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Summer outdoor thermal comfort assessment in city squares—A case study of cold dry winter, hot summer climate zone

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ABSTRACT

Human thermal perception varies with climate. The Dwa climate zone covers vast areas. Conducting outdoor thermal comfort (OTC) studies here would benefit energy efficiency and the economy. However, since OTC research methods are not standardized, different research methods hamper comparing studies in the Dwa climate. This paper aims to determine the summer OTC of typical Dalian squares in the Dwa climate. Dalian is located in the cold A zone (2A) of the China Building Climate Division. The thermal environment of three typical squares was field measured, and a questionnaire survey of the residents was conducted. 33.2 % of Dalian residents evaluated the thermal environment as neutral, and 39.3 % considered it comfortable. And psychological perception and physical perception were not the same. Multiple methods were used to calculate outdoor thermal benchmarks and calibrate thermal stress for three thermal indexes, SET*, PET, and UTCI. Furthermore, PET, with a prediction accuracy of 25.3 %, was determined to be the best indicator applicable to Dalian in the summer. Finally, a comparison of studies under the Dwa climate zone, including Tianjin and Harbin, reconfirmed the mobility of the human thermal zone. These findings are precious and can contribute significantly to ensuring the sustainability of the outdoor environment.

1. Introduction

As urban populations continuously grow, cities can either expand outward into suburbs or embrace the benefits of increased density and height within their existing city limits. In either case, urban environment will be changed. And it has been shown that urban geometry has the most significant effect on the thermal environment of the city (Lai et al., 2019). Globally, air temperatures (Ta) are rising in many locations, and the thermal environment is worsening (Higashino et al., 2021; Kwofie et al., 2022; Ren et al., 2022; Ruml et al., 2017; Xin et al., 2022). A decrease in the quality of outdoor thermal environments greatly impacts public health, overall well-being, and outdoor thermal comfort (OTC) (Huang et al., 2019; Krüger & Rossi, 2011). OTC in urban areas is also significantly affected by numerous human-made settings, including the

Abbreviations: Aw, Tropical, Savannah; ARSET*, Acceptable Temperature Range of SET*; ARPET, Acceptable Temperature Range of PET; BMI, Body Mass Index; BSh, Arid Steppe, Hot; BSk, Arid Steppe, Cold; BWk, Arid Desert, Cold; Cfa, Temperate without Dry Season, Hot Summer; Cfb, Temperate without Dry Season, Warm Summer; Csa, Temperate Dry Summer, Hot Summer; Cwa, Temperate Dry Winter, Hot Summer; Dfb, Cold without Dry Season, Warm Summer; Dwa, Cold Dry Winter, Hot Summer; GOCI, Global Outdoor Comfort Index; MTSV, Mean Thermal Sensation Vote; NPET, Neutral Temperature of PET; NRPET, Neutral Temperature Range of PET; NRSET*, Neutral Temperature Range of SET*; NRUTCI, Neutral Temperature Range of UTCI; NSET*, Neutral Temperature of SET*; NUTCI, Neutral Temperature of UTCI; OTC, Outdoor Thermal Comfort; PET, Physiological Equivalent Temperature; PMV, Predicted Mean Vote; PTSV, Predicted Thermal Sensation Vote; RH, Relative Humidity; SDGs, Sustainable Development Goal; SDG 13, Sustainable Development Goal 13; SET*, Standard Effective Temperature*; Ta, Air Temperature; Tg, Global Temperature; Tmrt, Mean Radiation Temperature; TAV, Thermal Acceptability Vote; TCV, Thermal Comfort Vote; TPV, Thermal Preference Vote; TSV, Thermal Sensation Vote; UCB, UC-Berkeley; UTCI, Universal Thermal Climate Index; Va, Air Speed; WBGT, Wet Bulb Globe Temperature; 1B, Severe Cold B Zone; 2A, Cold A Zone; 2B, Cold B Zone; 3A, Hot Summer and Cold Winter A Zone; 3B, Hot Summer and Cold Winter B Zone; 4B, Hot Summer and Warm Winter B Zone.

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materials used (Davtalab et al., 2020; Salata et al., 2017), spatial arrangements (Deb & Ramachandraiah, 2010; Li & Liu, 2020), and the impacts from human activities such as heat release and energy consumption (Jin et al., 2018), which is not beneficial to sustainable urban development and must be addressed (Su et al., 2022a). To tackle the problem, there is a push to accelerate the achievement of Sustainable Development Goal 13 (SDG 13) of the United Nations Sustainable Development Goals (SDGs). This goal calls for urgent action to address climate change and its impacts (Huang et al., 2021). Identifying human thermal comfort has essential implications for developing adaptation strategies for urban life. As an important node in urban areas, squares not only carry political, economic, and cultural social activities but are usually places where people and traffic flow collect and disperse. By meticulously examining the thermal comfort levels of these areas, we can significantly enhance the outdoor experience for citizens and provide guidelines to address climate issues within cities.

Thermal environment studies are objectively presenting meteorological data to characterize the thermal environment (Kroemer et al., 2020). Human beings are the primary users of the environment, and the subjective response of users to the warmth and coldness of the thermal environment is called thermal sensation (ANSI, 2017). How to establish an evaluation method to directly evaluate the quality of the thermal environment between human thermal sensation and the complex thermal environment is the study of thermal comfort. Human adaptation to the thermal environment varies according to the climate (Binarti et al., 2020). Scholars have conducted extensive research on enhancing OTC and assessing the impact of such enhancements in varying climatic regions. OTC studies have primarily focused on residential blocks (Su et al., 2022), campuses (Ghaffarianhoseini et al., 2019; He et al., 2020; Huang et al., 2019), urban parks (Aljawabra & Nikolopoulou, 2018; Xu et al., 2019), urban streets (Jin et al., 2019; Kubilay et al., 2019), and hub squares (Hirashima et al., 2018; Xiao & Yuizono, 2022). Table 1 summarizes thermal comfort studies covering the last six years with squares as the target. It can be found that there are a limited number of thermal comfort studies only for urban squares. The climatic zones studied abroad (except China) for OTC in squares are mainly concentrated in Aw (De Arêa Leão Borges et al., 2020; Hirashima et al., 2018; Johansson et al., 2018; Kruger & Drach, 2017; Lucchese & Andreasi, 2017), Csa (Aljawabra & Nikolopoulou, 2018; Nouri & Costa, 2017; Samira et al., 2017; Sayad et al., 2021; Tseliou et al., 2017), Cfb (Hirashima et al., 2018; Kenawy & Elkadi, 2018, 2021; Kenawy et al., 2021), Dfb (Lindner-Cendrowska & Błażejczyk, 2018; Xiao & Yuizono, 2022), BSh (S & Rajasekar, 2020), and Cwa (S & Rajasekar, 2022). Domestic studies in China have focused on Cwa (Huang et al., 2017; Li et al., 2018; Liu et al., 2021), Dwa (An et al., 2021; Chen et al., 2018; Jin et al., 2017; Lei, 2018; Leng et al., 2020; Li, 2019; Xi et al., 2020), Cfa (Fang et al., 2019, 2018, 2021; Huang & Peng, 2020; Huang et al., 2019; Li & Li, 2021; Liu et al., 2017; Wei & Liu, 2018; Wei et al., 2022; Xiang & Zheng, 2022; Xie & Li, 2020), BSk (An et al., 2021; Zhen et al., 2021), and BWk (An et al., 2021). Research in China's Dwa has focused on Harbin and Beijing. China covers a great land area, and to guide the thermal construction of buildings in different regions, the government has made zoning according to the climatic characteristics of each region, as shown in Fig.1. Cities belonging to 2A are numerous, as high as 17.3 %, only compared to 18.5 % in 3A, which is the most numerous (Ministry of Housing and Urban-Rural Development, 2016). According to the secondary zoning, Harbin and Beijing are 1B and 2B, respectively, with limited reference values for OTC studies in Dalian in 2A. Meanwhile, Dwa is mainly located in the northeast, and central parts of Asia, and 2A is primarily in the northeast, southwest, and northwest parts of China. Therefore, conducting an OTC study on Dalian in this paper is necessary to provide a direct reference to other 2A climate zones.

The most commonly used indicators for OTC studies in China and abroad are physiological equivalent temperature (PET), universal thermal climate index (UTCI) and standard effective temperature* (SET*) in that order (Table 1). This is consistent with studies (Binarti et al., 2020; Li & Liu, 2020). Assuming that the skin and core temperatures of a male with a height of 180 cm, a weight of 75 kg, a clothing thermal resistance of 0.9clo, and a metabolic rate of 80 W in an actual environment are equal to those in a typical room with a mean radiant temperature (Tmrt) equal to the Ta, a water vapor pressure equal to 1200 Pa, and an air speed (Va) equal to 0.1 m/s, the Ta in the typical room is considered to be PET (Höppe, 1999). If the average skin temperature and skin humidity of a person wearing standard clothing in a standard environment (50 % relative humidity (RH), still air, Tmrt equals to Ta) are the same as in the actual environment, the Ta in the standard environment is SET* (Gagge et al., 1986). In an ideal environment (Ta equal to the Tmrt, RH of 50 % or water vapor pressure of 20 hPa, Va of 0.5 m/s at 10 m from the ground), a standard adult male (weight 73.5 kg, fat content of 14 %, body surface area of 1.86 m^2) walks at a speed of 1.1 m/s with a human metabolic rate of 135 W/m^2, when the resulting thermal response is the same as the actual environment, the Ta in the ideal environment is the UTCI (Jendritzky et al., 2012). All of them are equivalent temperatures, the main difference being that different models are used in the calculation of the heat balance condition of the body. Both SET* and PET utilize a simplified two-node model of the human body to calculate heat transfer between the core layer and the skin layers. However, it is important to recognize that UTCI employs a more complex Fiala multi-node model and garment adaptive model, which divides the human body into 12 segments consisting of 187 tissue nodes. This unique approach allows for automatic adjustment of garment thermal resistance based on ambient temperature, resulting in a more accurate representation of real-world human heat transfer. Predicted mean vote (PMV) is an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale based on the heat balance of the human body (Fanger, 1970). The difference between PMV and the first three indicators is that it is applicable indoors and is an empirical indicator, while the other three are rational indicators.

The applicability and correction of thermal comfort indicators have been one of the research hotspots in OTC, as well as an important scientific problem to be solved. In a comparative study of several indicators, Liu B. et al. concluded that PMV was not applicable to Shanghai (Cfa) (Liu et al., 2017). Lei found that PET, UTCI and SET* were not equally accurate in predicting the outdoor thermal environment in Harbin (Dwa) by season (Lei, 2018). And Fang Z. et al. evaluated the applicability of UTCI, wet bulb globe temperature (WBGT), PMV, SET* and PET to the outdoor thermal environment in Guangzhou (Cfa), still the relationship between these indicators and mean thermal sensation vote (MTSV) was not clear (Fang et al., 2019). Huang et al. found that PET, UTCI and UC-Berkeley (UCB) were not good predictors of actual thermal sensation and OTC of pedestrians (Huang et al., 2017). Binarti F et al. found in a review of OTC research in hot-humid regions that the neutral temperature ranges of SET*, PET, and UTCI could not cover the actual neutral temperature range (Binarti et al., 2020). So the correction of indicators according to the region has become one means to address barriers to OTC research. Lucchese and Andreasi (2017), Johansson et al. (2018), Fang et al. (2019) and others have partially adjusted the range of thermal stress for different thermal comfort indexes according to regional climate. However, studies by Kántor et al. (2016) and Kenawy et al. (2021) soon realized that using different methods to determine neutral temperatures made comparing studies on an international scale difficult. Salata et al. (2016) and Cheung and Jim (2017) also pointed out that another reason was the different understanding of the concept. Regarding the former question, Golasi I. et al. proposed a new indicator, the global outdoor comfort index (GOCI), based on empirical relations which had been previously identified in the existing literature to address the differences in instruments and methods across studies (Golasi et al., 2018). Based on the above, the applicability and calibration of thermal comfort indicators in the Dalian area need to be addressed urgently.

The aim of this paper is to use a transverse survey method to gain a comprehensive understanding of the overall OTC of Dalian residents in

Table 1
Studies targeting OTC in squares in the last six years (2017–2022).

Issue	Authors	Köppen/ Thermal Design of China	City	Time	Objectives	Index	Responses
2017	Kruger and Drach (2017)	Aw	Rio de Janeiro	Summer	City square Street	UTCI	985
	Samira et al. (2017)	Csa	Constantine	Jul.	City square	PET	2220
	Lucchese and Andreasi (2017)	Aw	Grand camp	Winter Spring Summer	City square	PET	524
	Nouri and Costa (2017)	Csa	Lisbon	Jul.	City square	PET	110
	Tseliou et al. (2017)	Csa	Athens	Mar. - Jul. Sep. - Nov.	City square Park	PET	2313
	Huang et al. (2017)	Cwa 4B	Hong Kong	Summer Autumn Winter	Campus square	PET UTCI UCB	1107
	Jin et al. (2017)	Dwa 1B	Harbin	Summer Winter	City square	PET	410
	Liu et al. (2017)	Cfa 3A	Shanghai	Aug. - Jan.	City square	PMV PET SET*	878
2018	Aljawabra and Nikolopoulou (2018)	Csa	Marrakech	Summer Winter	City square Park	–	303
	Lindner-Cendrowska and Błażejczyk (2018)	Dfb	Warsaw	All year	City square	PET	662
	Johansson et al. (2018)	Aw	Guayaquil	Mar. - Apr. Jun.	City square Park Pedestrian arcade Waterfront	PET SET*	544
	Kenawy and Elkadi (2018)	Cfb	Melbourne	Summer Winter	City square Campus	PET	2123
	Hirashima et al. (2018)	Aw	Belo Horizonte	Unclear	Park City square	PET	1182
		Cfb	Kassel & Freiburg		Neighborhood City square		776
	Fang et al. (2018)	Cfa 4B	Guangzhou	Jul. - Aug. Oct. - Nov.	Campus square	PET UTCI	2007
	Li et al. (2018)	Cwa 4B	Hong Kong	Summer Autumn Winter	Campus square	UTCI	1107
	Wei and Liu (2018)	Cfa 3A	Shanghai	Aug. Nov. - Dec.	City square	PET	870
	Chen et al. (2018)	Dwa 1B	Harbin	All year	Campus square	PET	4131
2019	Lei (2018)	Dwa 1B	Harbin	All year	City square Street Park Campus	PET SET* UTCI	2047
	Fang et al. (2019)	Cfa 4B	Guangzhou	Jun. - Jul.	Campus square	WBGT PMV SET* PET UTCI	644
	Li (2019)	Dwa 1B	Harbin	Sep. - Oct.	City square Park	–	624
	Huang et al. (2019)	Cfa 3A	Mianyang	Jan. Jun. Aug.	Campus square	PET	523
	Huang and Peng (2020)	Cfa 3B	Chongqing	Jan.	City square	PET	484
2020	S & Rajasekar (2020)	BSh	New Delhi	Jun.	Religious square	PET UTCI	353
	De Arêa Leão Borges et al. (2020)	Aw	Cuiaba	Autumn Winter Summer	Street Campus square	UTCI	685
	Leng et al. (2020)	Dwa 1B	Harbin	Apr.	Residential square	PET	301
	Xi et al. (2020)	Dwa 1B	Harbin	Jun. - Jul. Dec. - Jan.	City square Park	–	1740
	Xie and Li (2020)	Cfa 4B	Guangzhou	Summer Autumn Winter	City square	PET	7515
2021	Kenawy et al. (2021)	Cfb	Melbourne	Jan. - Feb.	City square Botanic garden Campus	PET	4717
	Kenawy and Elkadi (2021)	Cfb	Melbourne	Summer Winter	City square Campus	PET	2123

(continued on next page)

Table 1 (*continued*)

Issue	Authors	Köppen/ Thermal Design of China	City	Time	Objectives	Index	Responses
	Fang et al. (2021)	Cfa 4B	Guangzhou	All year	Campus square	–	4675
	Zhen et al. (2021)	BSk & Cwa 2B	Xi'an	Spring	Campus square	PET	258
	Liu et al. (2021)	Cwa 4B	Zhanjiang	Jul.	City square	DI	–
	An et al. (2021)	Dwa 2B	Beijing	Winter	Park City square	UTCI	496
		BSk & Cwa 2B	Xi'an				1055
		BWk 2B	Hami				199
	Li and Li (2021)	Cfa 3A	Wuhan	Winter	City square	–	100
2022	S & Rajasekar (2022)	Cwa	Chandigarh	Summer Winter	City Square Park Waterfront	PET	2585
	Xiao and Yuizono (2022)	Dfb	Hokuriku	–	Station square	PMV	–
	Sayad et al. (2021)	Csa	Guelma	Summer	City square	UTCI	–
	Xiang and Zheng (2022)	Cfa 3A	Changsha	–	City square	SET* UTCI PET	–
	Wei et al. (2022)	Cfa 3A	Shanghai	Summer Autumn Winter	City square	PET	1748

Note: The building thermal design of Hong Kong refers to Shenzhen City of Guangdong Province.

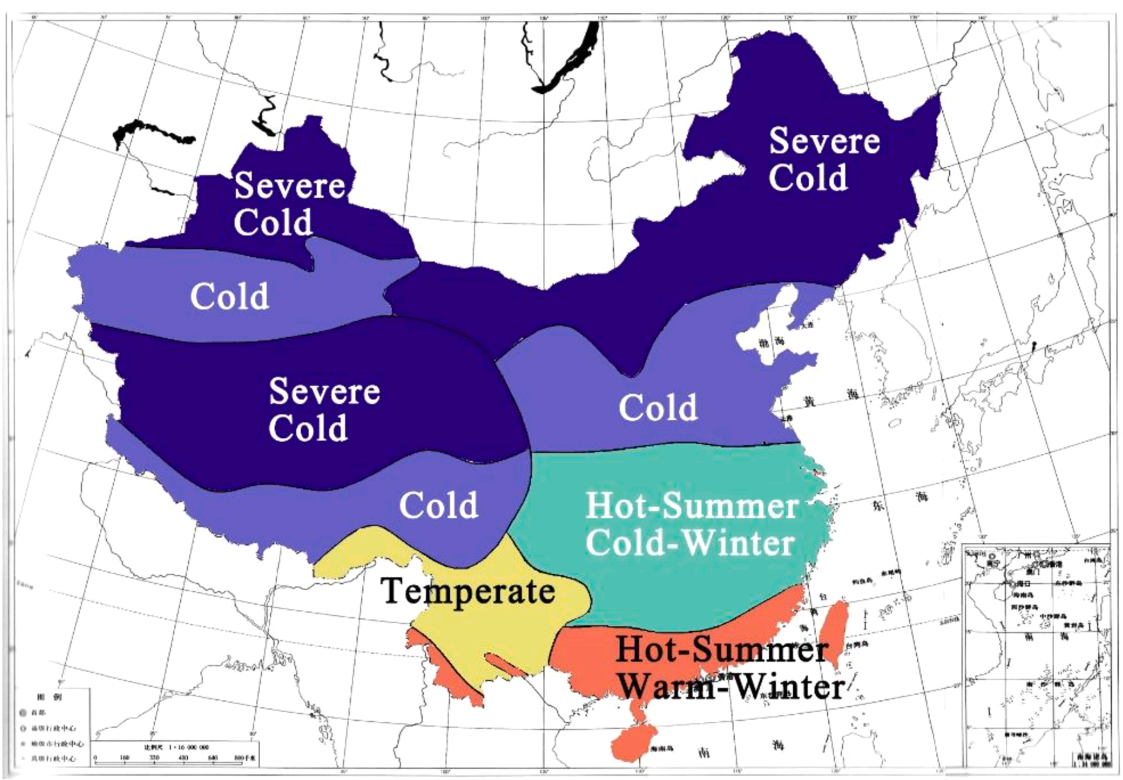

Fig.1. China building climate division (Ministry of Housing And Urban-Rural Development 2016).

summer climatic conditions and to compare it with OTC studies in other regions. This study evaluates the OTC of Dalian residents in urban squares through thermal environment field measurements and subjective questionnaires. Secondly, thermal benchmarks are established based on three indicators, SET*, PET and UTCI, with various methods for Dalian urban squares. The most suitable indicator for OTC research in Dalian is identified. Finally, a comparative analysis with the OTC of other studies is carried out to clarify the OTC characteristics of the square in Dalian, a representative city in the Dwa and 2A regions. This paper enriches and complements the study of the Dwa and 2A climate zones based on a comparative analysis of thermal benchmarks determined by different international methods. The thermal benchmarks in this study must serve as an indispensable guide for the creation of outdoor spaces adapted to the climate zone, which can attract people to the outdoors, thereby reducing indoor energy consumption, activating the commercial value of the site and its neighboring plots, and bringing economic benefits.

2. Subjects and methods

2.1. Study area

According to the *Code for Thermal Design of Civil Building* (Ministry of Housing and Urban-Rural Development, 2016), Dalian belongs to 2A. It is located between 38°43′–40°12′ N latitude and 120°58′–123°31′ E longitude. The climate is mainly characterized by short spring and autumn seasons and long, cold and dry winters (Ministry of Housing and Urban-Rural Development, 1993). Fig. 2 shows the meteorological situation in Dalian for each month of a typical year, and the data comes from a *Meteorological dataset for thermal environment analysis of buildings in China* (China Architecture & Building Press, 2005). The hottest month in Dalian is August, with a monthly average Ta of 24.6 °C. The coldest month is January, with a monthly average Ta of −4.0 °C. July and August have the highest monthly average RH of 87.2 % and 76 %, respectively, while April has the lowest average RH of 50.8 %. The region under study receives abundant sunshine throughout the year. The period between April to June exhibits the highest solar radiation levels, ranking in the top three for the entire year. However, radiation levels tend to decrease during July. Monsoons prevail in Dalian, with the highest Va in winter, followed by autumn and spring, and the lowest in summer, with an average Va of 4.8 m/s throughout the year.

2.2. Field data collection

Outdoor spaces in Dalian are known nationwide for their urban squares. According to Su et al. (2022b), Dalian is a city with the most different types of urban squares in China. In this paper, three urban squares shown in Fig. 3 were finally selected as research objects based on four characteristics of urban squares: attributes, scale, spatial design and number of activities. Regarding attributes, squares A and B are culture squares, and C is a leisure square, and they are similar in scale. Square A is surrounded by a circle of buildings, a typical enclosed square. Square B has fewer buildings at the boundary, which is a semi-enclosed square. Square C, a representative of many squares adapted to the hilly topography of Dalian city, is surrounded by mountains and structures. Also, they represent three different spatial designs. Square A consists of hard paving and greenery, square B consists of hard paving, vegetation and water, and square C consists of a large area of hard paving and is close to the seashore, representing coastal squares. In addition, the three squares attracted many people due to their historical status, ease of access and entertainment, which lays the foundation for the successful collection of the questionnaire.

The instruments for monitoring thermal environmental factors were placed in the center of the square and a sunlit area free from shadows, with the monitoring height 1.5 m above the ground. Instruments were set up on hard pavement. Questionnaires were conducted with pedestrians. Pedestrians were not more than 5 m from the instruments. Clear and cloudless days were selected for two days in each city square for thermal environment monitoring. The field measurements and questionnaire interviews were conducted on 6th and 7th August 2021 for square A, on 5th July and 8th August for square B, and on 2nd July and 10th July for square C. 415 valid questionnaires were received for square A, 308 for square B, and 341 for square C, for a total of 1064 that was above 400 of minimum sample size required in Dalian city determined through Eq. (1) according to Krüger E. (Krüger et al., 2017) The lack of official information on the health distribution of Dalian residents made it impossible to compare the samples collected randomly. The experiment lasted from 8:00 a.m. to 6:00 p.m., and Fig. 4 shows the location of test sites as well as the respondents during the survey period.

$$n = \frac{N\cdot\left(1/E^2\right)}{N + \left(1/E^2\right)} \tag{1}$$

Where n is the minimum size of the sample, N is the population of the examined city and E is the sampling error (assumed to be 5 %).

2.3. Micrometeorological measurements

The seasons of Dalian were defined according to the national

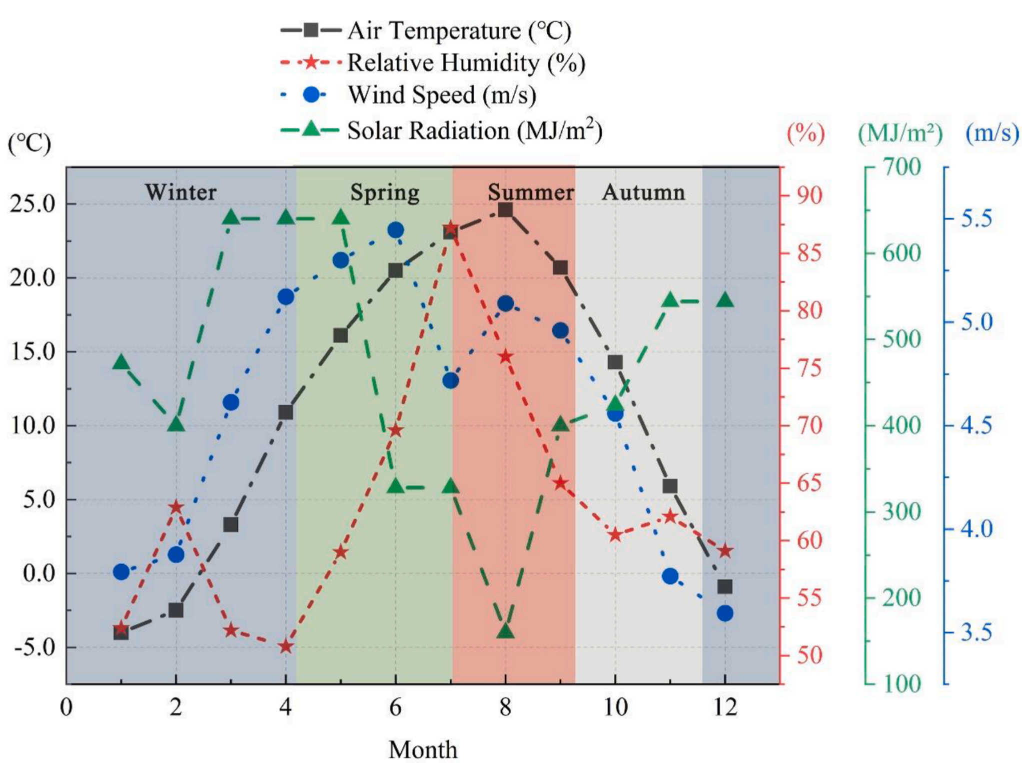

Fig. 2. Meteorological data of typical meteorological year in Dalian.

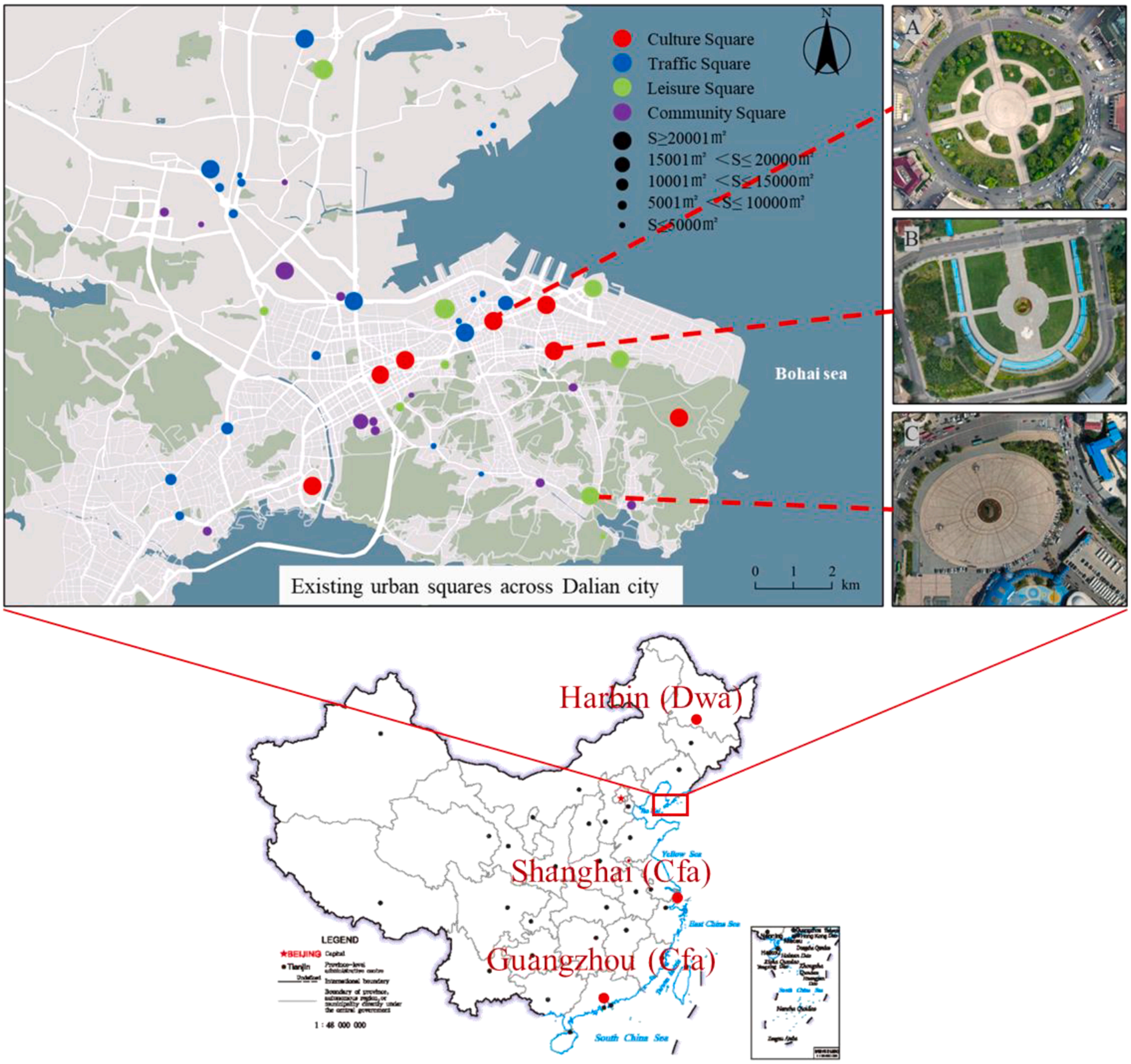

Fig. 3. Measured site.

Fig. 4. On-site research.

standard *Division of Climatic Season* (CMA 2012) and confirmed by sliding average temperature calculations using typical meteorological year data of Dalian from 1971 to 2003. The summer duration of Dalian was determined to last from July 1st to September 7th. The results of other seasonal divisions are shown in Fig. 2. The instruments of Ta and RH recorder (product type WSZY-1) were used to measure, with the accuracy of 0.1 ℃ and 0.1 %, respectively. And thermal comfort recorder (product type SSDZY-1) measured Va and global temperature (Tg) with the accuracy of 0.01 m/s and 0.01 ℃, respectively. The recording frequency was 1 min for all. All instruments were compliant with the ISO 7726 standard (ISO Standard, 1998). The probes that collect Ta and RH were treated with radiation protection.

2.4. Questionnaire

The questionnaire was divided into three parts; the first section related to personal information, such as gender, age, weight, and height (Mi et al., 2020). The second section related to personal characteristics, including clothing, main activity status in the last 15 min, and duration of stay in the research space (Kenawy & Elkadi, 2021). And accompanying situation (Galindo & Hermida, 2018) and state of health (Chen et al., 2018; Lindner-Cendrowska & Błażejczyk, 2018) were added. The third section was a survey of various thermal perceptions, including thermal sensation vote (TSV), thermal comfort vote (TCV), thermal acceptability vote (TAV) and thermal preference vote (TPV). TSV is the vote on thermal sensations reported by people (Wang et al., 2021). The ASHRAE Standard 55 (ANSI, 2017) defines the 7-point thermal sensation scale as seven categories. However, considering the climate of Dalian, this research adopts the now widely used 9-point scale (Fang et al., 2019; Johansson et al., 2018; S & Rajasekar, 2022). TCV is the vote on the condition of thermal comfort that expresses satisfaction with the thermal environment. Similarly, thermal comfort adopts a 9-point scale (Fang et al., 2019; S & Rajasekar, 2022) for the current study. TAV is the vote on thermally acceptable reports by people in a thermal environment, adopting a 6-point scale in the research. TPV is the vote on

Questionnaire on outdoor thermal environment quality

Date: **Site:**

Time:

Please describe your current thermal sensation:

Very cold	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	Very hot
-4	-3	-2	-1	0	1	2	3	4

Please describe your current thermal comfort:

Cold				Moderate	Hot			
Very discomfort	Discomfort	Slightly discomfort	Slightly cold comfort		Slightly hot comfort	Slightly discomfort	Discomfort	Very discomfort
-4	-3	-2	-1	0	1	2	3	4

Please describe your acceptable level for current thermal environment:

Completely unacceptable	Unacceptable	Just unacceptable	Just acceptable	Acceptable	Completely acceptable
1	2	3	4	5	6

Please describe your current preference about the following meteorological parameters:

	Lower（-1）	No change（0）	Higher（1）
Air temperature			
Relative humidity			
Wind speed			
Solar radiation			

Gender: □Male / □Female **Height:** **Weight:**

Age: □＜10 □11-20 □21-30 □31-40 □41-50 □51-60 □61-70 □71-80 □>81

Companion: □Self □One companion □≥Two companions

How long have you been here? (min): □<5 □5-15 □15-30 □30-60 □>60

Your major activities in past 15 min:

□Seating □Standing □Walking □Jogging □Babysitting □Other______________

Did you spend any time in air conditioning before came here? □Yes □No

What are you wearing right now?（If there is no corresponding clothing, please note.）

Upper: Vest、T-shirt(short sleeves / long sleeves / sleeveless)、Sweater（short sleeves / long sleeves）、One-piece dress(thin / thick)、Jacket or blazer(thin/thick)

Trousers: Dress、Pants(sweatpants / jeans / informal)、Length(Ankle-length / Knee-length / shorts)

Socks: Knee socks、Stockings、Ankle-length socks

Shoes: Sandals or flip flops、Boots、Shoes

Overall color: □Dark □Light

How long have you lived in Dalian:

□native □<3d □3-7d □8-30d □31-90d □91-180d □181-365d □>365d

State of health: □Normal □Cold □Asthma □Rhinitis □Allergy □Other____________

State of smoking: □Never □Quit smoking □Smoking

Fig. 5. Questionnaire.

expectations or preferences for the current thermal environment by people. And the research's preferences use the 3-point McIntyre scale. The details of all subjective evaluation indicators of the thermal environment (TSV, TCV, TAV and TPV) are shown in Fig. 5.

2.5. Thermal indexes

The literature review found that the main evaluation indicators for OTC in domestic and abroad studies are PET, SET* and UTCI, so these three indicators will also be used in this paper. RayMan software was used for the calculation of PET and SET*. The meteorological parameters (Ta, RH, Va, Tmrt), personal parameters (age, height, weight, clothing and activity) and geographical parameters (longitude, latitude and altitude) were inputted into the RayMan. UTCI was selected from the Pythermalcomfort calculation package, a highly efficient and accurate Python programming software developed by Tartarini, F., of the University of California, Berkeley, USA (Wang et al., 2021). The inputs of the package included Ta, RH, Va, and Tmrt.

Notably, Tmrt was calculated based on Eq. (2) from ISO 7726 (ISO Standard, 1998). Tg, Va, and Ta were obtained from field measurement. Globe emissivity (ε) was assumed to be 0.95, and globe diameter (D) was 150 mm in this study. Va 10 m above ground (V_{a10}) was used for UTCI calculation, which was corrected by Eq. (3) based on measured Va at 1.5 m height ($V_{a1.5}$). Mean speed exponent (α) was 0.33 for city centers (Tartarini & Schiavon, 2020).

$$T_{mrt} = \left[\left(T_g + 273\right)^4 + \frac{1.10 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} \left(T_g - T_a\right) \right]^{\frac{1}{4}} - 273 \tag{2}$$

$$V_{a10} = V_{a1.5} \left(\frac{H_{10m}}{H_{1.5m}}\right) \left(\frac{H_{10m}}{H_{1.5m}}\right)^{\alpha} \tag{3}$$

After calculating the thermal comfort indexes, for the calculation of the thermal benchmark, three methods were used: linesar regression, quadratic regression and probabilistic analysis.

3. Results

3.1. Characteristics of the thermal environment

In this paper, the representation of solar radiation intensity characteristics is used indirectly through the difference between Tg and Ta, where a larger difference between the two indicates a stronger solar radiation intensity. This method has also been used by research scholars (GA, US & ASHRAE, 2013; Nikolopoulou et al., 2003). The overall trend of Ta in the city squares during the research period was a warming phase in the morning. Most of the squares reached the highest between 13:00–15:00, and there was a slow cooling trend thereafter. A city squares, the maximum Ta occurs in the morning or in the afternoon. Observation of the solar radiation intensity reveals that Ta is likely to be at its maximum during the phase of increasing solar radiation intensity, which shows that solar radiation intensity is an important factor affecting the outdoor thermal environment. As far as RH is concerned, it was found that RH follows an opposite trend to that of Ta. When the Ta increases, the RH decreases and vice versa. As for Va, it fluctuates in a wide range and with high frequency, which is related to topographic and spatial morphological features and the complexity of airflow movement. For the monitoring points, there is no obvious change law of Va.

3.2. Respondents information

A total of 1064 valid questionnaires were obtained in this paper. To study the OTC of local people in Dalian, the investigation of living time in Dalian was included in the questionnaire design, and 129 questionnaires who lived in Dalian for less than 7 days were excluded. The anthropometric data of respondents are shown in Fig. 6. In the field study, there were slightly more men than women, with a proportion of 52.2 % men and 47.8 % women. This equates to an almost equal ratio of 1:1 between the two genders. According to the Dalian Statistical Yearbook of 2020, there were 2961,870 males and 3025,053 females in Dalian City, accounting for 49.5 % and 50.5 %, respectively. The size of

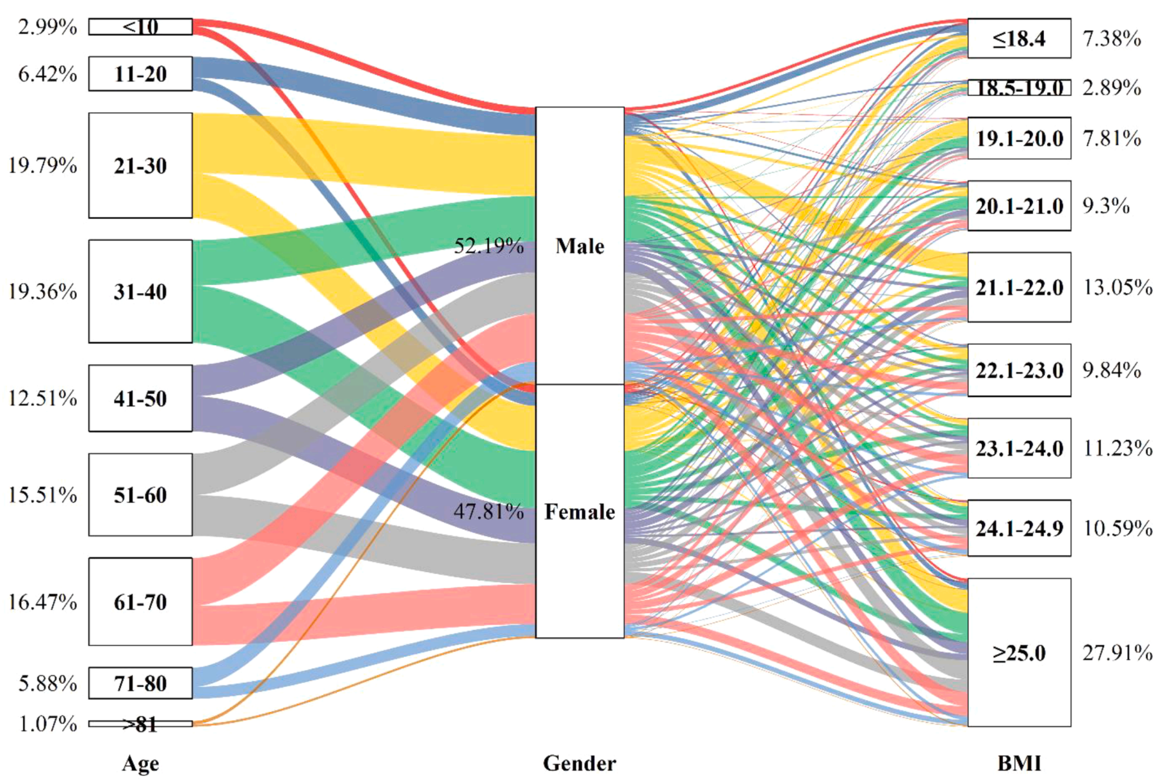

Fig. 6. Anthropometric data of respondents.

the sample utilized in this paper is aligned with the gender ratio of the resident population in Dalian, which ensures that it can objectively reflect the viewpoints held by Dalian inhabitants concerning the thermal environment of the city square.

The age range of respondents was widely distributed, ranging from children as young as 6 years old to elderly people as old as 92 years old. 9.4 % (5 % officially) of the respondents were younger than 10 years old. 67.2 % of the surveyed adults were aged between 21 and 60 (66.6 % officially), while 23.4 % were seniors aged above 60 years (28.4 % officially). This was, in general, consistent with the official data released by the authority's Dalian Statistical Yearbook of 2020. Respondents were mainly concentrated within the age range of 21–30, 31–40 and 61–70. Body mass index (BMI) reflects the relationship between the human's weight and height and the degree of obesity and an individual's health status. The World Health Organization (Shu, 2019) classifies BMI as follows: a BMI of 18.4 or lower is considered thin, a BMI of 18.5–24.9 is considered normal, and a BMI of 25.0 or higher is considered overweight. The survey covered the health status of the participants. The results showed that 7.38 % were considered lean, 64.71 % normal, and 27.91 % overweight. Physical health status may affect thermal perception. However, due to the lack of official data on the health status of Dalian residents, there was no way to verify the health status of the sampling personnel, which may make the research results slightly deviate from the true situation of understanding the thermal comfort goals of the whole city.

3.3. Characteristics of OTC

To ensure the credibility of the data, the options receiving less than 10 votes were excluded from this study, such as TCV = −2. As shown in Fig. 7(a), according to the TSV results, the options of "Neutral (0)" and "Hot (+3)" received the highest number of votes, totaling 33.2 % and 26.2 %, respectively. The option "Very Hot (+4)" received the lowest votes, with only 4.5 % of the total. Compared to squares in other regions, the dominance in Warsaw (Dfb) during the summer was "Slightly Warm (+1)" at 38 %. "Neutral (0)" came in second at 27 % (Lindner-Cendrowska & Błażejczyk, 2018). In Chandigarh (Cwa), the highest was "Hot (+3)" at 61.1 %, followed by "Very Hot (+4)" at 27.7 % (S & Rajasekar, 2022). This indicates that OTC varies depending on the climate zone. In the TCV, "Comfortable (0)" received the highest number of votes at 39.3 %, while "Slightly Hot Comfort (+1)" came in second with 33.2 %. During the summer months in Dalian, 57.1 % of residents experienced thermal comfort in the hot zone (TCV>0), while only 3.3 % experienced thermal comfort in the cold zone (TCV<0). According to Fig. 7(b), the rate of thermal acceptability showed a nearly linear increase when TSV and TCV were between +4 and 0. When TCV=−1 and TSV=−1, their acceptability is lower than that of TCV=1 and TSV=1, this indicates that people were more receptive to warmer conditions in summer compared to cooler ones.

As shown in Fig. 7(c), regarding Ta preference, 54.7 % of respondents expressed the desire for a "Decrease (−1)", while 41.9 % preferred it to remain "The Same (0)". In Warsaw (Dfb), the majority of questioned people accepted thermal conditions and wished them not to change (Lindner-Cendrowska & Błażejczyk, 2018). This also indicates that respondents in Dalian generally prefer cooler Ta during the summer. Regarding RH, 57.3 % of the respondents found their environment suitable, while 37.2 % preferred a less humid atmosphere. Based on the survey on Va, a clear majority of 57.9 % of respondents expressed their preference for Va to remain "The Same (0)", while only 31.0 % indicated a desire for an "Increase (+1)". According to solar radiation, almost half of the respondents, 47.4 %, expressed a desire to decrease solar radiation. Meanwhile, approximately 40.0 % of the participants did not indicate a preference for any changes.

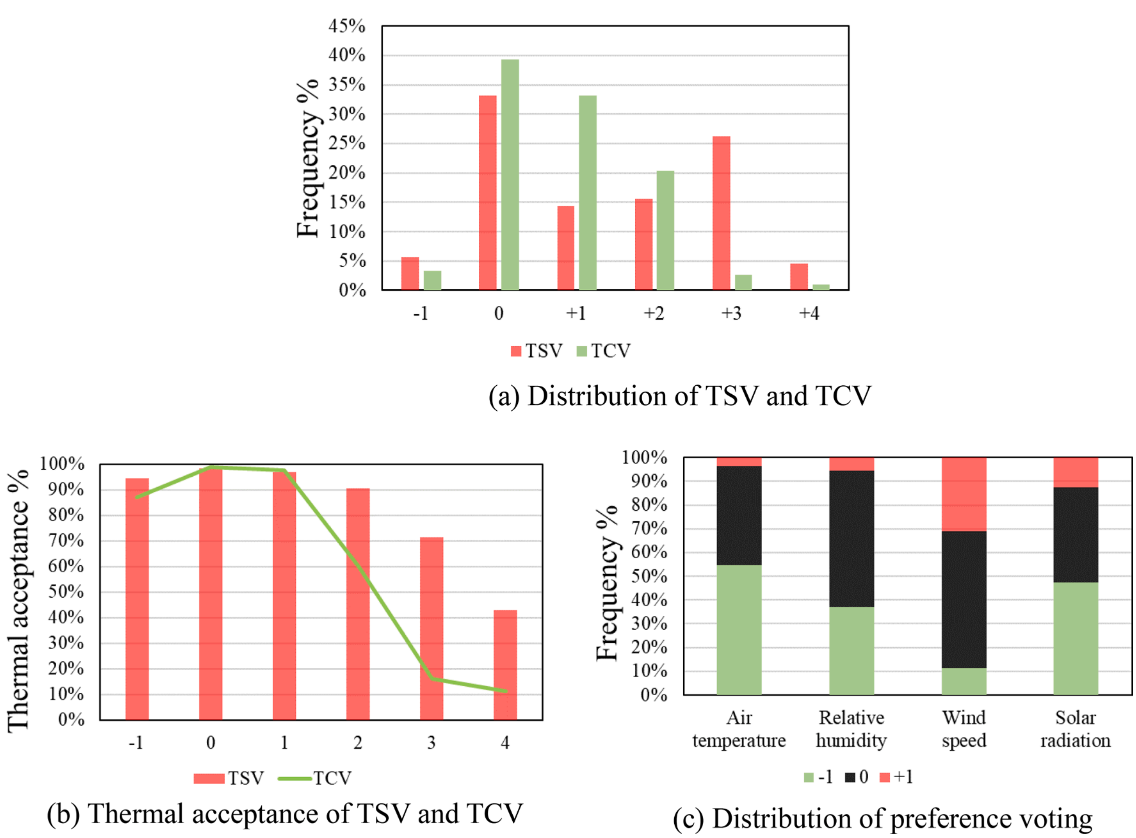

Fig.7. Characteristics of OTC.

3.4. Thermal benchmarks

3.4.1. Neutral temperature

The term “Neutral Temperature” refers to the point at which individuals do not feel cold or hot (Fanger, 1970). Two types of linear regression are used in studying thermal comfort indicators: linear regression of MTSV (1 °C) and thermal comfort indicators and linear regression of raw TSV and thermal comfort indicators. The index is used as the dependent variable, and MTSV or TSV as the independent variable. To ensure accurate data, a minimum of five respondents per 1 °C bin is necessary to remove any potential outliers.

According to the TSV vote depicted in Fig. 8, it is evident that the thermal conditions of Dalian square are, overall, quite comfortable for its inhabitants. The majority of the votes were centered around 1.5, indicating a high degree of satisfaction. The values of MTSV and TSV showed a positive correlation with the thermal comfort index. As SET*, PET, and UTCI values increased, so did MTSV and TSV. According to Table 2, the results were statistically significant, with a significance level of ≤ 0.001. However, it should be noted that MTSV showed a high correlation with SET*, PET, and UTCI. The R^2 values are approximately 0.95, indicating a strong correlation between the variables and clearly explaining the observed values.

After conducting additional linear regression analysis on MTSV and thermal comfort index, we found that each regression equation had a different slope. The slopes were 0.14, 0.13, and 0.2, indicating that each index has a different thermal sensitivity which affects the unit MTSV. Consequently, the SET*/TSV, PET/TSV, and UTCI/TSV values need to be changed by 7.1 ℃, 7.7 ℃, and 5.0 ℃, respectively. Setting MTSV and TSV equal to 0, the neutral temperatures of each thermal comfort index were calculated as shown in Table 2. Among them, both methods' neutral temperature of SET* (NSET*) values were not in the range of the subjective questionnaire values.

Fig. 9 shows the quadratic regression of SET*, PET and UTCI with MTSV (1 °C). The index is used as the dependent variable, and MTSV as the independent variable. As seen from Table 2, the method provides a more accurate equation fit than linear regression. A more precise representation of the connection between individual thermal perception and each indicator can be established. Setting MTSV equal to 0, the neutral temperature of each indicator was calculated in Table 2.

Probit analysis provides the possibility of reaction to a stimulus (World Health Organization 1995). Considering TSV to be the response variable and the aggregated indices values as a stimulus, probit analysis produced indices' values in which 50 % of the respondents were on the verge of changing their vote to the next higher class of thermal sensation, such as from +1 to +2 (Pantavou et al., 2014). Calculation methods based on probit analysis can be divided into three types. To determine the neutral temperature, one method selects the intermediate temperature from “Slightly Cool” to “Neutral” (TSV≥0) and from “Neutral” to “Slightly Warm” (TSV ≥ 1) (Pantavou et al., 2014). Another method selects the temperature where TSV > 0 and TSV < 0 have equal probability voted as the neutral temperature (Ballantyne et al., 1977). The third method selects the temperature with the maximum probability of “Neutral” is selected as the neutral temperature (Kántor et al., 2016). In this paper, the above three methods were used to calculate the neutral temperature for SET*, PET, and UTCI, as shown in Fig. 10, and the statistics of the results are shown in Table 2.

The neutral temperature of PET (NPET), NSET*, and neutral temperature of NUTCI (NUTCI) were determined through the averaging of the two transition temperatures of the probit curves with TSV≥0 and TSV≥1. The resulting figures are as follows: 18.1 °C for NSET*, 21.5 °C for NPET, and 25.7 °C for NUTCI. Similarly, the values obtained through the intersection of the probit curves with TSV>0 and TSV<0 were 16.8 °C for NSET*, 20.9 °C for NPET, and 25.3 °C for NUTCI. The subtraction of two probabilities of TSV>0 and TSV<0 by 100 % yielded the figures for NSET*, NPET, and NUTCI as 19 °C, 20 °C, and 26 °C, respectively.

3.4.2. Preferred temperature

The preferred temperature refers to the temperature when people prefer neither warm nor cold (Feng, 2018), which is also considered the ideal thermal condition for the human body. Calculating the preferred temperature is relatively simple compared to the neutral temperature and uses a probabilistic analysis method. As shown in Fig. 11, when the probit curves of “Want Warmer” (TPV=1) and “Want Cooler” (TPV=−1) intersect, where respondents have an equal probability of wanting a warmer or cooler thermal environment, then the temperature is the preferred temperature.

According to the statistics and findings presented in Table 2, it is evident that the preferred temperatures for SET*, PET, and UTCI are 7.9 °C, 14.6 °C, and 20.2 °C, respectively. The preferred temperature for most people is actually lower than the neutral temperature under the same OTC index. This is because neutral conditions are not the ideal preferred conditions for the public, and people always prefer a slightly cooler environment than neutral during summer.

3.4.3. Neutral temperature range

The neutral temperature range, also known as the heat stress-free range, is typically determined by a TSV vote between −0.5 and +0.5. Scholars believe that the neutral temperature range is more reasonably solved using probit regression (Cheung & Jim, 2017). Linear regression is fitted to find the temperature values of TSV between −0.5 and 0.5. Probit regression utilizes the probit curve of cumulative TSV rating. The boundary of neutral temperature is determined by the temperature corresponding to two curves with a 50 % probability of TSV ≥ 0 and TSV ≥ 1.

The information as a function of the two methods is shown in Table 2. The neutral temperature range of SET* (NRSET*), neutral temperature range of PET (NRPET), and neutral temperature range of

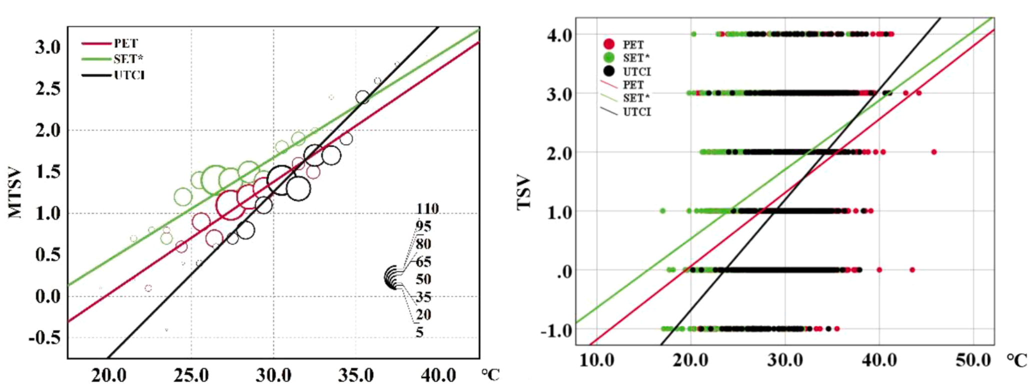

Fig. 8. Linear regression of SET*, PET and UTCI on MTSV (1 °C) and TSV, respectively.

Table 2
Thermal benchmarks of SET*,PET and UTCI.

Index	Method	TSV	TPV	Equation	R^2	T_0/T_1	Bin (℃)	Sig.	Neutral temperature/ *(TSV=0)* (℃)	Neutral temperature range (℃)	Preferred temperature (℃)	Acceptable range (℃)
SET*	LR	–	–	MTSV=0.14SET*−2.32	0.939	–	19.0–34.0	<0.001	16.6	10.9–19.3	–	–
	LR	–	–	TSV=0.12SET*−1.81	0.072	–		<0.001	15.1	–	–	–
	QR	–	–	MTSV=0.00177SET*^{2} + 0.23SET*−3.53	0.942	–	–	<0.001	18.4	–	–	–
	LR	–	–	TPA=−0.14SET*^{2} + 5.52SET*+40.79	0.696	–	–	<0.001	–	–	–	13.6–25.8
	PRO	≥0	–	Probit(p)=0.112SET*−1.367	–	12.2	–	–	18.1	12.2–24.0	–	–
		≥1	–	Probit(p)=0.089SET*−2.141	–	24	–	–			–	–
	PRO	>0	–	Probit(p)=0.089SET*−2.141	–	–	–	–	16.8 / *19*	–	–	–
		<0	–	Probit(p)=−0.112SET*+1.367	–	–	–	–		–	–	–
	PRO	–	1	Probit(p)=−0.043SET*−0.706	–	–	–	–	–	–	7.9	–
		–	−1	Probit(p)=−0.061SET*−1.626	–	–	–	–	–	–		–
PET	LR	–	–	MTSV=0.13PET-2.7	0.951	–	20.0–40.0	<0.001	20.8	16.9–24.6	–	–
	LR	–	–	TSV=0.12PET-2.43	0.171	–		<0.001	20.3	–	–	–
	QR	–	–	MTSV=0.00216PET^2+0.00575PET-0.83	0.957	–	–	<0.001	20.8	–	–	–
	LR	–	–	TPA=−0.13PET^2+6.1PET+23.35	0.754	–	–	<0.001	–	–	–	17.3–29.6
	PRO	≥0	–	Probit(p)=0.121PET-1.858	–	15.4	–	–	21.5	15.4–27.5	–	–
		≥1	–	Probit(p)=0.1PET-2.756	–	27.5	–	–			–	–
	PRO	>0	–	Probit(p)=0.1PET-2.756	–	–	–	–	20.9 / *20*	–	–	–
		<0	–	Probit(p)=−0.121PET+1.858	–	–	–	–		–	–	–
	PRO	–	1	Probit(p)=−0.064PET+0.013	–	–	–	–	–	–	14.6	–
		–	−1	Probit(p)=0.066PET-1.886	–	–	–	–	–	–		–
UTCI	LR	–	–	MTSV=0.2UTCI-4.81	0.968	–	23.0–38.0	<0.001	24.5	20.6–25.8	–	–
	LR	–	–	TSV=0.19UTCI-4.41	0.172	–		<0.001	23.2	–	–	–
	QR	–	–	MTSV=0.00174UTCI^2+0.09UTCI-3.23	0.969	–	–	<0.001	24.4	–	–	–
	LR	–	–	TPA=−0.21UTCI^2+9.95UTCI-22.14	0.731	–	–	<0.001	–	–	–	18.5–28.9
	PRO	≥0	–	Probit(p)=0.194UTCI-4.257	–	22	–	–	25.7	22.0–29.3	–	–
		≥1	–	Probit(p)=0.164UTCI-4.803	–	29.3	–	–			–	–
	PRO	>0	–	Probit(p)=0.164UTCI-4.803	–	–	–	–	25.3 / *26*	–	–	–
		<0	–	Probit(p)=−0.194UTCI+4.257	–	–	–	–		–	–	–
	PRO	–	1	Probit(p)=−0.092UTCI+0.937	–	–	–	–	–	–	20.2	–
		–	−1	Probit(p)=0.097UTCI-2.882	–	–	–	–	–	–		–

Note: LR means linear regression, QR means quadratic regression, and PRO means probit regression.

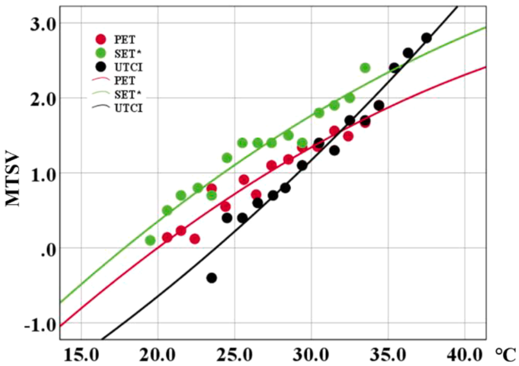

Fig. 9. Quadratic regression of SET*, PET and UTCI with MTSV (1 °C).

UTCI (NRUTCI) were found to be 10.9–19.3 °C, 16.9–24.6 °C, and 20.6–25.8 °C, respectively, based on simple linear regression. According to the probit analysis, the temperature ranges were 12.2–24.0 °C, 15.4–27.5 °C, and 22.0–29.3 °C, respectively.

3.4.4. Acceptable temperature range

The ASHRAE standard (Feng, 2018) clearly defines that a thermal environment is acceptable if more than 80 % or 90 % of the respondents consider it acceptable. The calculation method is similar to that of the neutral temperature. As shown in Fig. 12, the thermal acceptability votes for OTC indicators were grouped by 1 °C intervals and ensured no less than five respondents per 1 °C bin. The thermal percentage accepted within each group was calculated, and the results are shown in Table 2. The acceptable temperature range is wider than the neutral range because people adjust their behavior and mindset to adapt to the continuously changing thermal environment.

The acceptable range widths of SET*, PET and UTCI are 2.1 °C, 2.1 °C and 4.1 °C more than the neutral temperature range. And the bottom of the acceptable temperature range for SET* (ARSET*) and the acceptable temperature range for PET (ARPET) are higher than the bottom of NRSET* and NRPET calculated by two methods. This is because the linear equations for the neutral temperature range are well-matched, and the values calculated using probit regression were all present in the field measurement. In contrast, the data for the bottom of ARSET* and ARPET is based on a quadratic equation that isn't as well-matched as the rest. While it still has some level of predictiveness, it causes the bottom values of the acceptable range to appear higher than the bottom of the neutral temperature range.

3.4.5. Thermal stress categories

When it comes to thermal stress categories, scholars use the ASHRAE standard's definition, where the range of each thermal stress is within ±0.5 of the TSV. The classification is typically done through two methods: linear regression or probit regression.

Based on the results of the previous linear regression equations of MTSV with SET*, PET and UTCI, as shown in Table 2, −0.5, 0.5, 1.5, 2.5 and 3.5 were substituted into the equations for calculation. The TSV results were reselected for TSV ≥ 4, TSV ≥ 3 and TSV ≥ 2, and the probit curves were drawn accordingly. The value of the probit curve intersecting with 50 % probability is the upper and lower interval taken for that thermal stress. Fig. 13 shows the plot of each thermal stress obtained using the probit regression for SET*, PET and UTCI. Finally, the results of the thermal stress categories according to the linear regression and the probit regression are shown in Table 3.

By referring to Table 3, we can observe that the linear regression displays a consistent thermal stress range for each thermal stress,

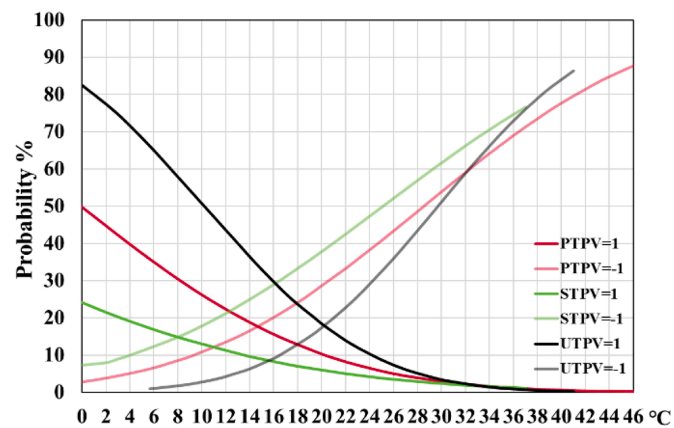

Fig. 11. Preferred temperature for SET*, PET and UTCI.

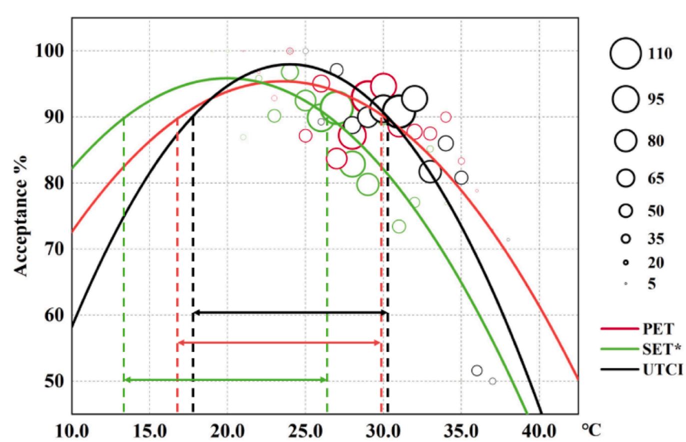

Fig. 12. Acceptable temperature range for SET*, PET and UTCI.

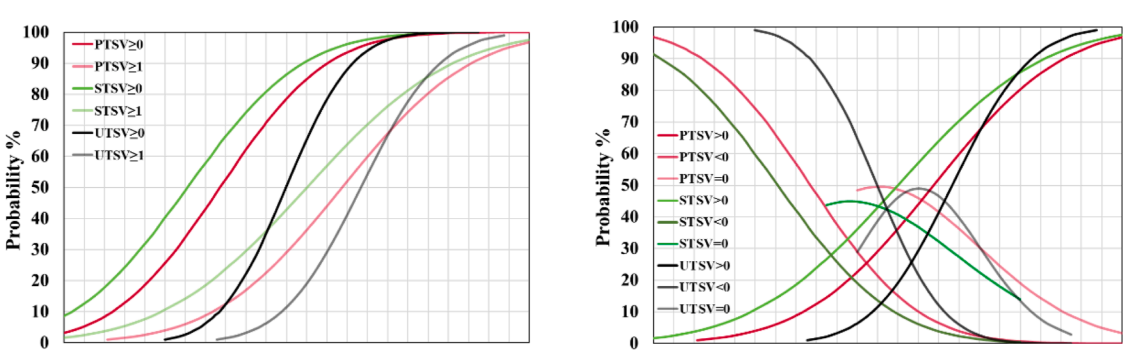

Fig. 10. Different methods for determining the neutral temperature of SET*, PET and UTCI by probit analysis.

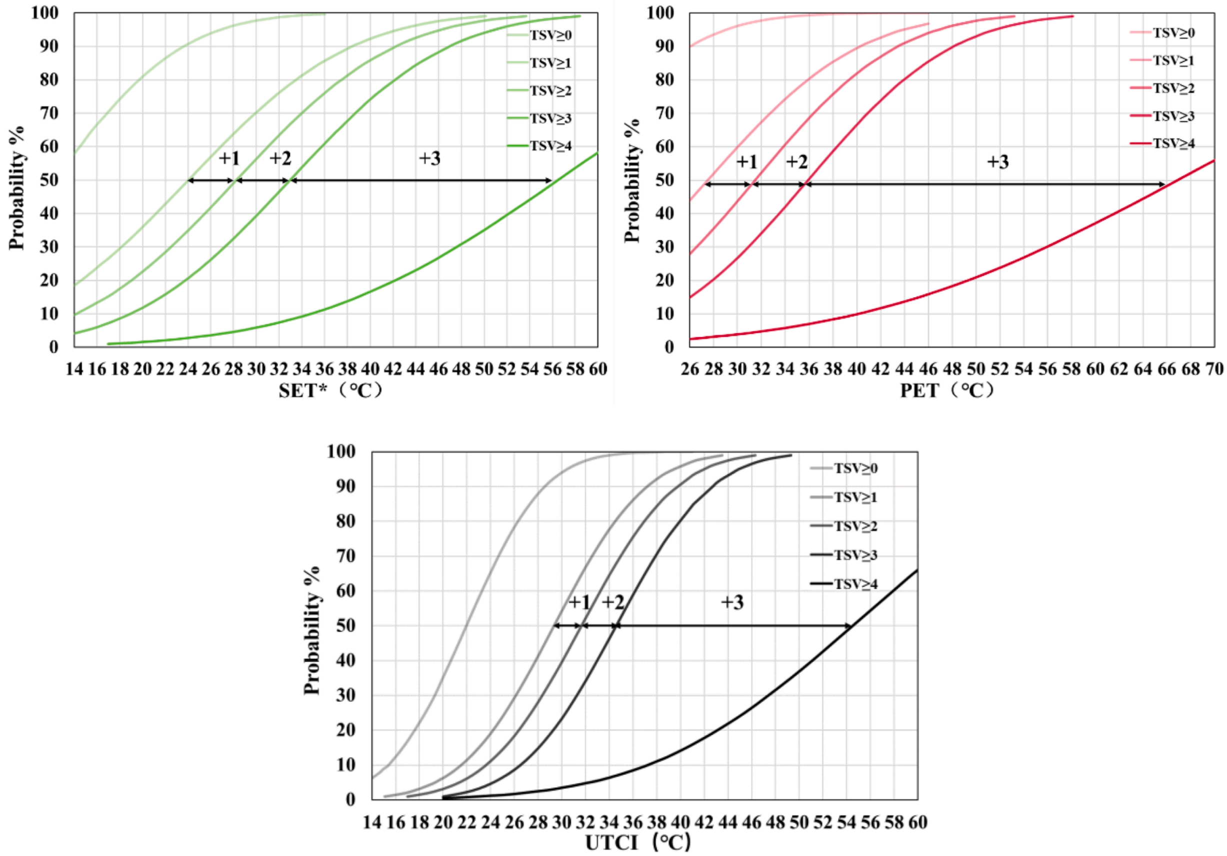

Fig. 13. Cumulative TSV of SET*, PET and UTCI.

regardless of the OTC index. However, the probit regression does not exhibit this consistency. The reason for this is that the linear slope remains constant, causing each thermal stress interval to grow at the same rate. In probit regression, the TSV interval that represents high temperatures includes a broad range of values. The values for thermal stress other than the original have either increased or decreased within the range. The limited number of votes collected for TSV=4 during the questionnaire distribution was caused by the hot weather and fewer people in the square. This resulted in the predicted part of the probit curve for TSV≥4 being much higher than the actual collected votes. In addition, the threshold for "Slightly Warm" and "Warm" levels are similar by different methods for the three OTC indicators.

3.5. Applicability

This paper examines the suitability of SET*, PET, and UTCI indicators in cold regions, as their applicability varies depending on the climate zone. The original model's predicted thermal sensation (PTSV) was compared with the actual mean thermal sensation (MTSV) to understand the general properties in applicability. As Fig. 14, the SET*-PTSV line is lower than the MTSV over the range of the actual MTSV, and the slope of SET*-PTSV is higher than the MTSV. This suggests that the initial version of SET* underestimated the actual MTSV of individuals, but as the temperature rose, SET* tended to overestimate their real conditions.

Table 3
Thermal stress calibration.

MTSV	Method	−0.5	0.5	1.5	2.5	3.5
Level	Slight cool	Neutral	Slight warm	Warm	Hot	Very hot
SET*	Regression	13.0	20.1	27.3	34.4	41.6
PET		16.9	24.6	32.3	40.0	47.7
UTCI		21.6	26.6	31.6	36.6	41.6
SET*	Probit	12.2	24.0	28.3	33.0	56.5
PET		15.4	27.5	31.5	35.9	66.9
UTCI		22.0	29.3	31.6	34.6	54.5
SET*	Original	22.2	25.6	30.0	34.5	37.5
PET		18	23	29	35	41
UTCI		9	26	32	38	46

Observing the relationship between the two lines of PET-PTSV and PET-MTSV revealed that the original PET model predicted the MTSV with high accuracy when the temperature was between 20 and 25 °C; in other words, between TSV=0 and TSV=1 and then showed a trend of increasingly overestimating the MTSV. The UTCI-PTSV line overestimated the MTSV for UTCI<26 °C and UTCI>26 °C, and the predicted values were more consistent with the reality only for UTCI=26 °C. This result is consistent with the studies of Feng X et al. (Ballantyne et al., 1977; Standard, 1992). Overall, the SET* model considers that the neutral temperature range is lower, while PET and UTCI are more accurate in reflecting the real feelings of Dalian residents.

To determine the applicability of SET*, PET and UTCI quantitatively, prediction accuracy (η) is introduced, as shown in Eq. (4). $Q_{PTSV-TSV}$ is the number of votes where the predicted TSV is the same as the actual TSV votes, and Q_{all} is the total number of votes.

$$\eta = \frac{Q_{PTSV-TSV}}{Q_{all}} \times 100\% \tag{4}$$

Table 4 shows the PTSV and actual TSV voting intersection for SET*, PET, and UTCI, respectively. Based on the above equation and the three cross-tabulations, the prediction accuracies for SET*, PET and UTCI are 21.6 %, 25.3 % and 18.2 %, respectively. So it is difficult for the OTC index to accurately predict the changeable outdoor conditions. PET has the highest prediction rate, followed by SET* and UTCI. Therefore, PET is the most suitable model for evaluating the OTC of Dalian among the

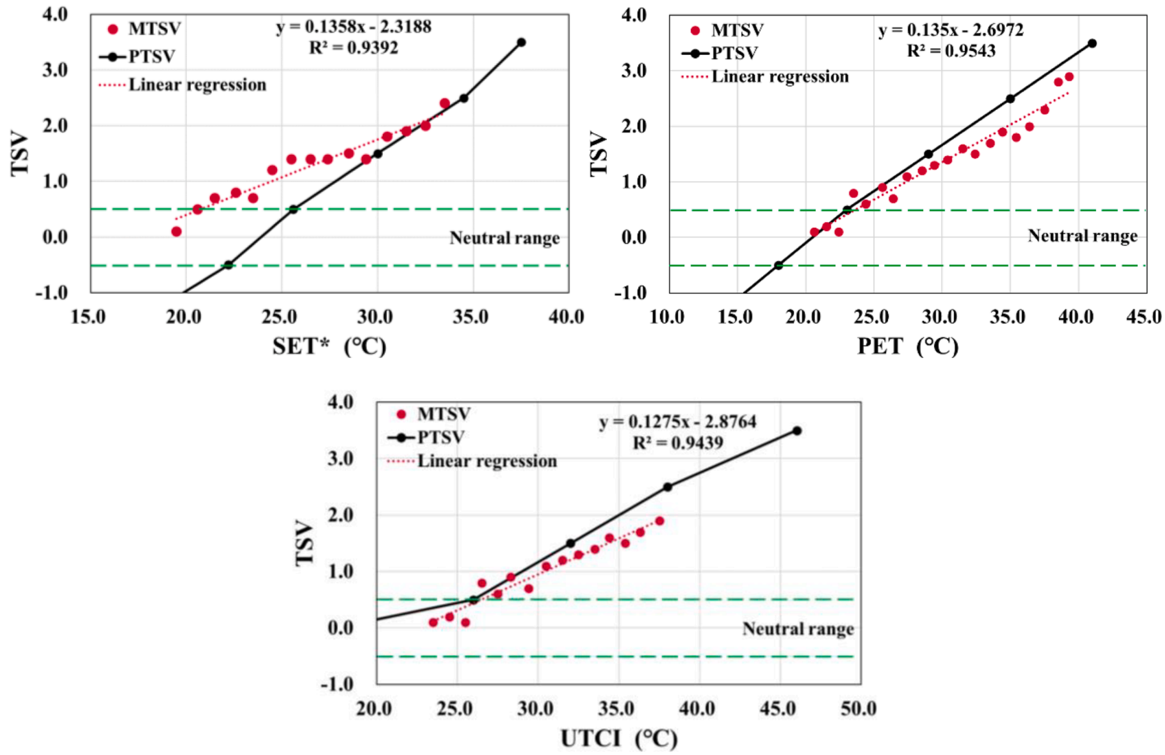

Fig. 14. Adaptation tests for SET*, PET and UTCI.

Table 4
SET*,PET and UTCI summer forecast TSV and actual TSV voting turnover table.

Index		TSV						Total
		−1	0	1	2	3	4	
PTSV	−1	15	27	9	4	7	1	63
(SET*)	0	15	92	33	34	39	8	221
	1	16	152	66	82	132	15	463
	2	7	34	26	26	65	17	175
	3	0	5	0	0	2	1	8
	4	0	0	0	0	0	0	0
Total		53	310	134	146	245	42	930
PTSV	−1	0	0	0	0	0	0	0
(PET)	0	18	31	7	3	5	0	64
	1	20	126	48	41	32	9	276
	2	14	125	60	76	129	18	422
	3	1	27	18	25	77	13	161
	4	0	0	0	1	2	3	7
Total		53	310	133	146	245	43	930
PTSV	−1	0	0	0	0	0	0	0
(UTCI)	0	13	22	5	3	4	0	47
	1	38	213	83	82	89	19	524
	2	2	75	45	61	149	20	352
	3	0	0	1	0	3	3	7
	4	0	0	0	0	0	0	0
Total		53	310	134	146	245	42	930

three indexes.

During summer in Guangzhou (Fang et al., 2019), the prediction accuracy of SET*, PET and UTCI were 32.1 %, 23.1 % and 28.7 %, respectively. Regarding prediction accuracy of the OTC index, the SET* ranked highest, followed by UTCI and PET in descending order. During summer in Harbin (Lei, 2018), the prediction accuracy of SET*, PET and UTCI were 52.5 %, 53.1 % and 62.3 %, respectively. The order of accuracy rate was UTCI, PET, and SET* from high to low. As well as in Rome, throughout the year, PET and UTCI were 25.4 % and 23 % (Golasi et al., 2018). In terms of summer, the result of this study is similar to that of Guangzhou and Rome but different from that of Harbin. This is because the study in Harbin adopted the idea proposed by de Dear (de Dear and Fountain, 1994) that considers TSV value within the range of −1, 0, and 1 as acceptable. The implementation of combining calculations for TSV values of −1, 0, and 1 has led to a noteworthy enhancement in accuracy. However, this modification, which artificially and actively widens people's thermal comfort range, has yet to be proven.

4. Discussion

To find out the OTC of the Dwa zone, this study compared the results of Dalian with other studies in the same climate. The evaluation of thermal perception is diverse, catering to the requirements of varying spatial designs and resident activities. To guide the design of outdoor thermal environments, summer and winter are the typical seasons. The results obtained by combining various seasons can differ from one season (Kenawy & Elkadi, 2021; Nikolopoulou & Lykoudis, 2006; Spagnolo & de Dear, 2003), and there is a risk of weakening or reinforcing the actual conditions of typical seasons. As shown in Fig. 15, A comparative analysis in the same seasons is necessary to avoid this risk.

4.1. Neutral temperature

In the Dwa zone, linear regression was used in all studies. According to the regression model, the NPET of Tianjin (Nikolopoulou & Lykoudis, 2006) is 15.6 °C and the NUTCI is 17.5 °C. Tianjin's data wasn't analyzed because it included data from the transition season, which interfered with the accuracy of the summer conditions. The NPET for Dalian is 20.8 °C between the three Harbin studies, which are 20 °C (Chen et al., 2018), 20 °C (Lei, 2018) and 26 °C (Jin et al., 2017). There are two reasons why this may be the case. First, in the 2A thermal zone, building design must take into account thermal insulation requirements. However, in the 1B zone, these requirements are explicitly stated as not being a consideration. It indirectly explains that the summer in Dalian is hotter than in Harbin. The role of Alliesthesia (Lai et al., 2014) is generally acknowledged (Johansson et al., 2018; Lai et al., 2014; Spagnolo & de Dear, 2003; Yao et al., 2018), meaning that the desire for

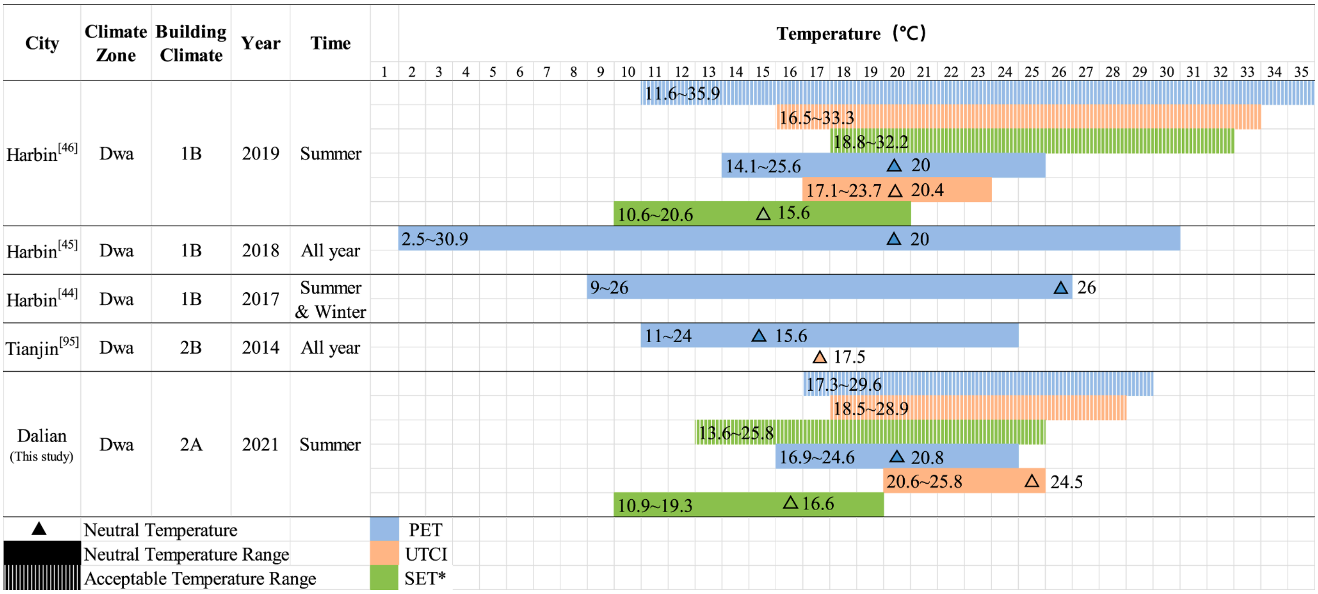

Fig.15. Comparing thermal benchmarks of researches in Dwa zone.

a cooler environment in a hot environment makes the Dalian residents want a lower neutral temperature situation to occur than that of Harbin (Jin et al., 2017). Second, comparing the regression equations of the studies reveals that the slope of 0.13 for Dalian is smaller than that of 0.136 for Harbin (Jin et al., 2017). This indicates that the residents of Dalian have a low sensitivity to temperature and need a higher temperature change than Harbin to experience a unit change in thermal sensation.

It is worth noting that in the other two Harbin studies, the slopes of the regression equations were 0.073 and 0.09. Chen et al. (2018) (0.073) did a longitudinal study with some restrictions and screening of the physiological parameters of the volunteers. According to the existing research, although the difference between males and females in thermal sensation is not statistically significant (Lai et al., 2020), the statistically insignificant relationship between health state and thermal sensations or preferences (Lindner-Cendrowska & Błażejczyk, 2018), volunteers' cultural and psychological factors can impact temperature sensitivity (Aljawabra & Nikolopoulou, 2018; Chen et al., 2018; Johansson et al., 2018; Li et al., 2018; Nikolopoulou & Lykoudis, 2006). This is why the sensitivity is the lowest among the four studies. It is more consistent with Xu et al. (2019), where regional differences were associated with volunteers. The study done by Lei (2018) (0.09) included areas with squares, settlements, parks, streets and campuses. However, due to the difference in Tmrt, PET of squares and streets can be more than 12.5 °C higher than in parks (Lai et al., 2020), or people can have an impact on thermal sensation due to visual experience (Cohen et al., 2013), which in turn can seriously affect the OTC of individual subjects (Lin et al., 2013; Shooshtarian et al., 2020). Thus making the sensitivity of Harbin (Lei, 2018) lower than that of Dalian and Harbin by Jin et al. (2017). The data collection duration may also contribute to the NPET gap between the two Harbin studies. Lei's study (Lei, 2018) was conducted from 8:30–17:00 for only 8.5 h, whereas Jin et al. (2017) were conducted from 10:00–20:00 for a total of 10 h, which was the same collection duration as this study.

In the application of SET* and UTCI indicators, the NSET* and NUTCI of Harbin (Lei, 2018) are 15.6 °C and 20.4 °C, respectively, while the NSET* and NUTCI of Dalian are 16.6 °C and 24.5 °C, respectively. The neutral temperature of Dalian is higher than that of Harbin under all three indicators. Except for the NUTCI, the NPET and NSET* were close in both studies, and NSET* was the lowest, and NUTCI was the highest. More basic data support is needed to compare the differences between the three indicators further. What can be determined is that the neutral temperature in Dalian is higher than that in Harbin under the same index, which confirms the intention of each OTC index to improve the accuracy of seeking the equivalent temperature by establishing a thermal transfer model that is more compatible with the human body.

4.2. *Neutral temperature range*

The NRPET is 11–24 °C for Tianjin and 14.1–25.6 °C (Lei, 2018), and 9–26 °C (Jin et al., 2017) for Harbin. The neutral temperature range for Tianjin has a lower bottom threshold compared to Harbin (Lei, 2018) because the data for Tianjin include winter, while Harbin (Lei, 2018) only provides summer. It has been demonstrated that the multiple seasons would follow the winter conditions (Spagnolo & de Dear, 2003). In another study by Harbin (Jin et al., 2017), the neutral temperature range directly used the neutral temperature in winter as the lower threshold and that of summer as the upper threshold. Using the same method as Lei (2018), which takes TSV = ±0.5 as the threshold of the neutral temperature range, the NRPET of Dalian is 16.9–24.6 °C. And NRSET* and NRUTCI are 10.6–20.6 °C and 17.1–23.7 °C for Harbin (Lei, 2018) and 10.9–19.3 °C and 20.6–25.8 °C for Dalian, respectively. The neutral temperature ranges of Harbin (Lei, 2018) are all broader than those of Dalian under the same indicators. The slope of the regression equation for all indicators in Dalian is higher than that of Harbin (Lei, 2018) with high sensitivity, so the range of values in Dalian is narrower. It is also found that the upper thresholds of the range are more similar, and the lower thresholds are more disparate, which is consistent with Cohen (Lai et al., 2020).

4.3. *Acceptable temperature range*

The acceptable temperature range is the most tolerated thermal benchmark (Cheung & Jim, 2017; Kenawy & Elkadi, 2018). Many studies have focused on determining and developing optimal environmental conditions for use in engineering and other projects. However, this has resulted in less research on the acceptable temperature range compared to the neutral temperature. In the Dwa region, for the 90 % acceptable temperature range in summer, the ARSET* is 18.8–32.2 °C, the ARPET is 11.6–35.9 °C, and the ARUTCI is 16.5–33.3 °C in Harbin (Lei, 2018). ARSET* is 13.6–25.8, ARPET is 17.3–29.6 °C, and ARUTCI is 18.5–28.9 in Dalian. The temperature amplitude in the Harbin (Lei,

2018) is wider than that in Dalian at any index. The measured data show that the average Ta and temperature difference in Harbin (Lei, 2018) are 27.7 °C and 4.9 °C, while those in Dalian are 28.6 °C and 7.1 °C. Despite the high Ta and temperature difference in Dalian, it is known from Section 4.1 that the thermal sensitivity of Dalian residents is greater than that of Harbin (Lei, 2018). That is, the acceptable range requirements in Dalian are higher than those in Harbin (Lei, 2018). Measurement points are only located in the city squares of Dalian, whereas Harbin (Lei, 2018) has more measurement points throughout the city, considering various characteristics of the urban environment. Salata F. et al. demonstrated that the difference between the two cities would be lower than the difference between multiple points in the same city (Salata et al., 2016). It is possible to elaborate on the site's unique characteristics to provide further clarification.

A disparity exists in the lower thresholds for neutral and acceptable temperature ranges when comparing Harbin's (Lei, 2018) SET* measurements to PET and UTCI measurements. Specifically, SET* has a lower threshold of 10.6 °C for a neutral temperature range, which is lower than its acceptable temperature range threshold of 18.8 °C. In contrast, PET and UTCI have a higher acceptable temperature threshold than their neutral temperature threshold. In Dalian, the neutral temperature range for SET* and PET is 10.9 °C and 16.9 °C, respectively. However, this falls below the acceptable temperature range of 13.6 °C and 17.3 °C.

Interestingly, UTCI contradicts this. The research suggests that humans have a flexible thermal zone (Cheung & Jim, 2017), which allows for overlap between the neutral and acceptable temperature ranges. This highlights the adaptable nature of humans in different temperature environments.

4.4. Thermal stress categories

The OTC indexes applied above are equivalent temperatures in accordance with the human thermal transfer model. The correspondence between equivalent temperature and thermal stress is intuitively understandable for the general public (Lin, 2009; Yang et al., 2013). For the thermal stress categories in Table 5, Harbin (Chen et al., 2018) uses discriminant analysis, while the other two Harbin (Jin et al., 2017; Lei, 2018) researches use linear regression. This study uses linear regression and probability analysis, and Tianjin (Nikolopoulou & Lykoudis, 2006) uses field measurement results and linear regression. From Section 4.1, it is clear that the NPET of Harbin (Chen et al., 2018) is 20 °C, but it is not within the neutral thermal stress, indicating a conflict between the results obtained from different research methods. This also confirms the view of Kenawy and Elkadi (2018) that some limitations occur with varying research methods. The study by Tianjin (Nikolopoulou & Lykoudis, 2006) includes four seasons, calculating the MTSV corresponding to each 1 °C PET interval and using the PET value at a TSV of ±0.5 as the threshold for the neutral stress, and so on. Limited field measurement time from 10:00–16:00 may result in inconsistent data collection. To address this issue, a regression model prediction will compensate for the unavailable data.

Probit analysis is widely used by scholars such as S & Rajasekar (2022), Fang (Standard, 1992), and Shooshtarian S. (Lin et al., 2010) to determine thermal stress. Linear regression is also used in the studies of Cheng (Shooshtarian & Rajagopalan, 2017), Kántor N. (Cheng et al., 2012) and Liu (Kántor et al., 2012). In the study of Harbin (Jin et al., 2017), the thermal stress is classified using winter and summer data, and the TSV is based on a 7-point scale without ``Very Cold'' and ``Very Hot'' data, but this does not affect the neutral temperature (Chen et al., 2018). Both this study and Lei's (Lei, 2018) use a 9-point TSV scale, categorized specifically for summer. The amplitudes of SET*, PET and UTCI for each thermal stress in Dalian are smaller than those of Harbin (Lei, 2018). And the UTCI has the minimum magnitude for each thermal stress in both studies. This is because the UTCI differs from PET and SET* in that the model considers the human initiative to change clothing due to external conditions constantly. According to Pantavou K, the clothing insulation of UTCI would be unusually low at high temperatures (Pantavou et al., 2013). The sensitivity of UTCI to temperature would be higher than that of SET* and PET. A wider range reflects the ability to adapt to OTC, and it seems like the residents of Harbin possess a stronger ability to adapt in comparison to those of Dalian.

4.5. Limitations

In summary, even for OTC studies conducted in the same city, arbitrary differences in the timing of the experimental phase (season and data collected duration), location (city and measurement point), respondents (specific and randomized), and methodology (statistical approach) can affect the thermal benchmarks. In the case of more similar experimental setups, the neutral temperature in Dalian is lower than that in Harbin (Jin et al., 2017). In the less similar cases, Dalian's is higher than Harbin's (Lei, 2018).

The results of this study represent an OTC study for Dalian within the Dwa and the 2A climate zone in China. Thermal benchmarks can be used as evaluation guidelines in the design and optimization phase of spaces

Table 5
Thermal stress categories of research in the Dwa zone.

Thermal sensation	TSV	PET / ℃					SET* / ℃		UTCI / ℃	
		Tianjin (Nikolopoulou & Lykoudis, 2006)	Harbin (Chen et al., 2018)	Harbin (Jin et al., 2017)	Harbin (Lei, 2018)	This study	Harbin (Lei, 2018)	This study	Harbin (Lei, 2018)	This study
unbearably cold			−30 ~ −23							
very cold	<−3.5	>−16	−23 ~ −10							
cold	−3.5 ~ −2.5	−16 ~ −11	−10 ~ −4	<−20						
cool	−2.5 ~ −1.5	−11 ~ −6	−4 ~ 3	−20 ~ −8						
slightly cool	−1.5 ~ −0.5	−6 ~ 11	3 ~ 13	−8 ~ 3	3~14.4		10.4~17.1		0.6~10.6	
neutral	−0.5 ~ 0.5	11 ~ 24	13 ~ 16	3 ~ 26	14.4~25.6	16.9 ~ 24.6	17.1~23.7	21.6~26.6	10.6~20.6	13.0~20.1
slightly warm	0.5 ~ 1.5	24 ~ 31	16 ~ 21	26 ~ 30	25.6~36.7	24.6 ~ 32.3	23.7~30.4	26.6~31.6	20.6~30.6	20.1~27.3
warm	1.5 ~ 2.5	31 ~ 36	21 ~ 28	30 ~ 44	36.7~47.8	32.3 ~ 40.0	30.4~37.1	31.6~36.6	30.6~40.6	27.3~34.4
hot	2.5 ~ 3.5	36 ~ 46	28 ~ 43	≥44	47.8~58.9	40.0 ~ 47.7	37.1~43.7	36.6~41.6	40.6~50.6	34.4~41.6
very hot	>3.5	>46	>43		>58.9	>47.7	>43.7	>41.6	>50.6	>41.6

that need to meet various outdoor activities. To ensure that citizens can enjoy a full six hours of outdoor activity during the daytime at a city square in summer, architects can utilize an acceptable temperature range or other thermal benchmarks as the foundational level for planning. From there, they can thoughtfully incorporate water features, greenery, and surrounding buildings to meet this activity requirement. The methodology in this study can be used to obtain local thermal benchmarks in other climate zones and study areas. However, our study has some limitations: 1) To prevent infection with COVID-19, some respondents still wore masks in the summer, whose effect on thermal comfort evaluation was not considered in this paper. 2) The study was conducted only in summer, and the lower threshold calibration for neutral thermal class calibration may be affected by the missing spring data. 3) Although the reasons for the differences in thermal benchmarks were analyzed based on the available information, there have been many factors affecting thermal comfort, and the coupling is complex, so there is a lack of consideration of the influence of potential factors. In the future, the coupling mechanism of each factor on thermal comfort will be explored.

5. Conclusions

To gain a comprehensive understanding of the overall OTC of Dalian residents, a randomized questionnaire survey was conducted among individuals who had resided in the city for at least 7 days. The survey participants were chosen to represent the characteristics of the population in three typical city squares. Various statistical methods were used to calculate the thermal benchmarks of Dalian residents, after screening their questionnaires to demonstrate OTC. The findings presented in this paper have been thoroughly measured and surveyed at Dalian city square during the summer. We draw the following conclusions based on these results and a comparison with previous research.

(1) 33.2 % of Dalian residents evaluated Dalian's thermal environment in summer as neutral, and 39.3 % considered it comfortable. And they could accept a warmer thermal environment than cooler ones yet prefer lower temperatures. That is, psychological perception and physical perception are not the same.
(2) Neutral temperatures, preferred temperatures, neutral temperature ranges, acceptable temperature ranges, and thermal stresses for SET*, PET, and UTCI were obtained using current mainstream methods, including linear regression, quadratic regression, and probabilistic analyses.
(3) After conducting both qualitative and quantitative analysis, PET with a prediction accuracy of 25.3 % was the most appropriate indicator for outdoor summer in Dalian.
(4) The overlapping relationship between the neutral temperature range and the acceptable temperature range highlighted the adaptable nature of humans in different temperature environments and reconfirmed the existence of mobility in the human thermal zone.
(5) Even for OTC studies conducted in the same city, arbitrary differences in experimental phase timing (season and data collected duration), location (city and measurement point), respondents (specific and randomized), and research methodology (statistical approach) could affect the thermal benchmark.
(6) This study also identifies a paucity of OTC research in the Dwa climate zone Chinese 2A climate zone. The thermal benchmark results presented in this paper can be used as an evaluation criterion for space design and optimization stages that need to meet various outdoor activities.

This study is conducted only in summer, and studies in other seasons are needed to complement the assessment throughout the year. The social background of the respondents should also be taken into account. Yet the methods in this study can be used to obtain local thermal benchmarks in other climate zones and study areas. The results are of direct reference and use for other OTC studies in Dalian.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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