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Developing adaptive thermal comfort models and evaluation criteria for rural low-income residents in China

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ABSTRACT: Adaptive thermal comfort plays important roles in predicting indoor comfort temperature and evaluating indoor comfort level in free-running buildings. This research intends to develop an adaptive thermal comfort models and evaluation criteria for rural low-income houses in China. Transverse field surveys were conducted in rural districts of Lankao County in the North China Plain in typical winter and summer seasons. Results show that the majority of researched residents lived in excessively cold indoor thermal environments which is lower than 10.0 ℃ in winter. However, a great number of those residents felt comfortable in the environments. The existing adaptive thermal comfort criteria in ASHRAE 55, EN 16798 and GB/T 50785 are not applicable for rural low-income residents in China. In this research, new adaptive thermal comfort models and evaluation criteria were developed for rural low-income residents. The new models and criteria include a reflection of the residents' needs and their acclimation abilities, and are applicable for extremely low outdoor temperatures conditions where existing standards are incapable.
KEYWORDS: Adaptive thermal comfort model, rural low-income residents.

1. INTRODUCTION

Urban areas benefited a lot in the booming development in the past 30 years in China. However, at the same time, rural areas were left far behind gradually in all aspects. In 2019, the per capital deposable income (PCDI) per year of rural areas was 13432 Yuan (about £1492), which was only 1/3 of the urban PCDI [1]. Indoor temperature reveals great difference in living condition between two areas. Indoor temperatures in rural low-income houses in North China can be as low as 5°C in winter which is far below that in urban dwellings [2]. Increasing reliance on air-conditioning to improve thermal comfort in rural houses results in even higher energy bills, causing financial stress for these vulnerable rural residents, increase in peak electricity demand, as well as higher carbon emissions and other environmental problems [3]. Emphasizing human adaptive abilities, such as the use of adaptive thermal comfort, can reduce this reliance, particularly when combined with improved building thermal performance.

Adaptive thermal comfort has been an important research topic since the 1970s. In 1973, Nicol et al. proposed the "adaptive principle" that if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort [4]. Adaptive thermal comfort is considered a necessary supplement for theoretical thermal comfort research as it values human adaptation ability which is lacking in theoretical models. Adaptive thermal comfort models were included in standards, such as US standard ASHRAE 55 and European standard EN 16798-1 (formerly EN 15251)[5-7]. The standards are based on field surveys in office buildings in urban contexts. Applicability of the adaptive thermal comfort standards among rural low-income residents are not well-defined.

A few previous researches have revealed the differences between urban and rural low-income residents. Zhang et al. indicated that the rural elderly had stronger adaptability to lower temperatures in severe cold climate region of China [8]. Xiong et al. acquired similar conclusion through field surveys in the Hot Summer Cold Winter climate region in China that rural residents tend to be more tolerant of cold conditions in winter and less tolerant of hot conditions in summer, compared to the urban residents [9]. A research in Chile indicated inapplicability of adaptive thermal comfort standards in low-come houses in central-south Chile and developed a novel adaptive model that best fits with thermal conditions and residents in the researched area [10].

This research investigated the indoor environments in rural low-income houses on the North China Plain, as well as the thermal perceptions of rural low-income residents. Then, this research evaluated the applicability of current adaptive thermal comfort standards in rural low-income conditions and developed adaptive models and evaluation criteria for winter and summer seasons respectively.

2. METHODOLOGY

2.1. Research districts

Lankao County is a typical agricultural county located in the centre of the North China Plain, as shown in **Figure 1**. About 60% of its population is living in rural areas. The Per Capita Disposable Income (PCDI) of the rural population in 2018 is only £1253 per year which is similar to the average value (£1543) of rural China [1, 11]. Lankao is in the "Cold Zone" climate region of China. Field surveys were carried out in rural areas of Lankao County.

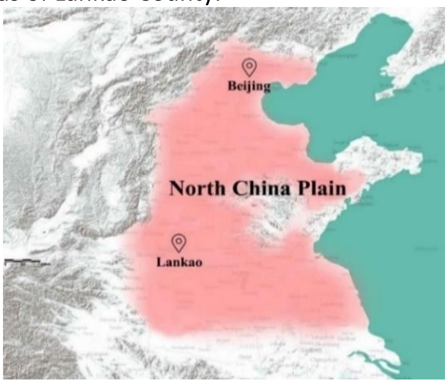

***Figure 1**: Location of the Lankao County*

2.2. Field survey

Transverse field surveys were adopted. Winter field surveys started from 21st December of 2018 and terminated on 23rd February of 2019. Summer field surveys were conducted between 22nd July and 4th September of 2019

Overall, 610 valid questionnaires were collected from field surveys. Each interview included a questionnaire survey and a simultaneous environment measurement in the researched room. The questionnaire survey acquired basic information (for example age, sex and clothing information) and thermal perceptions (thermal sensation vote, thermal acceptance vote, thermal preference vote) of the participants. The environment measurement measured environmental parameters, such as indoor air temperature (T_{in}), indoor globe temperature (T_g), indoor relative humidity (RH) and indoor air velocity (V_a). Outdoor environmental information was acquired from the closest weather station which is available on the NOAA website [12]..

3. RESULTS

3.1. Outdoor temperatures

Figure 2 shows daily outdoor air temperature between 1st October 2018 and 30th September 2019. Durations of winter and summer field surveys are highlighted separately. During the winter field survey, daily outdoor temperature varied from -7.3 °C to 8.1 °C with mean temperature of 0.7°C. During the summer field survey, daily outdoor temperature varied from 22.6 °C to 32.1 °C with mean temperature of 26.8°C.

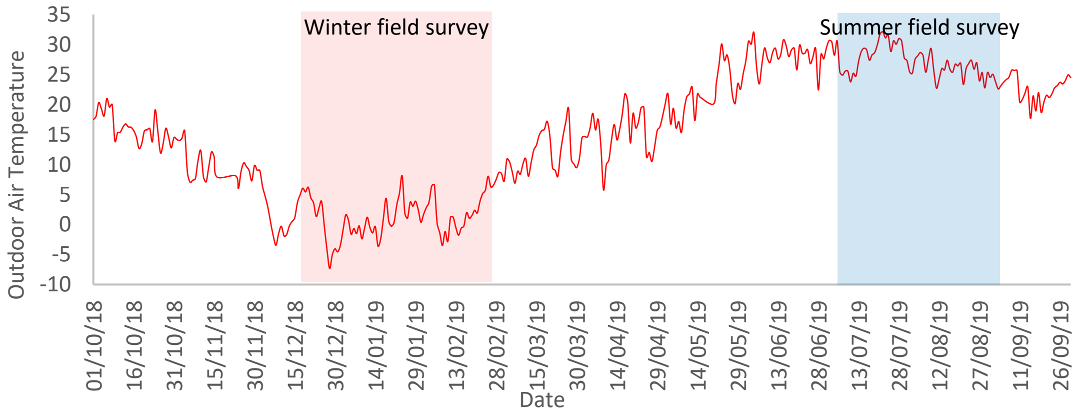

***Figure 2**: Daily outdoor temperature during winter and summer field surveys*

2.3 Indoor thermal environment

Recorded indoor operative temperature during interviews were sorted into temperature bins of an interval of 1.0°C. Results were plotted in **Figure 3** and **Figure 4**. In winter, the majority of rural low-income houses hold excessively cold indoor thermal environments. More than 90% of recorded indoor operative temperatures were below 10.0°C,and about 67.5% of recorded indoor operative temperatures assembled in an interval between 2.0°C and 7.0°C. Mean value of recoded indoor operative temperature was only 5.9°C. Indoor operative temperatures also varied greatly among houses as recorded indoor operative temperature distributed in a range between 0.7°C to 16.8°C.

In summer, indoor thermal environments

were relatively comfortable. The majority (80.9%) of recorded indoor operative temperatures were below 30.0°C. Mean value of recorded indoor operative temperature was 28.7°C. Similar to the winter result, recorded indoor operative temperature in summer also varied greatly among houses. Recorded indoor operative temperature spread in a range between 24.4°C to 37.8°C.

The wide distributions of indoor operative temperature are mainly the result of outdoor temperature changes. As shown in **Table 1**, high values in Pearson`s correlation and R-square indicate strong linear correlations between indoor operative temperature and outdoor temperature in both winter and summer.

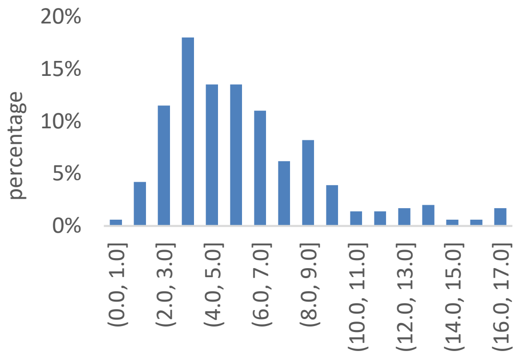

***Figure 3**: Distribution of recorded indoor operative temperature in winter field surveys.*

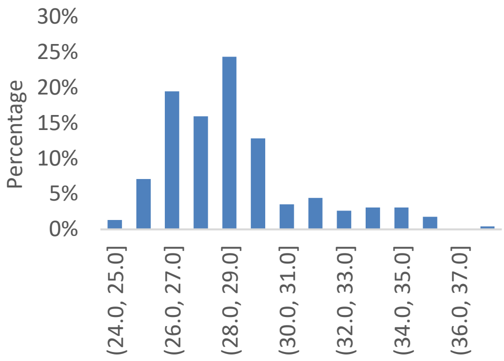

***Figure 4**: Distribution of recorded indoor operative temperature in winter field surveys.*

3.4 Feasibility of existing adaptive thermal comfort standards

At present, two adaptive thermal comfort standards are wildly used all around the world. They are ASHRAE 55 2017 in United States and EN 16798-1 2019 (formerly EN 15251) in Europe [6, 13]. Besides, a Chinese standard (GB/T 50785 2012) is widely used in China [14]. The applicability of three adaptive thermal comfort standards in rural low-income houses are analysed in this section. Three adaptive thermal comfort standards and field survey data are plotted in Figure 7, Figure 8, Figure 9. Titles of horizontal axes in three standards are different. However, the definitions and calculation equations are the same. Running mean outdoor temperature (T_{rm}) is used to represent the horizontal axis.

***Table 1**: Linear correlation between indoor operative temperature and outdoor temperature*

	Pearson correlation	Sig. (2-tailed)	Equation	R-square
Winter	0.736	0.000	$T_{op} = 0.5415\, T_a + 4.970$	0.5414
Summer	0.882	0.000	$T_{op} = 0.6478\, T_a + 11.384$	0.7775

3.2. Thermal perceptions

In spite of the indoor environments, a great number of the researched residents felt comfortable. Distribution of thermal sensation votes and thermal acceptance votes in winter and summer field surveys are plotted in **Figure 5** and **Figure 6**. In winter, 73.8% of the research residents voted between "-1 and 1" on thermal sensation vote (TSV). The proportion in summer was 67.3%. About 61.7% of the researched residents voted "acceptable" on thermal acceptance vote (TAV) during winter field surveys. The proportion in summer field survey was 76.1%.

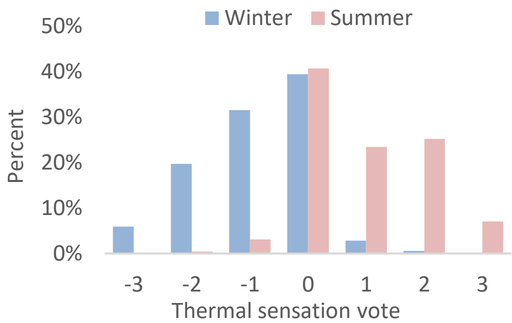

***Figure 5**: Distribution of thermal sensation votes (TSV)*

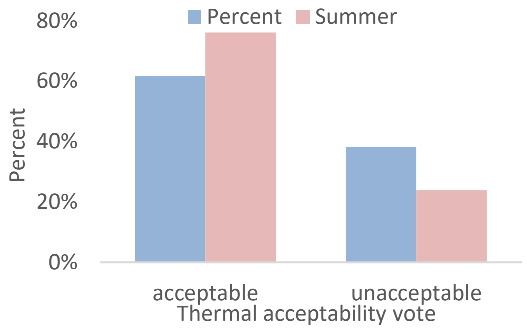

Figure 6: *Distribution of thermal acceptance votes*
horizontal axis.

As shown in **Figure 7**, running mean outdoor temperature of winter data distributed between -4.0℃ and 5.0℃. They were far beyond the range of application of ASHRAE 55 (10℃ <T_{rm} <33.5℃). In **Figure 8**, winter data were not plotted as adaptive thermal comfort standard in EN 16798 only applies during summer and shoulder seasons. In **Figure 9**, the Chinese standard has the widest temperature scope of application. It can be applied in a temperature interval which T_{rm} is between 3.7℃ and 31.3℃. The lower limit of temperature scope of application of the Chinese standard is much than other two standards. About 21.7% of the winter field survey data fell in the scope of application of the Chinese standard. The majority of them are beyond the acceptability range of the Chinese standard. Obviously, this is not in line with the thermal votes above.

A great number of researched residents seemed to be satisfied with their indoor thermal environment although both outdoor temperature and indoor temperature were beyond the scope of application of these three standards. No current standards are applicable for researched residents in winter conditions. New adaptive thermal comfort criteria are needed.

In summer data, running mean outdoor temperature (T_{rm}) varied between 24.0℃ and 31.0℃. They were in the application range of ASHRAE 55 and GB/T 50785 in term of running mean outdoor temperature. For the case of EN 16798, 12.4% of summer data fell out of the application range (10.0℃<T_{rm}<30.0℃). All three standards seem accurate in evaluating comfort level of indoor environment when T_{rm} is lower than 30.0℃. These standards are based on field surveys in office building and residential buildings in urban contexts[6, 13, 14]. As found in many previous researches, these standards didn`t consider the needs, dressing habits and acclimation abilities of rural low-income residents who live in excessively cold or hot indoor conditions and under great financial stresses. A novel bespoke summer adaptive model is also necessary for the rural low-income residents in China.

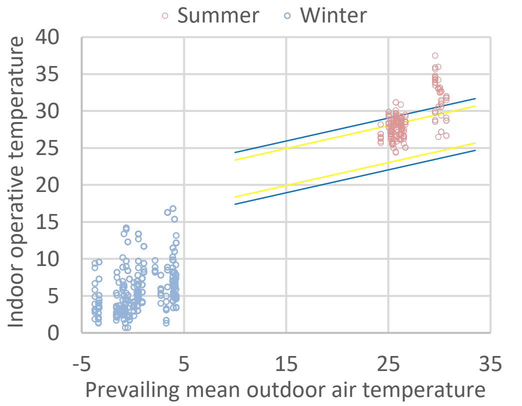

Figure 7: *Plot of adaptive thermal comfort criteria in ASHRAE 55 2017 and field survey data*

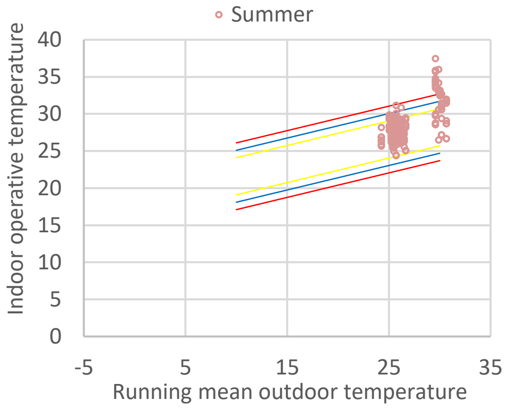

Figure 8: *Plot of adaptive thermal comfort criteria in EN16798-1 2019 and field survey data*

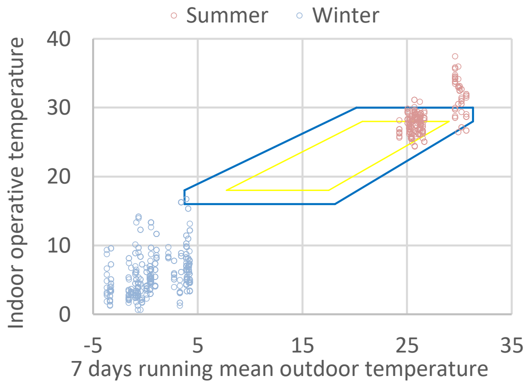

Figure 9: *Plot of adaptive thermal comfort criteria in GB/T50785 2012 and field survey data*

3.3. Development of adaptive model and evaluation criteria

An adaptive thermal comfort model relates indoor comfort temperature to the outdoor air temperature. Griffiths` method provide the theoretical basis for this analysis. In this research, linear regressions were conducted on comfort temperature ($T_c$) calculated by Griffiths` method and 7 days running mean outdoor temperature (T_{rm}). Equations of adaptive models are shown in **Table 2**. The winter model only applies when T_{rm} is higher than -4.0℃ and lower than 5.0℃. The summer model only applies when T_{rm} is higher than 24.0℃ and lower than 31.0℃.

The next step is to determine the 80% and 90% acceptability ranges. Width of the 80% and 90% acceptability ranges are usually derived from the bell shape curve of regression of thermal acceptance votes on indoor operative temperature. However, in this research, winter and summer conditions are researched separately, and no mid-season data are available. Therefore, two half bell shape curves were acquired from field survey data, as shown in **Figure 10**. There is no possibility to calculate the width of the acceptability ranges with this method. But we able to get the lower extremum temperatures for winter acceptability ranges, and upper extremum temperatures for summer acceptability ranges. In winter, the lowest temperature of 80% and 90% acceptability ranges are 7.5 ℃ and 8.7 ℃ respectively. In summer, the highest temperature of 80% and 90% acceptability ranges are 29.5℃ and 28.7℃ respectively.

Another method for acceptability range width calculation is through the weighted linear regression analysis of mean thermal sensation vote (mTSV) on indoor operative temperature (T_{op}), as shown in **Figure 11** and **Figure 12**. Slope of the regression equation determines width of the 80% and 90% acceptability ranges. Generally, -0.85 to 0.85 on ASHRAE thermal sensation scale corresponds to the 80% acceptability range, and -0.5 to 0.5 corresponds to the 90% acceptability range [13]. Deriving from the regression equations, width of the 80% and 90% acceptability ranges are 16.4 ℃ and 10.4 ℃ respectively in winter. Width of 80% and 90% acceptability ranges are 6.4 ℃ and 4.0 ℃ respectively in summer.

Upper and lower boundaries of 80% and 90% acceptability ranges are acquired by adding an offset to adaptive model. Offsets are half of the width of 80% and 90% acceptability ranges. Upper and lower boundaries for the 80% and 90% acceptability ranges in winter and summer are shown in

Table 3.

By combining the above results, adaptive thermal comfort models, 80% and 90% acceptability ranges for rural low-income residents can be acquired, as shown in **Figure 13** and **Figure 14**. The 80% acceptability ranges in two graphs are marked yellow, and the 90% acceptability ranges in are marked blue. The two zones can be used to evaluate comfort level of indoor thermal environment. With a given running mean outdoor temperature, if indoor operative temperatures fall in yellow zones, indoor thermal environment is acceptable for 90% occupants.

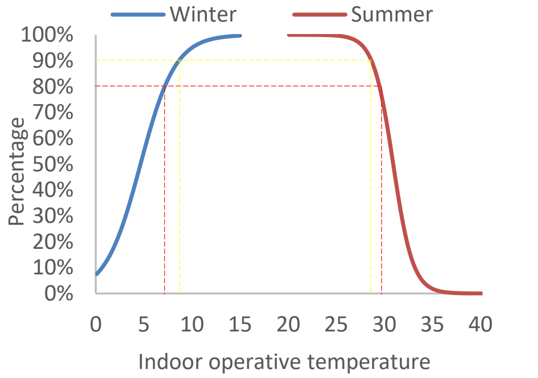

***Figure 10**: Logistic regression of thermal acceptance percentage and indoor operative temperature*

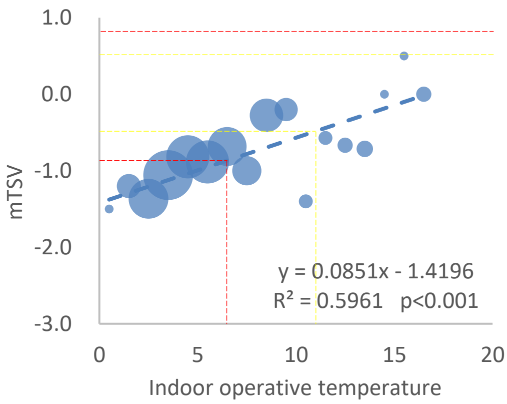

***Figure 11**: Weighted linear regression of mean thermal sensation vote on indoor operative temperature in winter season.*

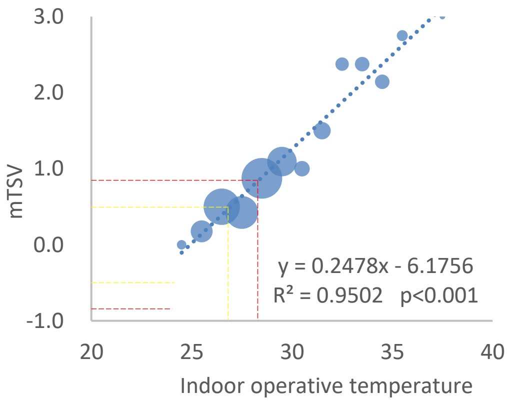

***Figure 12**: Weighted linear regression of mean thermal sensation vote on indoor operative temperature in summer season.*

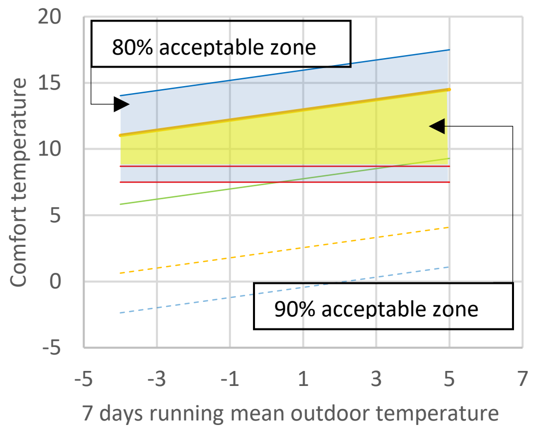

***Figure 13**: Plot of adaptive criteria, 80% and 90% acceptability ranges in for winter*

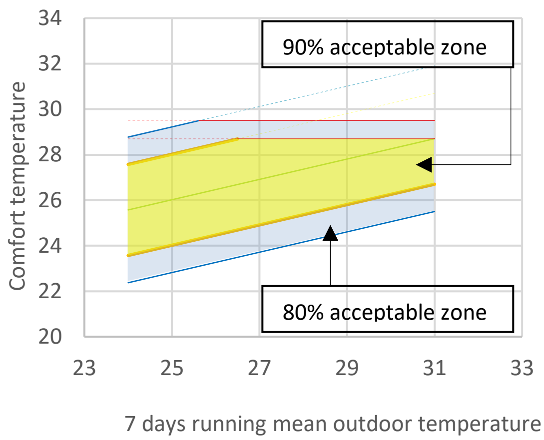

***Figure 14**: Plot of adaptive criteria, 80% and 90% acceptability ranges in for summer*

4. CONCLUSION

In winter, the majority of researched residents lived in excessively cold indoor environments. More than 90% of recorded indoor operative temperatures were lower than 10.0 ℃ . However, in summer, the majority (80.9%) of recorded indoor operative temperatures were lower than 30.0℃. Indoor operative temperatures varied greatly among investigated houses and were linearly correlated with daily outdoor temperatures.

In such indoor conditions, a great number of researched occupants felt the indoor environment acceptable and physiologically comfortable. 61.7% and 76.1% occupants voted "acceptable" on thermal acceptance scale (TSV) during winter and summer field surveys respectively. 73.8% and 67.3% of researched residents voted "-1, 0 or 1" on thermal sensation scale (TSV).

None of existing adaptive thermal comfort standards are applicable for target residents in winter, and are not accurate in summer. Bespoke adaptive thermal comfort models and evaluation criteria for rural low-income residents are needed in winter and summer seasons.

Local and specific adaptive thermal comfort models and criteria for rural low-income residents were proposed in this research. New models and standards reflect rural low-income residents` needs and acclimation abilities when artificial conditioning systems are rarely used due to financial stresses. New models and standards are applicable in extremely low outdoor temperature where existing standards are incapable. They are supplements for those standards.

There is possibility of the new adaptive model and evaluation criteria being applied in other residents who have similar dressing habits, financial level and live in similar climate and indoor thermal environments. Continuous updates of field survey data will improve the accuracy of new adaptive models and standards.

***Table 2**: Adaptive thermal comfort models for winter conditions and summer conditions respectively.*

Season	Adaptive model	R^2	p-value
Winter	$T_c = 0.385T_{rm} + 7.371$	0.325	0.017
Summer	$T_c = 0.447T_{rm} + 14.845$	0.515	0.000

***Table 3**: Upper and lower boundaries for adaptive standards in winter and summer*

Season	Boundary	Equation
Winter	80% Upper boundary	$T_c = 0.385T_{rm} + 15.571$
	80% Lower Boundary	$T_c = 0.385T_{rm} - 0.829$
	90% Upper boundary	$T_c = 0.385T_{rm} + 12.571$
	90% Lower Boundary	$T_c = 0.385T_{rm} + 2.171$
Summer	80%Upper boundary	$T_c = 0.447T_{rm} + 18.045$
	80% Lower boundary	$T_c = 0.447T_{rm} + 11.645$
	90% Upper boundary	$T_c = 0.447T_{rm} + 16.845$
	90% Lower Boundary	$T_c = 0.447T_{rm} + 12.845$

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