) in China. Thus, PET was selected as the index for evaluating outdoor thermal comfort in this study.

PET is an outdoor thermal environment evaluation index derived from the human thermal transformation equation (Munich energy balance model), which is defined as the heat balance of the human body in a typical indoor environment (with no solar radiation, a wind speed of 0.1 m/s, and water vapor pressure of 12 hPa) with a metabolic rate of 80 W and clothing thermal resistance of 0.9 clo to reach the same core and skin temperature as the complex outdoor conditions evaluated at equilibrium air temperature (Hoppe 1999). We used Rayman software to calculate PET values based on the microclimate parameter measurements. According to historical data, $PM_{2.5}$ is the primary pollutant influencing the air quality of Tianjin. Therefore, the $PM_{2.5}$ density was applied in the present

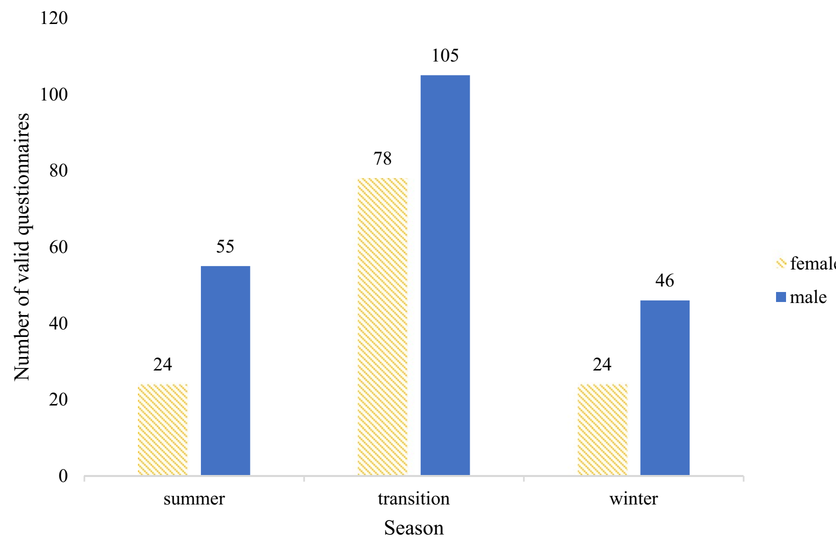


Fig. 7 Numbers of valid questionnaires completed in different seasons

paper to calculate the corresponding sub-index as the AQI value. Meanwhile, the sub-indexes of other pollutants (PM_{10}, CO, NO_2, SO_2, O_3) served as references. If their sub-indexes are greater than or equal to the sub-indexes corresponding to $PM_{2.5}$, the value should be taken as the AQI value. The computational method of the numerical values of the pollutants is the index amortized computation, as shown in Formula (2):

$$AQI = \frac{I_{\text{high}} - I_{\text{low}}}{C_{\text{high}-}C_{\text{low}}}\left(C - C_{\text{low}}\right) + I_{\text{low}} \quad (2)$$

C is the measured pollutant concentration (μg/m^3), C_{high} is the concentration limit greater than or equal to C, C_{low} is the concentration limit lower than or equal to C, L_{high} is the index limit corresponding to C_{high}, and L_{low} is the index limit corresponding to C_{low}. According to the National Ambient Air Quality Standards (NAAQS) (Cheremisinoff 2016), air quality can be classified into six categories, during which the standard in the category of $PM_{2.5}$ are shown in Table 2.

Results

Description analysis

The present study was conducted from July 2019 to January 2020 in the summer, transition, and winter seasons. Surveys were conducted from 5:00 to 21:00 to cover the entire day from sunrise to sunset.

In total, 332 valid questionnaires were collected, where 79 were completed in the summer, 183 in the transition season, and 70 in the winter, with 206 by males and 126 by females (Fig. 7). The numbers of questionnaires completed in different locations, months, and age groups are shown in Figs. 8 and 9. Among the respondents, 42.17% were young people aged 20–30 years and

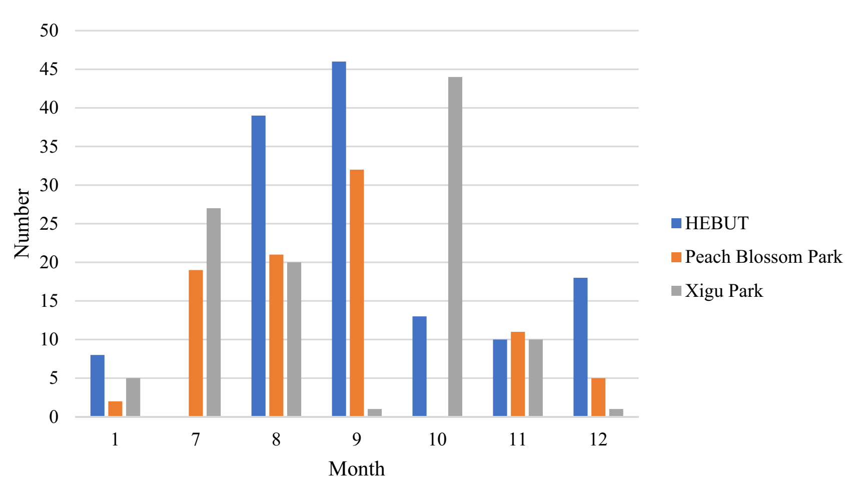
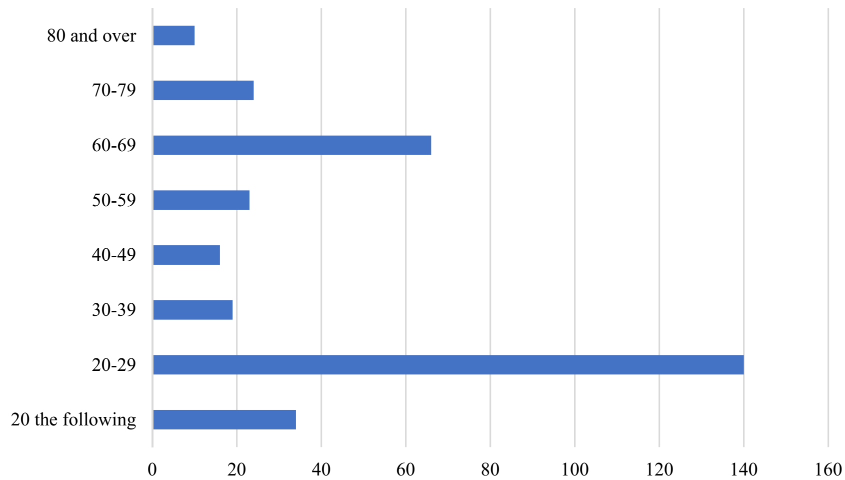


Fig. 8 Numbers of valid questionnaires completed at different study sites in each month

Fig. 9 Numbers of valid questionnaires completed by different age groups



19.89% were older people aged 60–69 years. The average clothing thermal resistance was 0.5164 clo, the main activity was walking (48.19%), and the average metabolic rate was 2.02 met.

The clothing thermal resistance of the respondents was correlated with the ambient temperature ($R^2 = 0.77$) (the ambient temperature is the average ambient temperature), and the clothing thermal resistance generally decreased as the temperature increased, thereby indicating that people reduced their amount of clothing to adapt to a warmer environment, but this was also influenced by factors such as the weather and wind speed. The clothing thermal resistance followed a class step change with temperature, probably because people dress in a similar manner in the same season, and differently in different seasons. When the temperature exceeded 28 °C, the clothing thermal resistance no longer changed significantly, thereby indicating that people had reached the minimum amount of clothing (Fig. 10).

The air quality index (AQI) was grouped by season to produce the box plot shown in Fig. 11. The mean AQI values in different seasons followed the order of transitional season ($AQI = 97$) > summer ($AQI = 81$) > winter ($AQI = 76$), and there were significant differences in the upper quartile and median among seasons, but not in the lower quartile. These results indicate that the air quality was worse in the transitional season than the other seasons.

PET and thermal evaluation

Based on the study by Lin et al. (2009b), the subjective voting values were grouped according to each 1 °C PET interval and the mean value was calculated for each group. Fitting analysis was performed using the number of samples as the weights and the regression equation between the TSV and PET was obtained as follows (Fig. 12).

$$TSV = 0.088PET - 1.9075 \left(R^2 = 0.7969\right) \tag{2}$$

The relationship determined between PET and TSV showed that the sensitivity to PET was basically the same at different thermal environment levels, i.e., every increase of about 11 °C in PET led to a change of 1 TSV unit. These results are consistent with those obtained in a previous study in the Harbin area (Xi and Lei 2021b), which also showed that PET is an appropriate thermal evaluation index. When $TSV = 0$, the neutral PET was calculated as 21.7 °C.

The regression equation calculated between TCV and PET is as follows (Fig. 13).

$$TCV = -0.0038PET^2 + 0.1514PET - 0.8543\left(R^2 = 0.5387\right) \tag{3}$$

PET had an about quadratic relationship with thermal comfort, thereby indicating that excessively cold or hot PET values could cause discomfort. According to the statistical results, the most comfortable PET value in this study was around 23 °C, which resulted in a thermal comfort level of 1.75. But when PET higher than 25 °C, TCV showed a downward trend. In addition, the results indicate that a high level of thermal comfort was not reached even at the highest point. This may result to other environmental factors, such as the sound, light, air quality, or even psychological and behavioral factors.

AQI and air satisfaction

After calculating the average values according to the air quality classifications shown in the "Index" section, Eq. (4) was obtained by fitting the AQI and ASV data (Fig. 14), as follows:

$$ASV = -0.0044AQI + 0.9654\left(R^2 = 0.949\right) \tag{4}$$

Within limits, satisfaction with the air quality (ASV) had a good relationship with the AQI. Every increase of

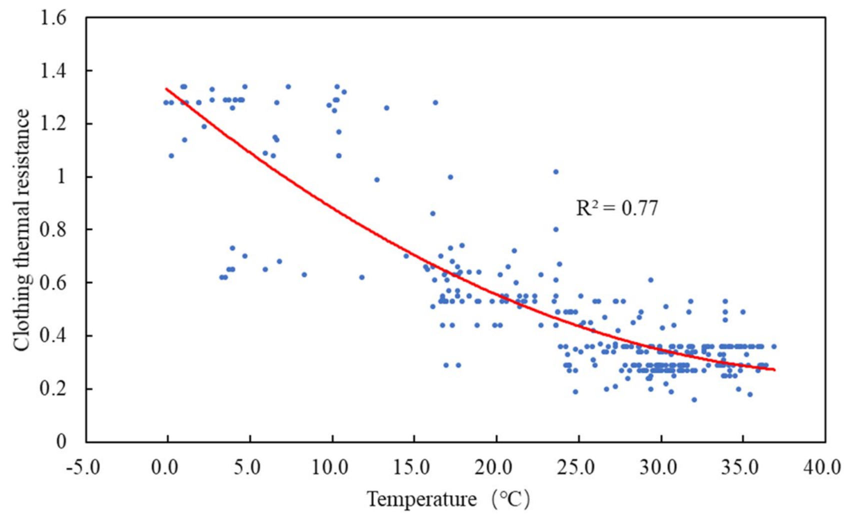


Fig. 10 Relationship between temperature and clothing thermal resistance

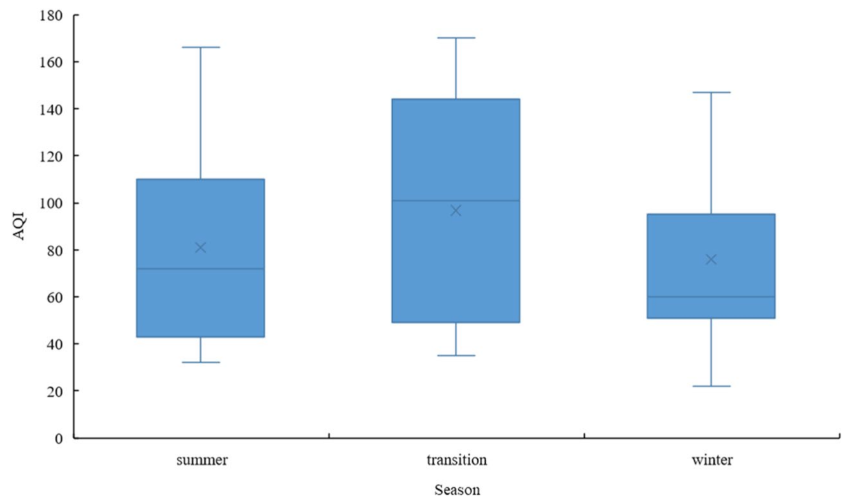


Fig. 11 Air quality index (AQI) in different seasons

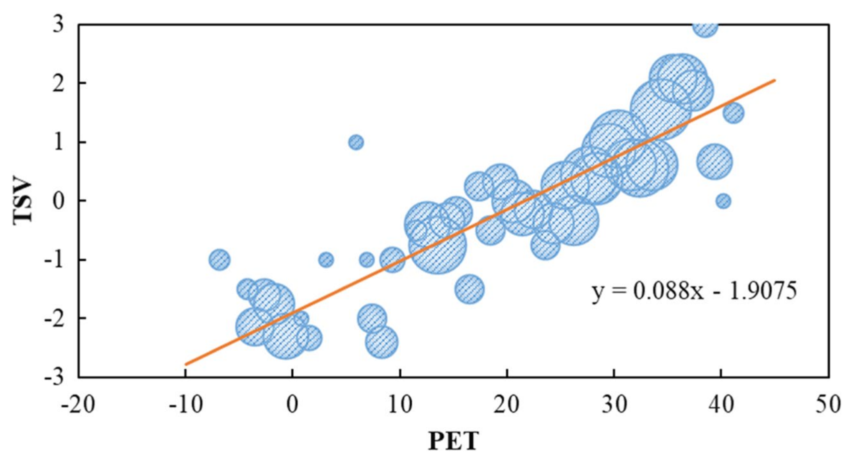


Fig. 12 Correlation between TSV and PET

about 230 in AQI decreased the satisfaction by one unit, thereby indicating that people in Tianjin perceived the air quality accurately, but they were not demanding. Better air quality resulted in higher satisfaction. When $ASV = 0$, the predicted neutral AQI was calculated as 219, i.e., there was no tendency to be satisfied or dissatisfied with the air environment. Even when the AQI was 0, satisfaction with the air quality did not reach a high level, which means that other factors beyond $PM_{2.5}$ also affect people's judgments.

Fig. 13 Correlation between TCV and PET

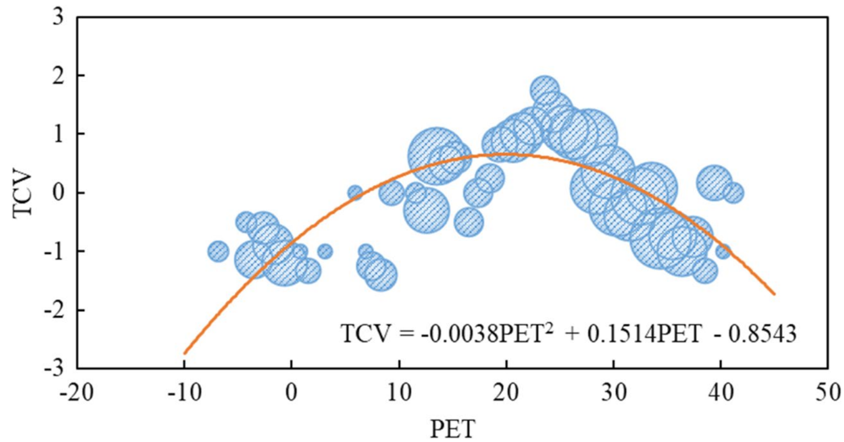
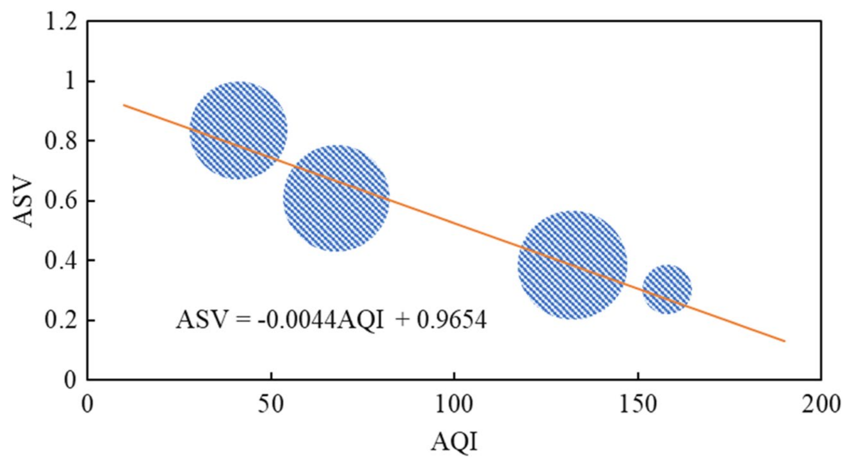


Fig. 14 Correlation between ASV and AQI



TSV and TCV

The TCV values were grouped according to the TSV level and the mean value was calculated for each group. The mean value for each group was then regressed against the corresponding TSV level to obtain the regression equation between TCV and TSV to quantify the relationship between TCV and TSV for outdoor space users in Tianjin (Fig. 15). The equations fitted between TSV and TCV for each season are as follows:

$$\text{Summer}: TCV = -0.034TSV^2 - 0.324TSV + 0.173\left(R^2 = 0.930\right) \tag{5}$$

$$\text{Transition Season}: TCV = -0.1552TSV^2 - 0.2167TSV + 0.7415\left(R^2 = 0.700\right) \tag{6}$$

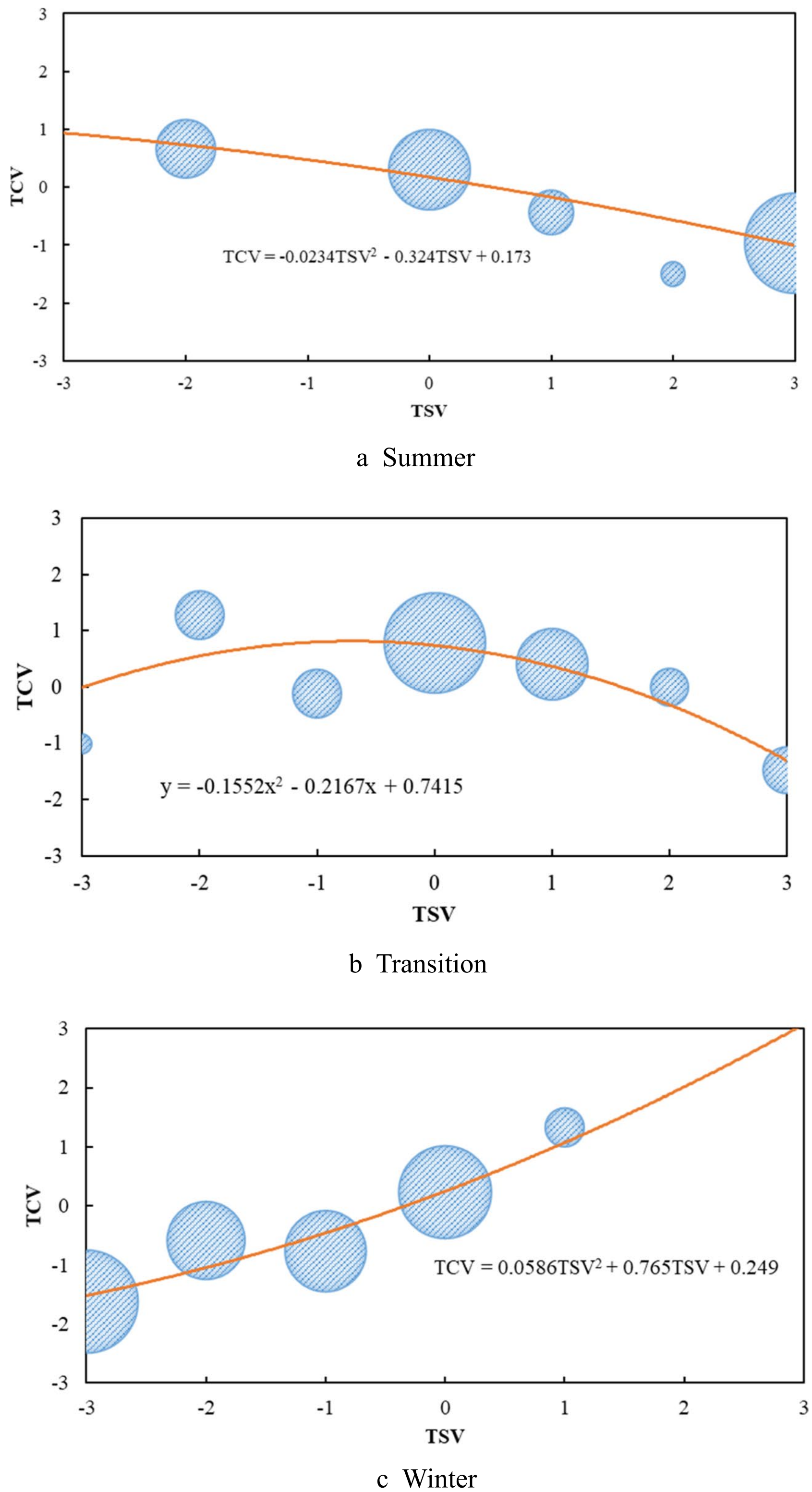
$$\text{Winter}: TCV = 0.0586TSV^2 + 0.765TSV + 0.249\left(R^2 = 0.906\right) \tag{7}$$

As shown in Fig. 15, there was a good quadratic function relationship between TCV and TSV in all three seasons. In the transition season, TCV peaked when TSV was −0.70 (slightly cooler), and the thermal comfort experience worsened when the environment became variable or warmer. In the summer, TCV was higher when TSV was cooler, where the neutral ($TCV =$ 0) $TSV = 0.507$. In winter, TCV gradually increased as TSV increased, where the neutral $TSV = -0.334$. The TSV and TCV results in the winter and summer showed that the thermal sensation was “moderate” ($TSV = 0$). However, these results are not consistent with those obtained by Tianyu et al. in Harbin (Xi and Lei 2021a), who found that “slightly warm” in the winter and “slightly cool” in the summer led to a neutral state. Thus, it is possible that people in this region have lowered their expectations of comfortable temperatures after becoming accustomed to excessively hot or cold temperatures in the summer or winter, and thus neutral comfort can be achieved with slightly warm temperatures ($TSV = -0.334$) in summer and slightly cool temperatures ($TSV = -0.334$) in winter.

Combined effects of AQI and PET on TCV

PET was grouped per 5 °C and AQI was graded according to the US National Ambient Air Standards. Grouping PET by 5 °C, making the distribution among PET and TCV

Fig. 15 Relationships between TSV and TCV in different seasons. **a** Summer. **b** Transition. **c** Winter



clearly, which also make fitting degree identify easier. Figure 16 shows the trends in TCV for different air quality and thermal environments, which indicate that the thermal comfort of people differed significantly at the same PET. Irrespective of the air quality, TCV increased as PET increased initially with a peak at about 20 °C, before then decreasing under excessively hot conditions. Under the same PET conditions, better air quality made people more

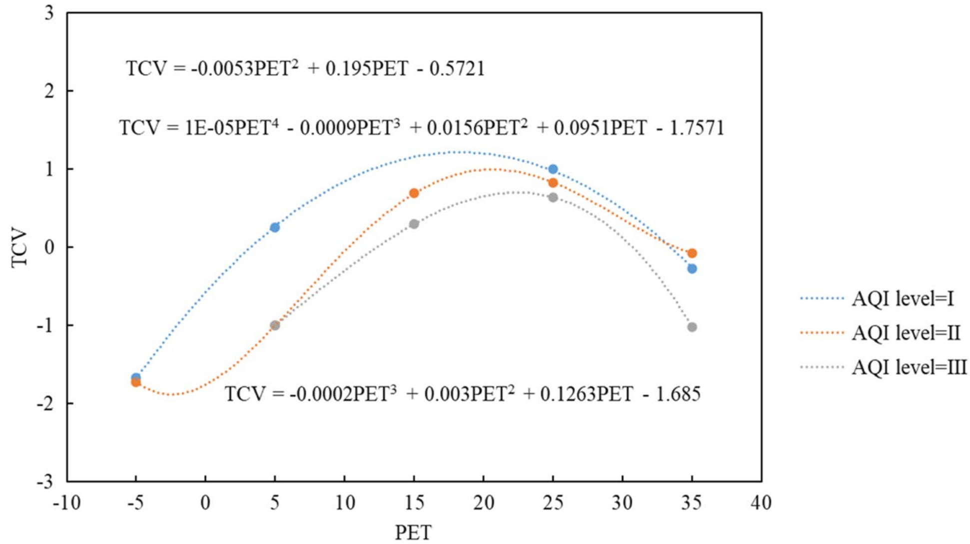


Fig. 16 TCV under different air quality and thermal environment conditions

comfortable with the TCV, especially in the range from 10 to 30 °C.

Analysis of variance showed that the air quality had a significant relationship with TCV ($p = 0.0485 < 0.05$), and the relationship between PET and TCV was highly significant ($p = 5.59\text{E-}5 < 0.01$).

However, the strength of the relationship between the air quality and TCV decreased or deviated from the pattern mentioned above in excessively hot and cold environments, i.e., the air quality had less influence on TCV when people were uncomfortable, and PET became a more dominant factor. It is possible that people were already very uncomfortable in excessively hot or cold environments and they were not greatly concerned with the effect of the air quality.

According to the above images, polynomial fitting is carried out, and the equations obtained are as follows:

AQI level=I: $TCV = -0.0053PET^2 + 0.195PET - 0.5721$ ($R^2 = 0.9997$)
AQI level=II: $TCV = -0.0034PET^2 + 0.1539PET - 1.109$ ($R^2 = 0.8886$)
AQI level=III: $TCV = -0.0074PET^2 + 0.2988PET - 2.361$ ($R^2 = 0.9759$)

Figure 16 and equation show that good air quality may enhance the mood of people to improve their thermal acceptability and result in a more comfortable thermal experience. By contrast, a poor air quality environment with reduced visibility in severe cases will lower the mood of people and affect their evaluations of the thermal environment. This is consistent with the life experiences and theoretical expectations of people. In addition, we suggest that harmful components of poor air may enter the respiratory system and change the physiological state to affect the body temperature, blood flow rate, and hormone secretions, thereby influencing the comfort level. Due to space constraints, we do not discuss these effects in detail, but we hope that subsequent studies will investigate the specific mechanisms involved.

Conclusion

In this study, we investigated the effects of the air quality and thermal environment on the thermal comfort of people in a cold region (Tianjin city) based on questionnaire surveys and environmental measurements throughout 1 year. Based on the results obtained, we can make the following main conclusions.

(1) The thermal sensation in the cold study region was positively correlated with PET, and every 11 °C rise in PET led to an increase of 1 TSV unit, where the neutral PET was 21.68 °C. The thermal comfort had a quadratic relationship with PET, and the most comfortable state was reached at about 23 °C.
(2) The subjects in Tianjin were sensitive to the air quality but not demanding. Every rise in AQI of about 230 led to a decrease of 1 ASV unit, i.e., people did not tend to be satisfied or dissatisfied.
(3) The thermal comfort peaked in the transition season when the thermal sensation was −0.70 (slightly cool). Cooler temperatures in the summer and warmer temperatures in the winter felt more comfortable. Due to the influence of seasonal habits and lowered expectations, the thermal sensation did not necessarily reach the "comfortable" state when it was "moderate" ($TSV = 0$). The neutral TSV was 0.507 when it was warm in the summer and the neutral TSV was −0.334 when it was cool in the winter.

(4) TCV varied significantly under different air quality conditions and analysis of variance showed that air quality had a significant effect on TCV (p = 0.0485 < 0.05). PET had a highly significant effect on TCV (p = 5.59E-5 < 0.01). We suggest that the air quality may affect thermal comfort by influencing psychological and physiological states.

Author contributions Xiangyu Gao wrote the paper. Meng Zhen modified the paper and performed the field tests. Guangmeng Bian designed the questionnaire. Qi Cheng and Zilin Chen reviewed and edited the paper. Shiyan Sha, Qi Cheng, and Tianyi Sun conducted the questionnaire survey. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability Data derived from the current study can be provided to readers upon request.

Declarations

Ethical approval and consent to participate This research was approved by the Human Ethics Committee of School of Human Settlements and Civil Engineering, Xi'an Jiaotong University. Before conducting the questionnaire survey, the research team had informed participants that the questionnaire was anonymous and aiming at academic research.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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