Wind Engineering Joint Usage/Research Center
FY2024 Research Result Report

Research Field: outdoor environment
Research Year: FY2024
Research Number:
Research Theme: Research on Thermal Comfort Evaluation in Beach Areas in Hot and Humid Regions

Representative Researcher: Qiong Li

Budget [FY2024]: 320,000Yen

1. Research Aim

The high temperature, high humidity, and strong radiation outdoor thermal and humid environments of the sea islands in China's hot and humid climate zones are characterized by prominent thermal safety problems. This study aims to systematically carry out the following work based on the common thermal safety and thermal comfort problems in tourism activities spaces under the outdoor high temperature, high humidity and strong radiation environment in island areas: Firstly, through on-site monitoring, the thermal environment characteristics of hot and humid islands are analyzed; Secondly, artificial climate chamber experiments are conducted to explore the influence of wind speed on thermal comfort. Based on the monitoring of thermal physiological parameters, questionnaire surveys and environmental factor data, the human thermal comfort benchmark of tourists in the beach environment and the human thermal physiological characteristics of the human body are clarified, which improve the theoretical system of thermal comfort research in outdoor spaces of island. Finally, the movement behavior suggestions for tourists in outdoor spaces of island and the management of coastal tourism are proposed.

2. Research Method

2.1 On-site thermal environments measurement

Through field research, the research site was determined to be Hailing Island in Yangjiang City, Guangdong Province, which is the fourth largest island in Guangdong Province and is representative. Microclimate measurements and tourists' thermal comfort-related experiments have been carried out in the beach scenic area (the site is shown in Figure 1), and the outdoor microclimate characteristics and thermal comfort characteristics of the island beach scenic area in summer have been clarified. The basic situation is as follows:

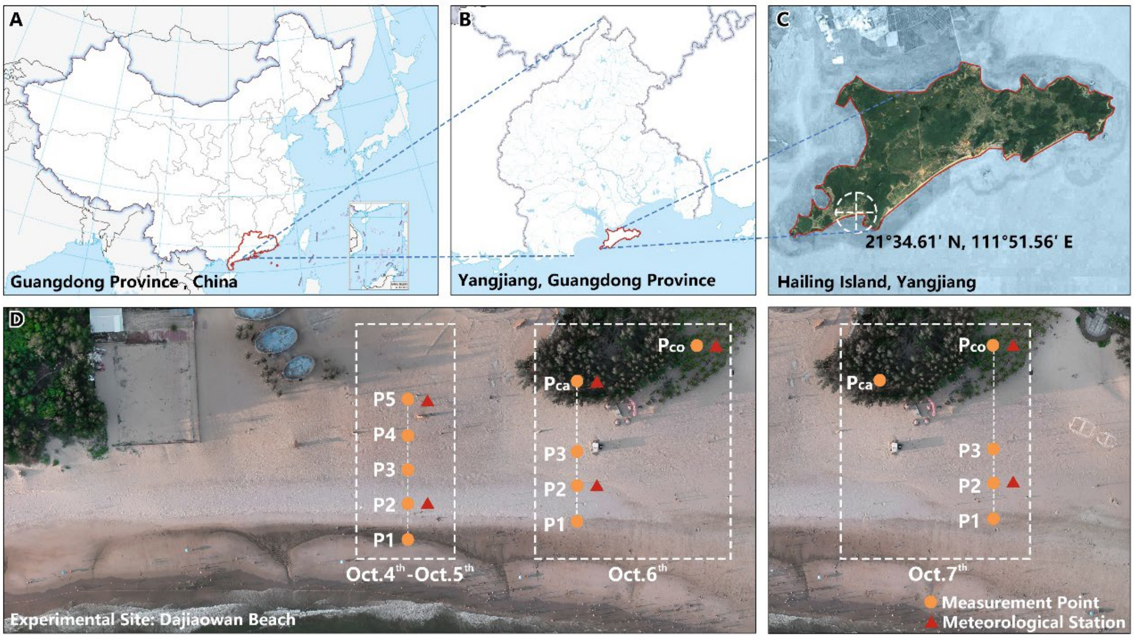


Figure 1 Experimental site and measurement point distribution.

2.2 Climate chamber experiment

People usually feel obvious thermal discomfort after exercising in the high temperature of summer. However, during the exercise process, the subjective sensation of heat often fails to respond to the changes in heat physiology in time, thus leading to the occurrence of the risk of midsummer heat. The purpose of this study is to better understand the real heat stress of people with moderate-intensity activities under the hot and high-humidity outdoor conditions in summer. The experiment was conducted in a climate chamber, as shown in Figure 2. A total of 20 male college students from China and Japan respectively participated in 9 experimental conditions of high temperature and high humidity. During the 40-minute exercise experiment, the core temperature, skin temperature and heart rate were continuously monitored, and the subjective votes and sweat volume of the subjects were collected.

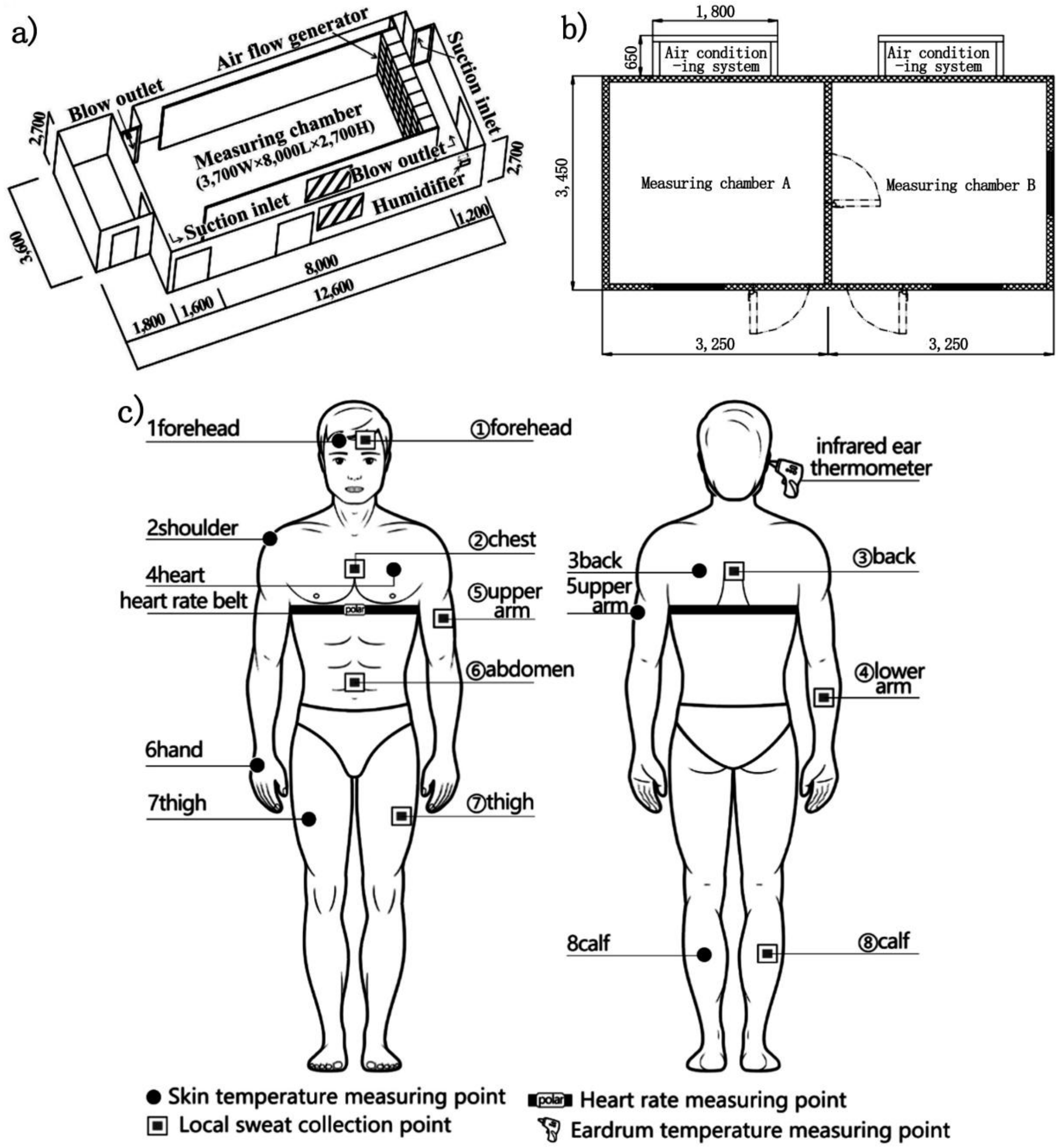


Figure 2 Climate chamber experiment equipment and measurement points：a)axonometric map of artificial climate chamber at Tokyo Polytechnic University; b)floor plan of the artificial climate chamber of South China University of Technology; c)thermophysiological parameters measuring points location distribution map

3. Research Result

3.1 The results of the on-site experiment on the island

3.1.1 The spatiotemporal distribution characteristics of the island thermal environment

(1) The radiation environment in the beach area is harsh during the day in summer

Taking the measurement data in 2022 as an example, the Mean Radiation Temperature (Tmrt) at the height of 1.5m on the beach can reach 70℃ during 10:30-14:00h (Figure 3), which is much higher than the urban underlying environment. The albedo of the beach on a sunny day in summer can reach up to 0.4, which is much higher than the surface albedo of common urban underlying surfaces such as grass, wood-plastic composites, and concrete paving (Table 1).

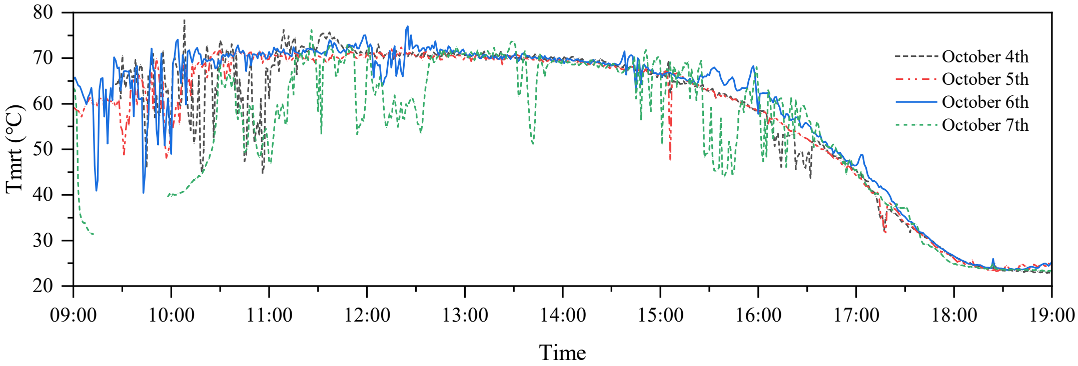


Figure 3 Tmrt in beach area.

Table 1 Albedo of underlying surface.

Underlying surface	City	Albedo
Beach (this study)	Hailing Island, Yangjiang	0.4
Grassland	Guangzhou	0.19
Wood Plastic Composites	Guangzhou	0.12
Concrete paving	Guangzhou	0.16

(2) The improvement effect of trees and sea breeze on the microclimate

Taking the summer experimental results of 2022 as an example, both *Casuarina equisetifolia L.* (Pca) and *Cocos nucifera L.* (Pco) on the beach can improve the microclimate within the forest, which significantly improves the radiation environment.

The difference in air temperature and relative humidity between beach area and forest environments shows obvious time differences during the day, which is due to the influence of the sea and land breeze during the day (Figure 4). On sea and land breeze days, the change in wind direction from land breeze to sea breeze between 10:20h and 13:00h will bring moist and cooler sea air into the island, effectively alleviating the thermal stress of the offshore beach. Sea and land breezes are of great significance to the improvement of the internal environment of the island.

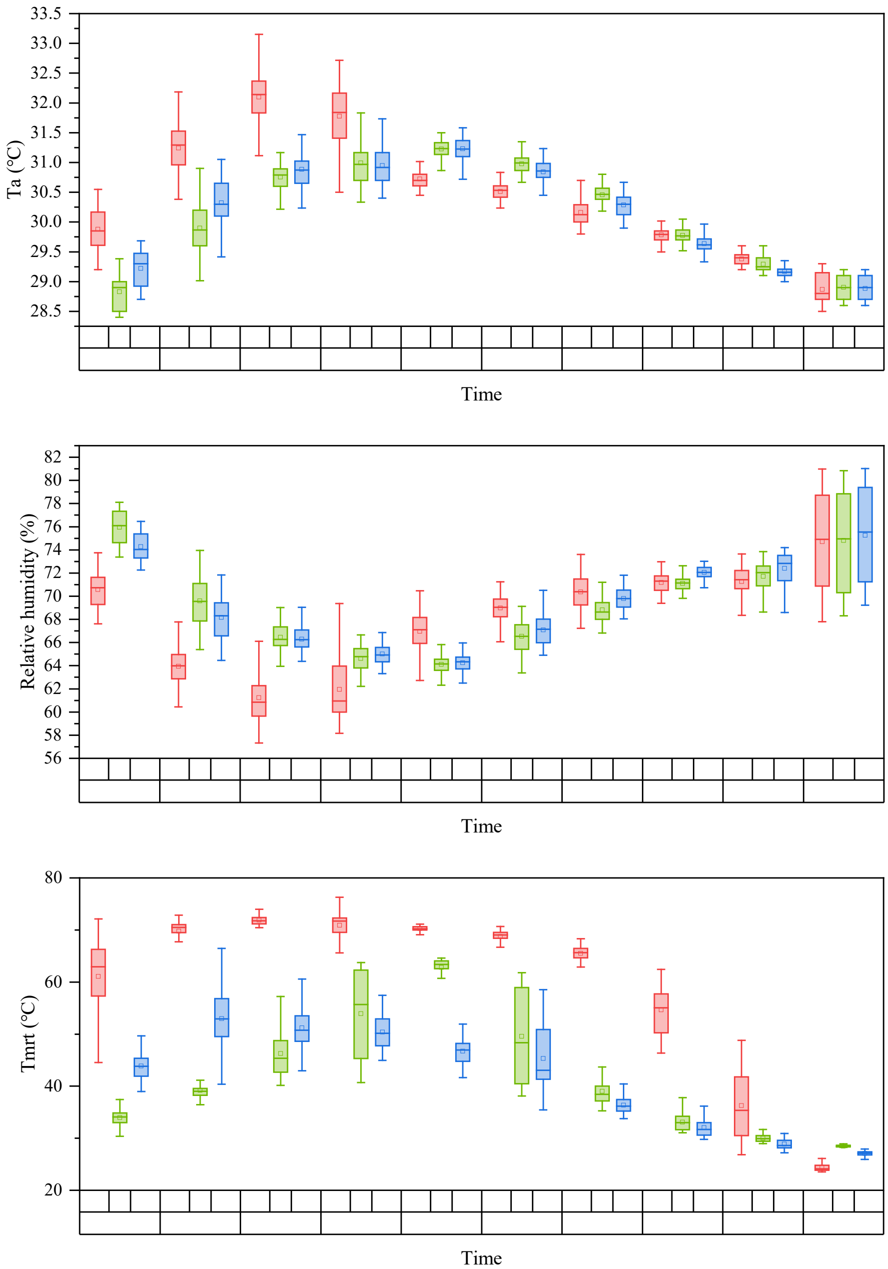


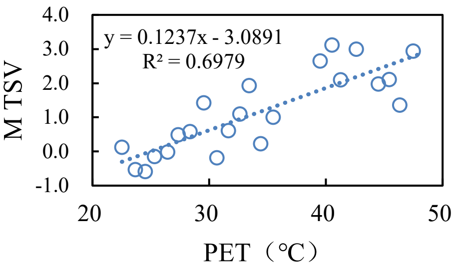
Figure 4 Microclimate differences in different beach environments.

3.1.2 Thermal safety benchmark for tourists in island beach areas

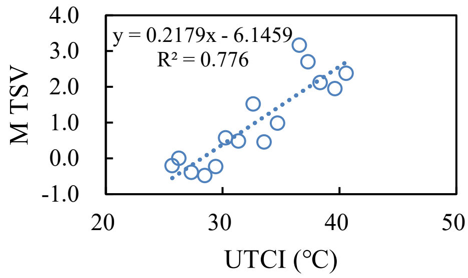
The experiment on the thermal physiological characteristics of human body on the beach was completed, and the prediction model is still being revised. The tourists' thermal comfort questionnaire experiment was completed to obtain tourists' subjective data such as thermal expectations. Some conclusions are as follows:

Combining the measured meteorological data and tourists' thermal comfort data, the thermal comfort index, physiological equivalent temperature (PET) and universal thermal climate index (UTCI), were calculated by RayMan model, and the regression equation was obtained by analysis: $MTSV = 0.1237PET - 3.0891$ (R^2 = 0.6979), $MTSV=0.2179\ UTCI- 6.1459$ (R^2 = 0.776). It was determined that the thermal neutral temperature range (PET, UTCI) of beach tourists in summer is 20.93-29.01 ℃ and 25.91-30.50 ℃ respectively (Figure 5: (a)-(b)).

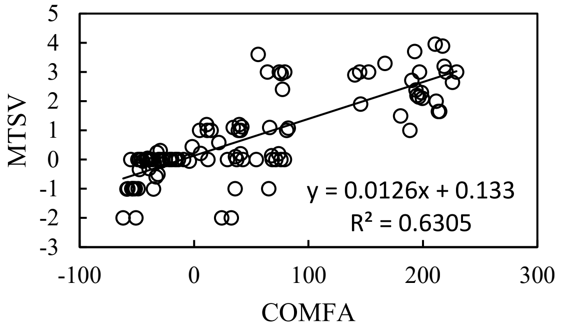
The modified COMFA model was used to evaluate the human energy budget of beach visitors, including human metabolic heat (q_{meta}), received radiation heat (q_{rad}), convection heat (q_{conv}), heat conduction (q_{cond}), and evaporative heat loss(q_{evap}). The regression equation of human heat load and human thermal sensation was obtained: $MTSV = 0.0126COMFA + 0.133$ (R^2 = 0.6305), which clearly showed that the heat load range of the beach area in summer when it was thermally neutral was: -29.13-50.24 W/m^2 (Figure 5: (c)).



(a)



(b)



(c)

Figure 5 Rgression equations: (a): MTSV and PET; (b): MTSV and UTCI; (c): MTSV and COMFA.

3.2 The laws of thermophysiological and thermopsychological changes in human movement

3.2.1 Thermophysiology Indicators

As shown in Figure 6, different Ta, RH, WS and the combination of the three factors had significant effects on TSV (P≤0.001), and the experimental results all deviated from neutral thermal sensation.TSV in the medium humidity environment (Figure 6(a)) is lower than that in the high humidity environment (Figure 6 (b)). Moreover, the thermal sensation gradually increased 15 minutes before exercise and slowly decreased after reaching the peak value 15 minutes later, indicating that reducing humidity can not only effectively reduce the initial thermal sensation at high temperature, but also significantly reduce the thermal sensation of the human body.There was a significant difference in TSV between windy and non-windy conditions at 35℃/60%RH (P < 0.01). Wind speed of 0.5m/s only slowed down thermal sensation. After 40 minutes of movement, TSV at 0.5m/s was similar to that at 0m/s. The wind speed in the range of 1.5m/ s-2.5m /s can effectively reduce the thermal sensation of the subjects during moderate intensity exercise under high temperature and humidity.

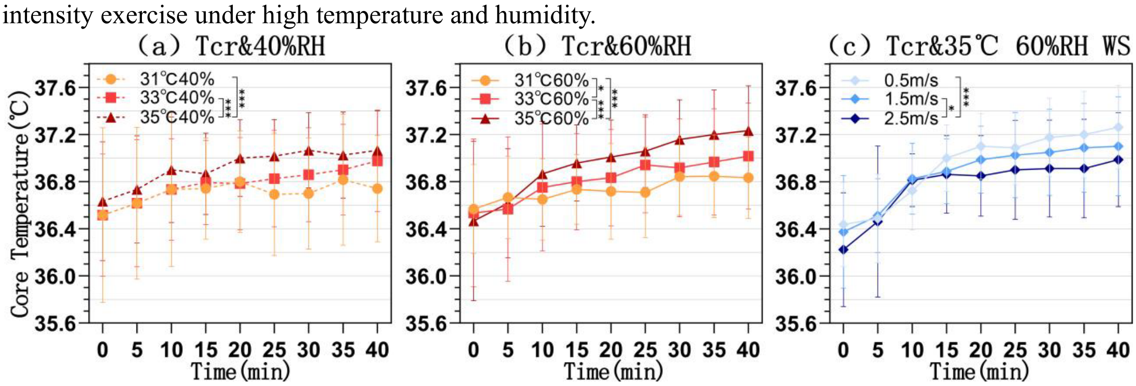


Figure 6 Changes of core temperature (Tcr) with time in different working conditions.

As shown in Figure 7, there was a significant difference in the average skin temperature between Chinese and Japanese subjects (P<0.05). Under the same humidity, there was a significant difference in the effect of increased air temperature (31°C→33°C→35°C) on skin temperature between Chinese and Japanese subjects ($P < 0.001$); At the same air temperature, the effect of the increase in relative humidity (40%→60%) on the average skin temperature of Japanese subjects at higher air temperatures (33°Cand 35°C) was significantly different ($P<0.001$). The effect of the increase in relative humidity (40%→60%) on the average skin temperature of Chinese subjects at a high temperature of 35°Cwas significantly different ($P<0.001$); There were significant differences in the average skin temperature between the wind speed conditions of 0.5m/s and those of 0m/s, 1.5m/s, and 2.5m/s respectively ($P<0.001$), while there were no significant differences in the average skin temperature among the wind speed conditions of 1.5m/s, 2.5m/s, and 0m/s ($P>0.3$).

This is because the wind speed of 0.5m/s brings the surrounding hot and humid air to the skin surface, forming a warm air layer, which increases the heat load on the skin surface and leads to an increase in the average skin temperature. When the wind speed is relatively high (such as 1.5m/s and 2.5m/s), convective heat transfer and evaporative heat dissipation can be significantly enhanced, thereby improving the heat dissipation efficiency

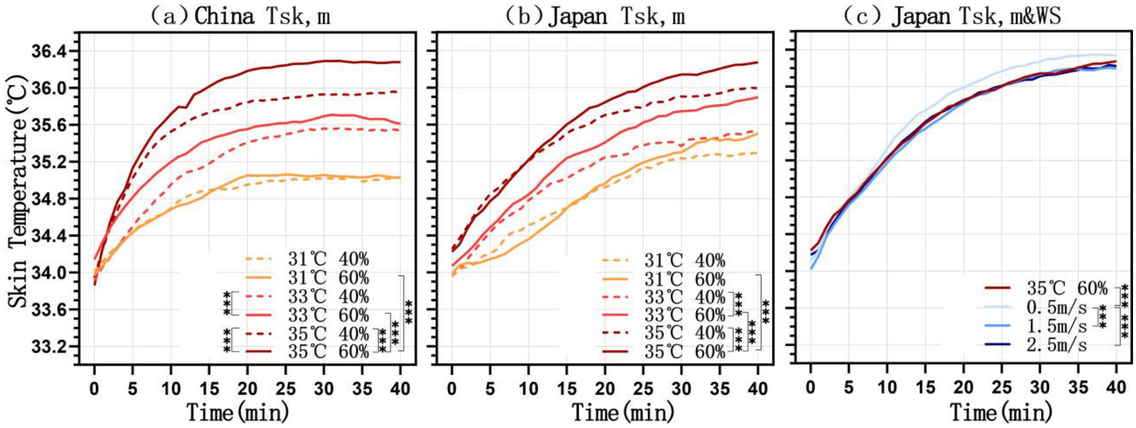


Figure 7 Changes of average skin temperature (Tsk,m) with time in different working conditions.

As shown in Figure 8, The areas with significant differences in local sweat volume between China and Japan are mainly the forehead, chest and back. The sweat volume of the forehead shows significant differences in 31°C/40%, 31°C/60%and 33°C/60% working conditions ($P<0.05$), the sweat volume of the chest shows significant differences in 35°C/40% and 35°C/60% ($P<0.05$), and the sweat volume of the back shows significant differences in 35°C/60% ($P<0.05$). These three parts are all the local areas closest to the important organs of the human body. By comparing the average amount of local sweating in China and Japan, the amount of sweating in all eight parts of the Chinese subjects was higher than that of the Japanese subjects. By comparing the local sweating amounts of subjects under different working conditions, the local sweating amounts of the subjects will change due to the influence of air temperature and relative humidity. Both an increase in air temperature and relative humidity will lead to an increase in local sweating amounts.

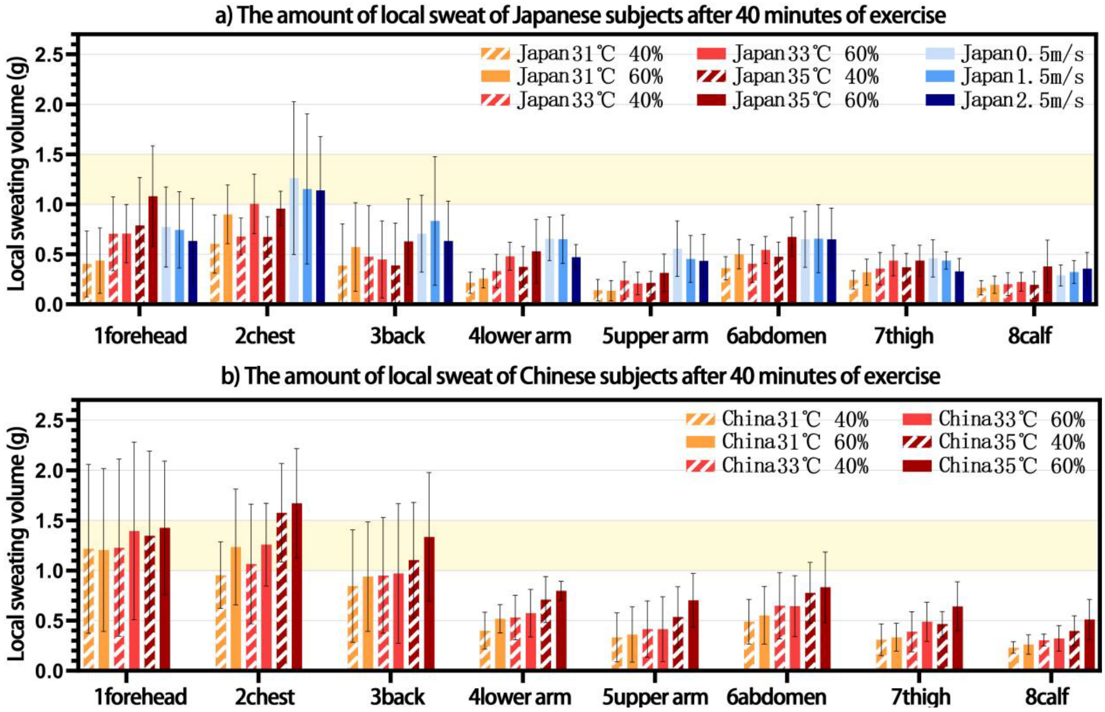


Figure 8 The local sweating amounts of eight parts under different working conditions.

3.2.2 Thermal Sensation Vote（TSV）

As shown in Figure 9, the changes in the thermal sensation of the subjects over time under all working conditions are reflected in the form of mean and standard deviation, indicating the hourly changes in thermal sensation under each working condition. During the process of moderate metabolic exercise in the experimental conditions, only in the NW2 condition did the thermal sensation difference between the Chinese and Japanese subjects show a significant difference ($P < 0.05$). The overall thermal sensation difference between the Chinese and Japanese subjects was not significant. From the mean value perspective, the deviation of thermal sensation between the Chinese and Japanese subjects was found through follow-up visits to the subjects. It was mainly due to the evaporation and heat dissipation of some Japanese subjects through sweating during exercise. This leads to a decrease in overall thermal sensation, and the differences in the mean thermal sensation of Chinese and Japanese subjects caused by individual subjective differences.

The thermal sensation of Chinese subjects increased with the increase of exercise time during the exercise process. Under the condition of the same relative humidity, the increase of air temperature (31℃→33℃→35℃) had a significant effect on the thermal sensation of the subjects ($P < 0.001$); Under the condition of the same air temperature, only at an air temperature of 33℃ did the increase in relative humidity have a significant effect on thermal sensation ($P < 0.05$). In the working conditions of medium and high temperatures for Japanese subjects, the increase in air temperature and relative humidity would have a significant impact on thermal sensation ($P < 0.001$). When compared with NW1 and NW2, the difference in thermal sensation was not significant. The thermal sensation of the Japanese subjects was lower than that of the Chinese subjects. The thermal sensation of the Japanese subjects reached its peak 15 minutes after exercise. As the amount of sweat increased, the evaporation of sweat took away part of the body's heat, and the thermal sensation of some Japanese subjects would decrease. However, although the growth rate of the thermal sensation of the Chinese subjects decreased after 15 minutes of exercise, it still maintained an upward trend.

When wind speed was added in a high-temperature and high-humidity environment of 35℃/60%, the increase in wind speed could significantly reduce the thermal sensation of the subjects ($P < 0.05$), and there was a significant difference in the effect of wind speed between 1.5m/s-2.5m/s and 0.5m/s on thermal sensation ($P < 0.05$). A wind speed of 1.5m/s-2.5m/s can reduce the subjects' feeling from hot to slightly warm.

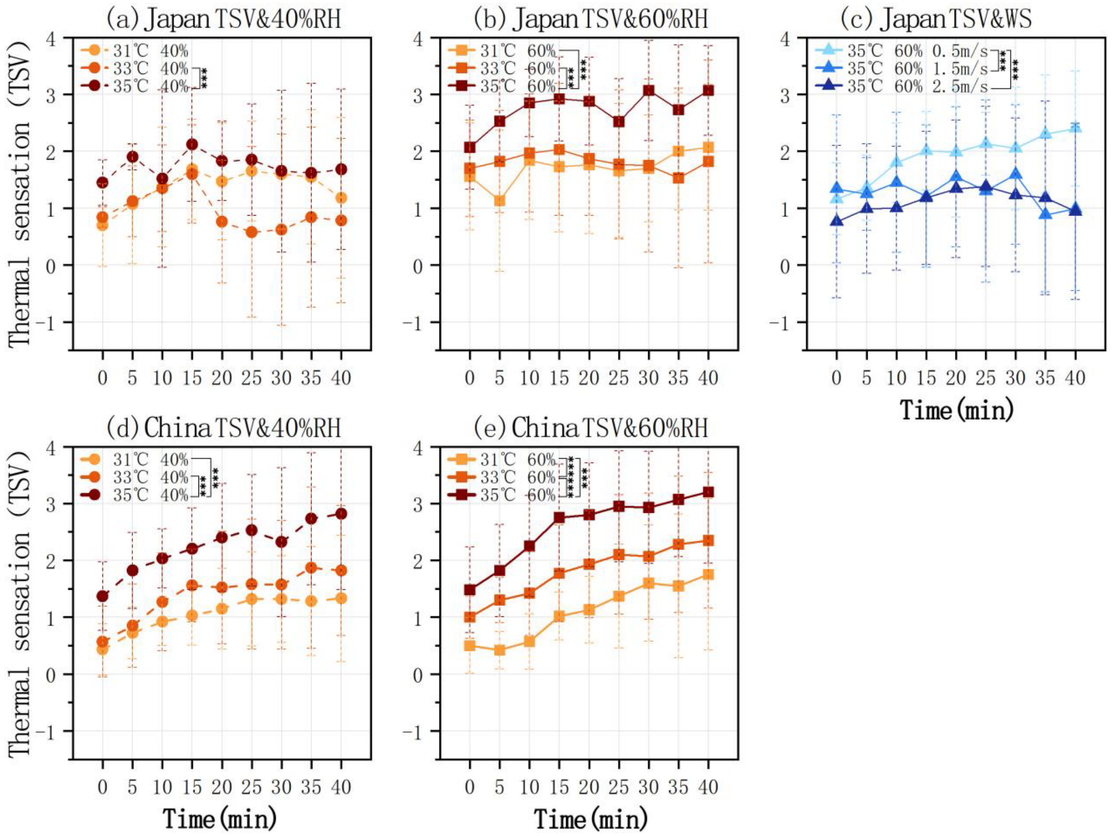


Figure 9The variation of thermal sensation over time under different working conditions

3.2.3 Correlation analysis

As shown in Table 2, the correlation between thermal physiological index and thermal psychological index is poor. Subjects in motion are in a state of constant heat dissipation, and the average skin temperature remains stable after reaching its peak. The thermal psychological subjective vote is affected by transient stimuli such as evaporative heat dissipation and convective heat dissipation on the skin surface, and the thermal experience will make the subjective thermal response dull and numb, so it is difficult for the subjective feeling to make a correct judgment on the physical condition during exercise.

Table 2 Correlation analysis of heat physiology and heat psychology

y	x	Equation	Pearson's r	R²	Degree of correlation
TCV	TSV	TCV=-0.689TSV+0.096	-0.83	0.69	Strong
TAV	TSV	TAV=-0.247TSV+0.051	-0.82	0.67	Strong
TCV	TAV	TCV=0.328TAV-0.014	0.9	0.81	Strong
Tcr	TSV	Tcr=0.074TSV+36.690	0.19	0.03	Strong
Tcr	TCV	Tcr=-0.101TCV+36.707	-0.22	0.05	weak
Tcr	TAV	Tcr=-0.289TAV+36.708	-0.23	0.05	weak
Tsk,m	TSV	Tsk,m=0.201TSV+34.900	0.27	0.07	weak
Tsk,m	TCV	Tsk,m=-0.258TCV+34.962	-0.29	0.08	weak
Tsk,m	TAV	Tsk,m=-0.706TAV+34.978	-0.29	0.08	weak
Tsk,m	Tcr	Tsk,m=0.772Tcr+6.778	0.4	0.16	Medium

4. Published Paper etc.

[Underline the representative researcher and collaborate researchers]

(1) Qiong Li, Qi Li, Jiayi Mi, Haotian Wu. A three-layer evapotranspiration model considering the vertical structure of urban green spaces. Urban Forestry & Urban Greening, 2024, 98:128389.

(2) Qiong Li, Qi Li, Haotian Wu, Jiayi Mi, Xiaohui Lu,Akashi Mochida,Yasuyuki Ishida,Zhixin Liu. Study on the modified three-temperature model for spatial extrapolation of evapotranspiration

based on individual urban vegetation evapotranspiration data. Building Simulation,2024,17(10):1767-1787.

(3) Qi Li, Qiong Li, Xiaohui Lu ,Yan Liu. Numerical simulation of the effect of street trees on outdoor mean radiant temperature through decomposing pedestrian experienced thermal radiation: A case study in Guangzhou, China. Urban Forestry & Urban Greening, 2024, 91:128189.

(4) Jiangnan Wang, Qiong Li, Guodong Zhu, Weijian Kong, Huiwang Peng, Meijin Wei. Recognition and prediction of elderly thermal sensation based on outdoor facial skin temperature. Building and Environment, 2024, 111326.

(5) Qinrong Yang, Huiwang Peng, Qiong Li. Study on urban heatwave characteristics and thermal stress scenarios based on China's heatwave hazard zoning. Urban Climate, 2024,101957.

(6) Yang Liu, Li Qi, Li Qiong, Zhao Lei, Luo Zhiwen, Liu Yan.Different explanations for surface and canopy urban heat island effects in relation to background climate. ISCIENCE, 2024,27(3):108863.

(7) Facheng Chen , Jiejin Cai， Nikolaos T. Chamakos, Athanasios G. Papathanasiou,Ziqi Gong Qiong Li. Evaporation of nonspherical droplets on chemically patterned substrate considering gravity:A computational study. Applied Thermal Engineering,2024,245:122787.

[Presentations at academic societies]

(1) Adviser: Qiong Li. Speaker: Weijian Kong & JiayiMi. Title: Research on thermal comfort evaluation in beach areas in hot and humid regions. Conference: The Joint Use and Research Program at Tokyo Polytechnic University of the Wind Engineering Research Center, March 11, 2025

(2) Speaker: Qiong Li. Title: Research on human heat sensation in beach areas of hot and humid regions. Conference: The 2024 National Conference on Thermal Comfort, November 15-17, 2024

5. Research Group

5.1 Representative Researcher

Qiong Li (South China University of Technology)

5.2 Collaborate Researchers

1)Yingli Xuan (Tokyo Polytechnic University)

2) Jiayi Mi (South China University of Technology)

3) Weijian Kong (South China University of Technology)

6. Abstract (half page)

Research Theme
Representative Researcher (Affiliation)
Summary・Figures

The high-temperature and high-humidity environment on islands in hot and humid regions poses a significant threat to outdoor human thermal safety and thermal comfort. Therefore, based on field experiments and the reproduction of high-temperature and high-humidity environments in artificial climate chambers, this study reveals the complex relationship between island climate and outdoor human and thermal comfort (including thermophysiology). The results can be used to provide guidance for outdoor activities on islands and ensure outdoor thermal safety and thermal comfort.

The results of the field experiment show that: 1) the beach underlying surface albedo is 0.4, which is much higher than the common urban underlying surface albedo. The beach radiation environment is strong and the thermal environment is poor in summer. 2) On sea-land breeze days, sea breeze can effectively alleviate the heat stress in the offshore areas of island beaches. 3) Forests have a significant attenuation effect on solar radiation. Even sparse coconut forests have a certain hindering effect on radiation and the thermal comfort of human beings in the forest space is relatively good. 4) Tourists' active thermal adaptation behaviors can avoid thermal discomfort, but the effect is limited. 5) This study obtained the thermal comfort benchmarks for beach tourists, and the thermal neutral ranges were: 20.93-29.01 ℃ (PET), 25.91-30.50 ℃ (UTCI), and -29.13-50.24 W/m^2 (COMFA), respectively.

By means of an artificial climate chamber to simulate an outdoor high-temperature and high-humidity environment, experiments on human thermal comfort during exercise under different high-temperature and high-humidity conditions were conducted. The variation laws of four thermal physiological parameters, namely core body temperature, average skin temperature, heart rate, and sweat volume, as well as the variation laws of subjective voting for thermal perception during moderate metabolic exercise in different high-temperature and high-humidity environments were obtained. Correlation analysis revealed that there was no significant linear relationship between thermophysiological parameters and thermal sensing parameters. Therefore, when exercising in high temperatures, thermal perception is difficult to make correct judgments about physical conditions. It is necessary to propose thermal safety activity guidelines and warnings corresponding to different high temperatures.