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Effects of Building Microclimate on the Thermal Environment of Traditional Japanese Houses during Hot-Humid Summer

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Abstract: The purpose of this study was to investigate the effects of building microclimate on the indoor thermal environment of traditional Japanese houses, focusing especially on the shading effect of trees as well as the cooling effect of spraying water. Basically, the indoor thermal environment was found to follow the outdoor conditions due to the open-plan and lightweight wooden structure. Nevertheless, air temperatures of the living rooms in the two case study houses were lower than the corresponding outdoors by approximately 0.5 °C and 2 °C, respectively. It was found that the semi-outdoor spaces acted as thermal buffers for promoting cross-ventilation as well as pre-cooling to provide "warm but breezy" conditions to the surrounding indoor spaces. The results showed that the surface temperature of semi-outdoor spaces can be reduced by shading and water spraying, among which shading has prolonged effects and water spraying can reduce the surface temperature during peak hours and the following night.

Keywords: building microclimate; traditional house; semi-outdoor space; courtyard; thermal comfort; spraying water

1. Introduction

The impact of buildings' energy consumption on global warming is clear now and major steps have been taken towards lowering the carbon footprint of residential buildings. In hot-humid climates like in the summer months of Japan, a major share of energy consumed in the residential sector is for space cooling [1,2]. On the other hand, vernacular architecture has developed over time to create comfortable spaces by using passive and low energy techniques. These buildings manifest humans' response to specific geographical and environmental settings and therefore have been studied by researchers to find potential solutions to issues in contemporary buildings [3–6].

Building microclimate is defined as one type of microclimate involving indoor spaces and spaces around the indoor spaces of a particular building, which is considered to be the extension of the indoor climate [7]. The existence of diverse types of spaces is one of the important features of the building microclimate, distinguishing it from a single indoor climate [7]. A naturally ventilated wooden traditional house, which is commonly seen in the hot-humid climates, often creates building microclimate by utilizing various types and sizes of semi-outdoor spaces such as corridors, courtyards and patios and contributes to provide thermal comfort to the connected indoor spaces.

In general, passive cooling strategies aim to: (1) minimize heat gain, (2) dissipate internal heat and (3) modulate the heat [8]. Heat gain can be minimized by using shading devices and careful design of the outdoor and semi-outdoor spaces. Cross ventilation can remove heat from the indoor when the outdoor air temperature is lower than that of indoor spaces [9]. To benefit from the comfort ventilation during the daytime, the outdoor air should be therefore cooled before entering the house. The study of the interaction of indoor thermal environments with their immediate outdoors that constitute the building microclimate is thus critical in designing passive buildings in hot climates.

The aim of this research is to investigate the effects of building microclimate on indoor thermal environment of the traditional Japanese houses. These houses have evolved over centuries from the pit houses to farmhouses (*minka*) and townhouses (*machiya*), and wisely crafted using the locally available natural resources and environmental forces to produce favorable spaces of living [10]. Among the common elements in these traditional Japanese houses are attached outdoor and semi–outdoor spaces.

The semi-outdoor space in residential buildings can be seen in different forms and differ based on its openness and interaction with the indoor spaces. Common examples of such space include gardens, porches, internal courtyards or patios, corridors and verandas [11]. For instance, in the traditional urban settings, the use of inner courtyards and patios is common because they provide light and air in those compact areas. Traces of this type of semi-outdoor space can be found in major parts of the world, especially in hot regions [12]. Recent studies in the traditional courtyard houses show the performance of this space in different climates [3,12–19].

In hot-dry climates, the outdoor air temperature often rises above the suitable range for natural ventilation, so the houses are designed to prevent direct infiltration to the outdoor air, using semi-outdoor spaces. In the semi-outdoor spaces, deciduous trees are often planned to provide shades to the spaces and water bodies are also commonly used to cool the ambient air while increasing the relative humidity which is undesirably low (below 20%). The shade provided by trees lowers the surface temperature and stratifies the air below and above the tree crown which does not mix with the outdoor hot air [9]. In this way, a cool zone is created near the ground surface which flows to the subterranean rooms and also reduces heat gain to the upper floors. Ernest and Ford [20] studied two courtyards in a traditional house in Egypt and found that using a hot-dry and a cool-wet semi-outdoor space in the house can induce air flow due to pressure difference from the cool to the hot courtyard. In the hot-dry regions, there is a large diurnal temperature swing and the air temperature drops greatly during the night-time. Consequently, the semi-outdoor spaces act as a cooling source to the adjacent spaces.

In hot-humid regions, overheating is not as great as in hot-dry regions, but higher levels of humidity may cause significant distress to the occupants. In contrast to the hot-dry regions, solar radiation is diffused in the sky due to the vapor content of the air [21]. Therefore, the openness of the outdoor spaces to the sky (measured as the sky view factor) is considered to be one of the important factors affecting the indoor thermal environments, rather than the solar orientation of the outdoor space [3]. Kubota et al. [3] studied 29 courtyards of Chinese shophouses, which are constructed of timber frame structure and brick walls, in Malacca and suggested that a deeper closed courtyard can maintain lower air temperature in and around the courtyards. A courtyard with sky view factor of less than 2% was proved to be well shaded while higher than 10% was suggested to be efficient for nocturnal radiant cooling. Because of the high humidity, continuous ventilation is needed to improve thermal comfort by sweat evaporation. However, the study of the Chinese shophouses showed that the courtyards could improve thermal comfort even without daytime comfort ventilation by preventing the air exchange between outdoor and indoor in addition to sufficient shading [3]. Alfata et al. [22] studied the Dutch colonial buildings in Indonesia and revealed that the veranda space provided shade while allowing cross-ventilation, thus it improved indoor thermal comfort in the adjacent rooms. In another research, the ventilation potential of a semi-outdoor space as the "*zaguan*" was investigated in the dense urban houses of Mexico [23] and Havana [24]. It was found that the arrangement of street-*zaguan*-courtyard resulted in air flow from the street to the courtyard and this semi-outdoor space experienced higher wind speeds.

The traditional Japanese houses generally have open-plan layout with less permanent internal partitions and external envelope. The use of low thermal mass material prevents the heat storage effect. The large sliding door can be removed to completely connect the outdoor to indoor and invite the outdoor air which dissipates heat from indoor spaces thanks to the open-plan layout. The role of semi-outdoor spaces is thus important in modifying the indoor thermal environment of these houses. Particularly in detached houses, the semi-outdoor spaces are usually larger in size, so the effect of cross-ventilation is stronger. These spaces are often shaded by trees, the ground surface is covered with moss and water is sprayed upon occasionally. Although the shade can prevent rising the air temperature in the outdoor spaces, lowering the air temperature below the ambient requires evaporation of water [9]. Hence, the traditional practice of water spraying and the use of water retentive material is supposed to be efficient in lowering the outdoor air before reaching the indoors.

Du et al. [7] revealed that the majority of previous studies on microclimate have focused on the urban microclimate in relation to the urban scale, i.e., neighborhoods, urban canyons and building blocks, and there are few studies focusing specifically on the microclimate at the single building scale, i.e., building microclimate. Traditional Japanese houses are among the fine examples of low thermal mass buildings with various types of semi-outdoor spaces, which may create favorable microclimate affecting the connected indoor thermal comfort. This paper attempts to supplement this study area with empirical findings obtained through field measurements. The thermal function of surrounding semi-outdoor spaces in the Japanese traditional houses is discussed, focusing especially on the shading effect of trees as well as the cooling effect of spraying water. The findings of this study are expected to contribute to accumulate a repository of design guidelines for bioclimatic houses utilizing building microclimate created in the surrounding semi-outdoor spaces.

2. Methodology

2.1. Case Study Houses: Traditional Japanese Houses

The Japanese archipelago lies between 25° and 45° N latitudes and experiences rainy seasons in addition to hot-humid summers and cold winters (Figure 1a). It is assumed that the house should be able to provide shelter during hot and humid summer while one can easily find comfort from the cold spell [25,26]. From north to south, these houses follow a common typology with minor alterations brought based on the locality [10]. For instance, the *minka*s in Hokkaido have the same thatched roof as in Kyushu, while the envelope is thin and flexible in Kyushu to allow cross-ventilation compared to the thermal mass used in Hokkaido (see Figure 1a).

The field investigation was conducted during summer from 18th to 28th August 2017 in two houses located in the historic district of Takehara City (34° N, 132° E), Japan (Figure 1). The city is located in the Chugoku region and faces the Seto inland sea. Because of this setting, wind flows from the sea (south, southeast) during the day and from the land (north) during the night. Historic townhouses (*machiya*) dating back to Edo and Meiji era are currently preserved by the government and function as tourist sites. Matsuzaka residence (hereafter referred to as H_1) was built in 1818 (renovated in 1879) during the Meiji era and functioned as a shophouse for Matsuzaka family (Figure 1c). This building is entirely made of lightweight wooden structure and the envelope material changes based on the space usage (Table 1). For instance, the living areas have *Tatami* mats on the floor, wooden lattice with rice paper (*shoji*) on the exterior façade and opaque paper-made sliding partitions (*fusuma*) between the spaces. On the other hand, the *doma* space has an earthen floor with thermal mass infills on the outer envelope and the kitchen and veranda space have wooden floors. This house has two semi-outdoor spaces but for the purpose of this study, we classified them into three based on the variation of vegetation and ground cover. H_1SO_1 is dry and sparsely vegetated, while the Morikawa residence (hereafter referred to as H_2) is shaded by trees and H_1CY_1 is the relatively smaller and shaded semi-outdoor space, which is enclosed by the building and boundary wall, with moss covering most of the ground surface (Figure 2a). Morikawa residence (hereafter referred to as H_2) was built in 1912 during the Taisho era and shares similarities with H_1 in material usage and structure (Figure 1d and Table 1). In contrast, H_2 covers a larger built area (550 m^2) and has a long *doma* space with three vegetated semi-outdoor spaces (Figure 2f). These two houses were chosen as case study houses because both houses are considered to represent a typical traditional Japanese house with tiled roof, wooden structure, open-plan, flexible partitions, and various types and sizes of attached semi-outdoor spaces.

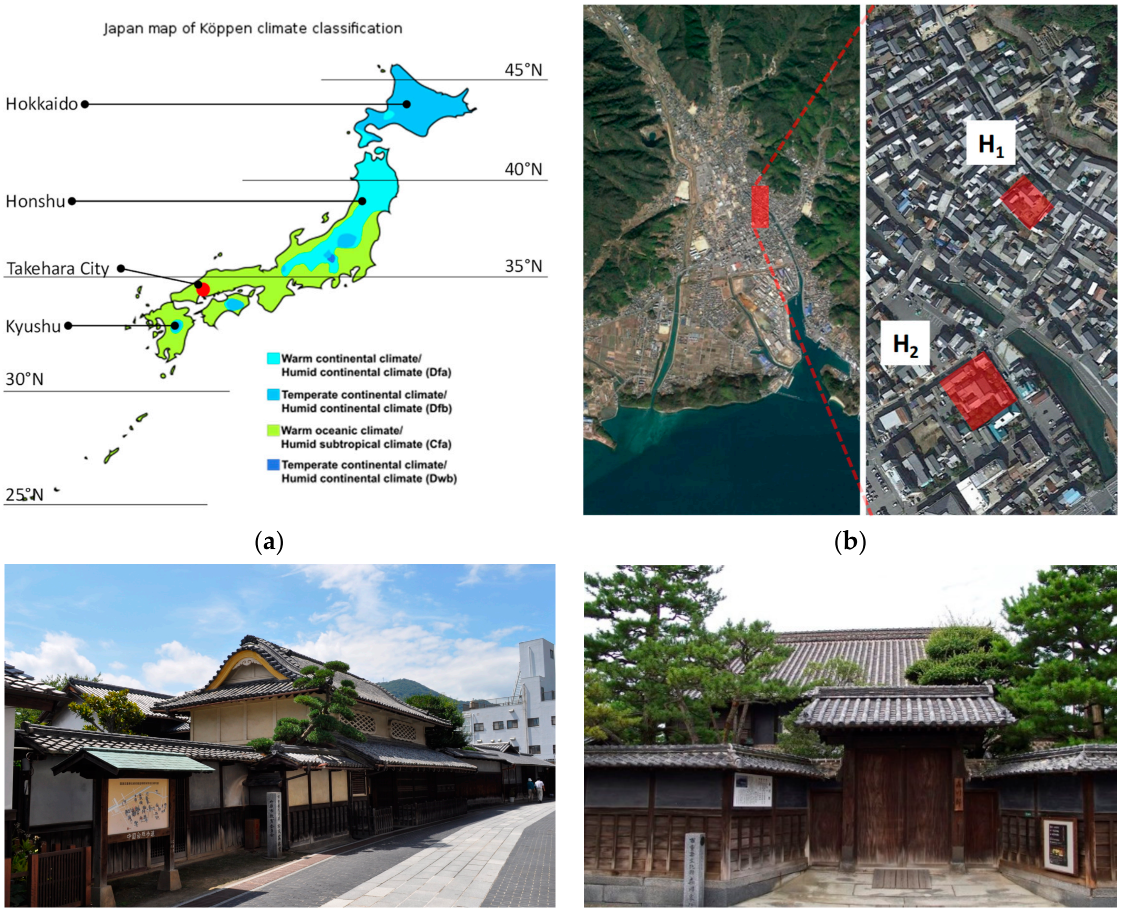


Figure 1. (**a**) Map of Japan with Köppen climate classification; (**b**) Location of the case study houses in Takehara city; (**c**) Matsuzaka residence (H_1); (**d**) Morikawa residence (H_2).

During the field measurements, the exterior sliding doors (*shoji*) and rain shutters (*amado*) were open and only three persons occupied the houses with few random tourists during the operation time (9:00 to 17:00). No mechanical cooling was used in the houses except the reception rooms which are excluded from this study (Figure 2). To investigate the effects of water spraying (*Uchimizu*) in the semi-outdoor spaces on the building microclimate, the routine watering schedule was followed.

2.2. Outline of Field Measurement

Air temperature (T_a), relative humidity (RH) and air speed (v) were measured at 1.1 m height above the floor in several locations inside the houses. Vertical distribution of T_a was investigated in semi-outdoor spaces, living room and earth floor space (*doma*). Mean radiant temperature ($\overline{T}_r$) was then calculated by the following equation [27]:

$$\overline{T}_r = \left[\left(T_g + 273\right)^4 + \frac{1.1 \times 10^8 \times v^{0.6}}{\varepsilon_g \times D^{0.4}} \left(T_g - T_a\right) \right]^{1/4} - 273 \quad (1)$$

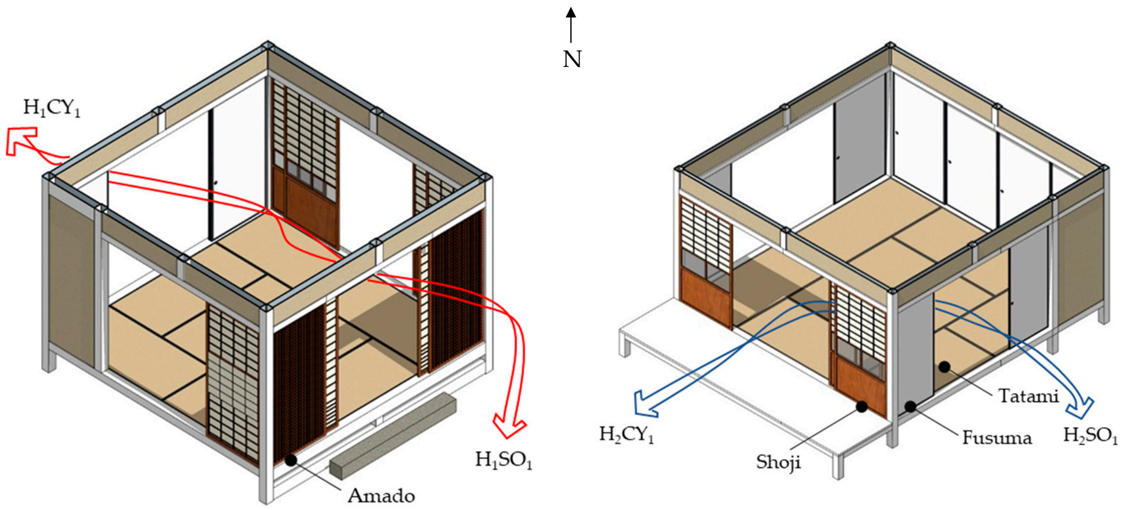
where T_g is the globe temperature (°C), v is indoor air speed (m/s), ε_g is emissivity of the black globe (0.98) (-), and D is the diameter of the globe (m). In addition, differential air pressure between living room and semi-outdoor spaces and soil moisture content of the semi-outdoor spaces were also measured. Outdoor weather condition was recorded with a weather station in the perimeter of the houses (Figure 2a,f). All measurements were logged automatically at 1 min interval (Table 2). All the sensors were further validated by comparing with more accurate sensors such as Assmann Psychrometer.

Table 1. Detailed description of the living rooms (LR_1) in case study houses.

Aspect	Description	
	Matsuzaka Residence (H_1)	**Morikawa Residence (H_2)**
Building Material		
Structure Roof Ceiling Floor	Timber frame structure Clay tiles Wooden false ceiling Rice straw mats (*tatami*)	Timber frame structure Clay tiles Wooden false ceiling Rice straw mats (*tatami*)
External façade	Wooden lattice sliding doors (*shoji*) with rice paper, glazing and wooden board.	Wooden lattice sliding doors (*shoji*) with rice paper, glazing and wooden board.
Internal partition Internal overhead opening	Opaque thick paper-covered wooden lattice sliding panels Bamboo reinforced clay wall (Thermal mass)	Opaque thick paper-covered wooden lattice sliding panels Bamboo reinforced clay wall (Thermal mass)
Shading element		
Roof eaves Plant	Roof eaves: 1.5 m Deciduous tree, height: 2.5 m, Crown Ø = 1 m	Roof eaves: 1.2 m Deciduous trees, height: 3.5 m Crown Ø = 2 m
Openings		
External façade (Type; % glazed are of opening area; size; position; % opening area of wall area; usage conditions)	**SE façade** Wooden lattice sliding door covered with rice paper (*Shoji*); nil; 1500 mm(W) × 1700 mm(H); floor level; 36%; open)	**SW façade** Wooden lattice sliding door covered with rice paper (*Shoji*); nil; 1800 mm(W) × 170 0mm(H); floor level; 36%; open)
Internal Partition		
(Type; % glazed area of opening area; size; position; % opening area of wall area; usage conditions)	**NW façade** Wooden lattice sliding door covered with thick paper (*fusuma*); nil; 1500 mm(W) × 1700 mm(H); floor level; 36%; open) **SW façade** Wooden lattice sliding door covered with thick paper (*fusuma*); nil; 1500 mm(W) × 1700 mm(H); floor level; 36%; open) **NE façade** Wooden lattice sliding door covered with rice paper (*shoji*); nil; 1500 mm(W) × 1700 mm(H); floor level; 36%; open)	**NW façade** Wooden lattice sliding door covered with thick paper (*fusuma*); nil; 1890 mm(W) × 1700 mm(H); floor level; 36%; open) **NE façade** Wooden lattice sliding door covered with thick paper (*fusuma*); nil; 3800 mm (W) × 1700 mm (H); floor level; 0%; closed) **SE façade** Wooden lattice sliding door covered with thick paper (*fusuma*); nil; 1420 mm(W) × 1700 mm(H); floor level; 37%; open)

Table 1. *Cont.*

Aspect	Description	
	Matsuzaka Residence (H_1)	**Morikawa Residence (H_2)**



3D of living rooms in H_1 and H_2 showing the structure, envelope, openings and material usage.

Other attributes		
Room height	2.3 m	2.3 m

Table 2. Description of the measurement instruments.

Measured Variables	Instrument Model	Accuracy
Atmospheric Pressure	T&D TR-73U	±1.5 hPa
T_a and RH at 1.1 m above floor (Living rooms)	T&D TR-72wf	±0.3 °C at 10~40 °C; ±2.5% at 15~35°, 30~80% RH
T_a and RH at 1.1 m above floor (Other rooms)	T&D TR-72Ui	±0.5 °C, ±5% RH
T_a (vertical distribution)	Type T thermocouple and Graphtec GL840-wv	±0.1% + 0.5 °C plus ± 0.5 °C for cold junction compensation
Globe Temperature (T_g)	Type T thermocouple and black copper globe of Ø = 70 mm	±0.1% + 0.5 °C plus ± 0.5 °C for cold junction compensation
Indoor air speed (v)	Kanomax sensor (0965-03) with Kanomax Airmaster	0.1–4.99 m/s: ±0.15 m/s, 5.00–9.99 m/s: ±0.3 m/s, 10.0–25.0 m/s: ±0.6 m/s
Outdoor weather station (T_{out}, RH and Rain fall)	Davis, Vantage Pro 2 & self-made aspirated radiation shield with T&D TR72wf [28]	±0.5 °C, ±3% RH (±4% RH when RH > 90), ±4% of full scale (rain fall), ±0.3 °C at 10~40 °C; ±2.5% at 15~35°, 30~80% RH
Outdoor wind speed and direction	Young 2D-Ultrasonic Anemometer	±2%, 0.1 m/s (30 m/s), ±3% (75 m/s); ±2 degrees
Solar radiation	Apogee SP-110 with Graphtec GL-840-wv	0.2 mV per W/m^2
Differential air pressure	GC62 with Time-lapse camera	1.5% F.S. + 1digit; less than a 200 Pa
Soil moisture content and soil temperature	WD-3-WT-5Y with Graphtec GL-840-wv	±5% F.S.; 0~50%, ±15% F.S; 50~100%, ±2 °C
Infrared images	FLUKE TiS45	±2 °C

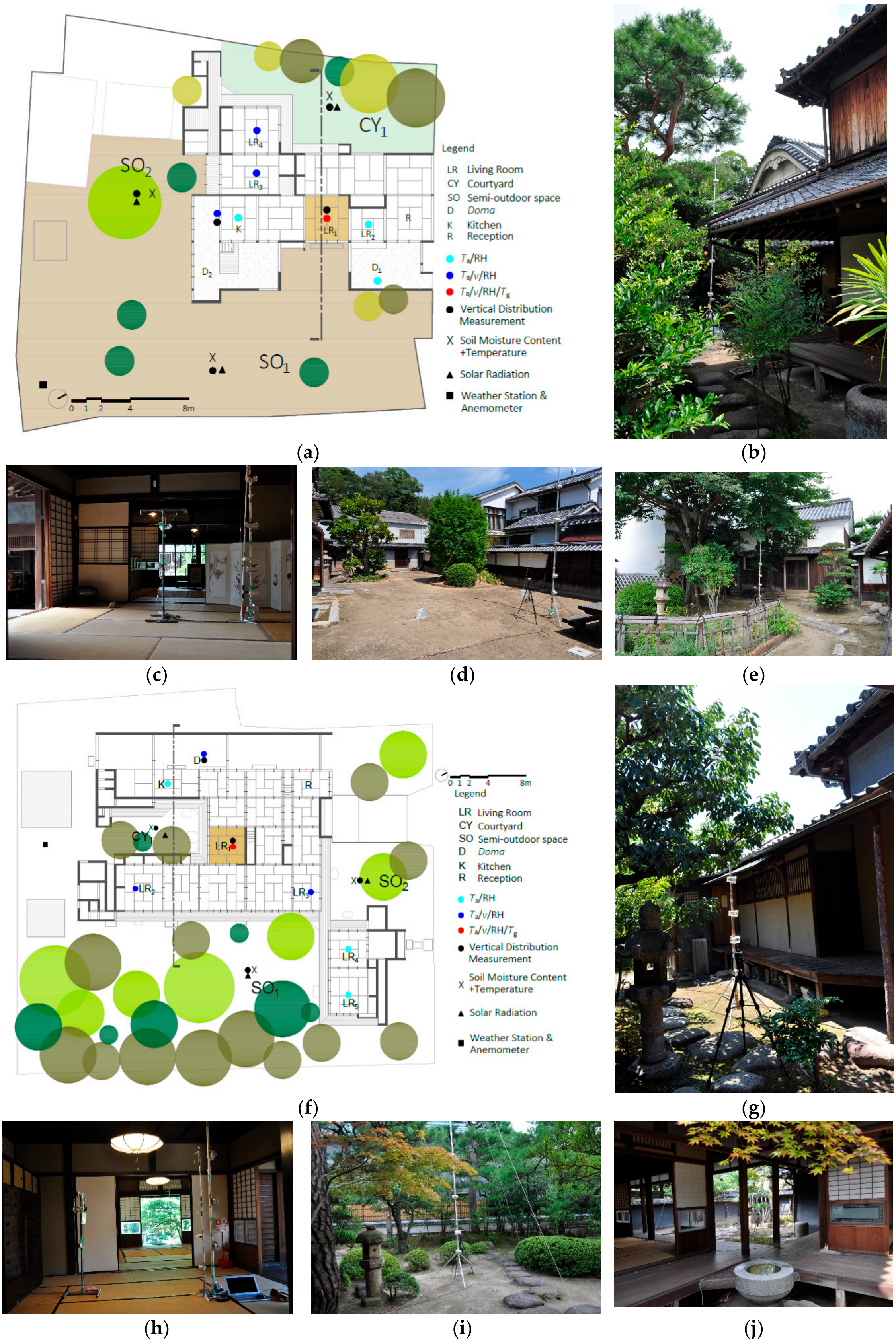


Figure 2. Floor plans and photographs of the case study houses, showing the measurement positions. (**a**) H_1; (**b**) H_1CY_1; (**c**) H_1LR_1; (**d**) H_1SO_1; (**e**) H_1SO_2; (**f**) H_2; (**g**) H_2CY_1; (**h**) H_2LR_1; (**i**) H_2SO_1; (**j**) H_2SO_2.

3. Results and Discussion

3.1. Detailed Thermal Environment in the Living Rooms

Figure 3 shows the measured air temperatures and humidity in the living rooms of H_1 and H_2 on fair weather days. As shown, overall, the maximum outdoor air temperatures were 32–34 °C while outdoor relative humidity ranged between 50–80%. Daily global horizontal solar radiation reached 900 W/m^2 on a fair sunny day. Winds flowed from the southwestern to southeastern side during daytime at a mean speed of 1.0 m/s, whereas at night-time, the flow was from the north in H_2 and from the south in H_1 at a mean speed of 0.6 m/s.

In general, the indoor air temperatures in both houses followed the pattern of the outdoors as expected, primarily due to the lightweight wooden structure. During daytime under open window condition, the indoor air temperatures were lower than the corresponding outdoor air temperatures by 0.5 °C and 2 °C in H_1LR_1 and H_2LR_1, respectively. The corresponding difference can be related to shading and proximity to a wet or dry semi-outdoor space as discussed in the following sections. Indoor air temperature rose by 3 °C on average in H_1LR_1 and 4 °C in H_2LR_1 compared to the outdoors at night-time under closed opening conditions. In terms of humidity, the indoor relative humidity followed the corresponding outdoors and remained higher values during operating hours. The difference of 8% in relative humidity was noted between indoor and outdoor in H_2LR_1, whereas H_1LR_1 closely followed the corresponding outdoor levels. This is probably due to the weak air speed conditions in H_2LR_1. The indoor absolute humidity was 17 g/kg on average.

The average indoor air speed was noted as 0.4 m/s in H_1LR_1 when the sliding doors were open during the daytime. The corresponding value in H_2LR_1 was 0.2 m/s despite the observed higher outdoor wind speed. Cross ventilation was poor in H_2LR_1 compared to H_1LR_1 probably due to vegetation density in the adjacent semi-outdoor spaces (see Figure 2), although the rooms faced the prevailing wind direction (SE) perpendicularly. The results of differential air pressure prove that the rooms were cross ventilated in both houses (Figure 4). In H_1, a relatively stronger back and forth air flow was seen between the H_1LR_1 and the semi-outdoor spaces, while the results of H_2 show a weaker exchange of air. The air flow direction in H_2 was from the room to the large front garden (H_2SO_1).

3.2. Thermal Comfort Assessment in the Living Rooms

Figure 5 presents the thermal comfort evaluation using operative temperature and the standard effective Temperature (SET*). The operative temperatures were computed based on the measured indoor air temperature (T_a), mean radiant temperature ($\overline{T}_r$) and airspeed (v), using the following equation [27].

$$T_{op} = \frac{T_a\sqrt{10v} + \overline{T}_r}{1 + \sqrt{10v}} \quad (2)$$

The comfortable ranges were evaluated on the basis of an adaptive comfort equation (ACE) developed in [29] for naturally ventilated buildings in hot-humid climates. Toe and Kubota [29] developed the ACE based on the statistical meta-analysis of the ASHRAE RP-884 database. The proposed ACE equation for naturally ventilated buildings in hot-humid climate was proven to have a regression coefficient of approximately 0.6, which is more than twice the existing standards. The 80% comfortable upper limit in Figure 5 was drawn on the basis of the daily mean outdoor temperature measured by the weather station. The resulting limit ranged between 28.6–30.0 °C on the fair weather days for H_1 and 29.2–29.8 °C for H_2. The indoor operative temperatures in both rooms exceeded the 80% upper limit during the afternoon until the midnight. At peak period, the indoor operative temperatures were 2.9 °C and 3.2–4.0 °C above the limit in H_1 and H_2, respectively. Operative temperatures exceeded the limit for about 58% of the time in H_1 and 64% in H_2. The operative temperature does not take evaporative heat exchange between the occupants and the ambient environment into account. Thus, to study the effects of sweat evaporation in cooling the occupants, SET* was also evaluated. SET* is considered to be one of the most comprehensive thermal comfort indices, which integrates the effects of air temperature, humidity, radiation, air speed, clothing insulation and metabolic rate on human thermal comfort.

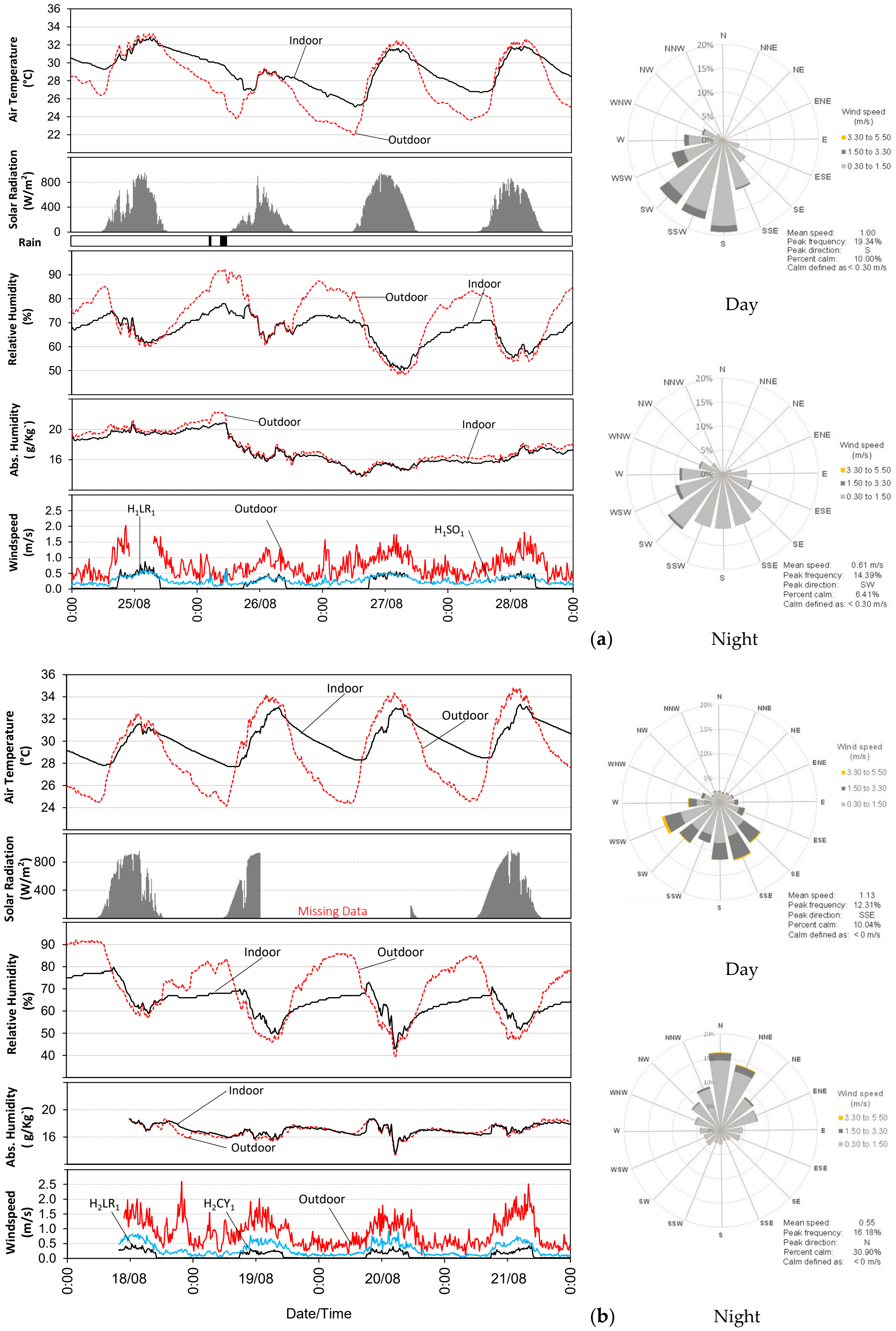


Figure 3. Temporal variations of the measured air temperature and humidity in the living rooms and the corresponding outdoor conditions. (**a**) H_1LR_1; (**b**) H_2LR_1.

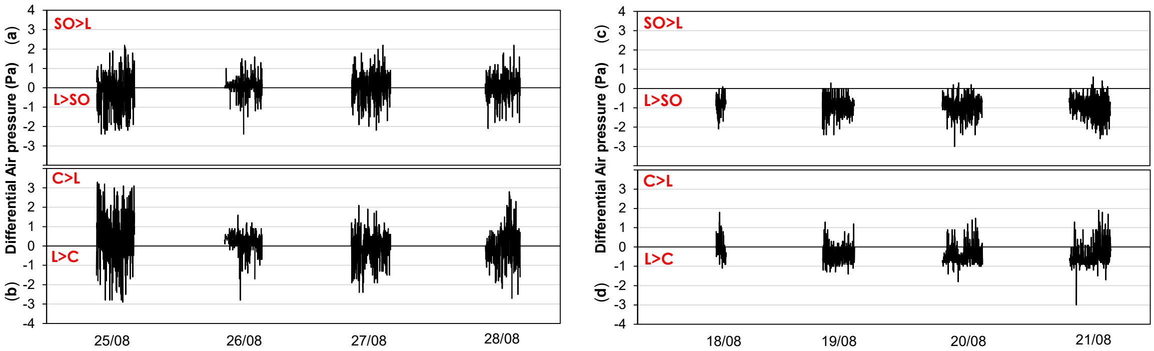
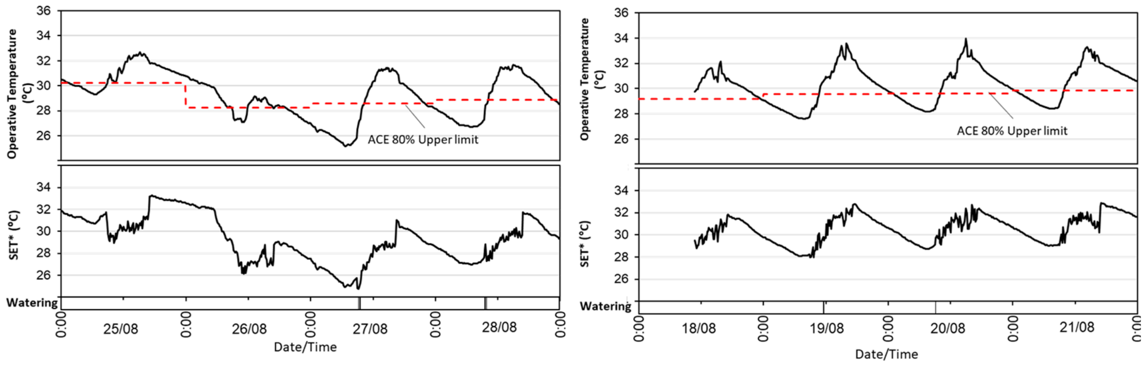


Figure 4. Differential air pressure between living rooms and adjacent semi-outdoor spaces during open window conditions. Positive values show air flow from the semi-outdoor spaces to the living rooms and vice versa. (**a**) H_1SO_1 & H_1LR_1; (**b**) H_1CY_1 & H_1LR_1; (**c**) H_2SO_1 & H_2LR_1; (**d**) H_2CY_1 & H_2LR_1.



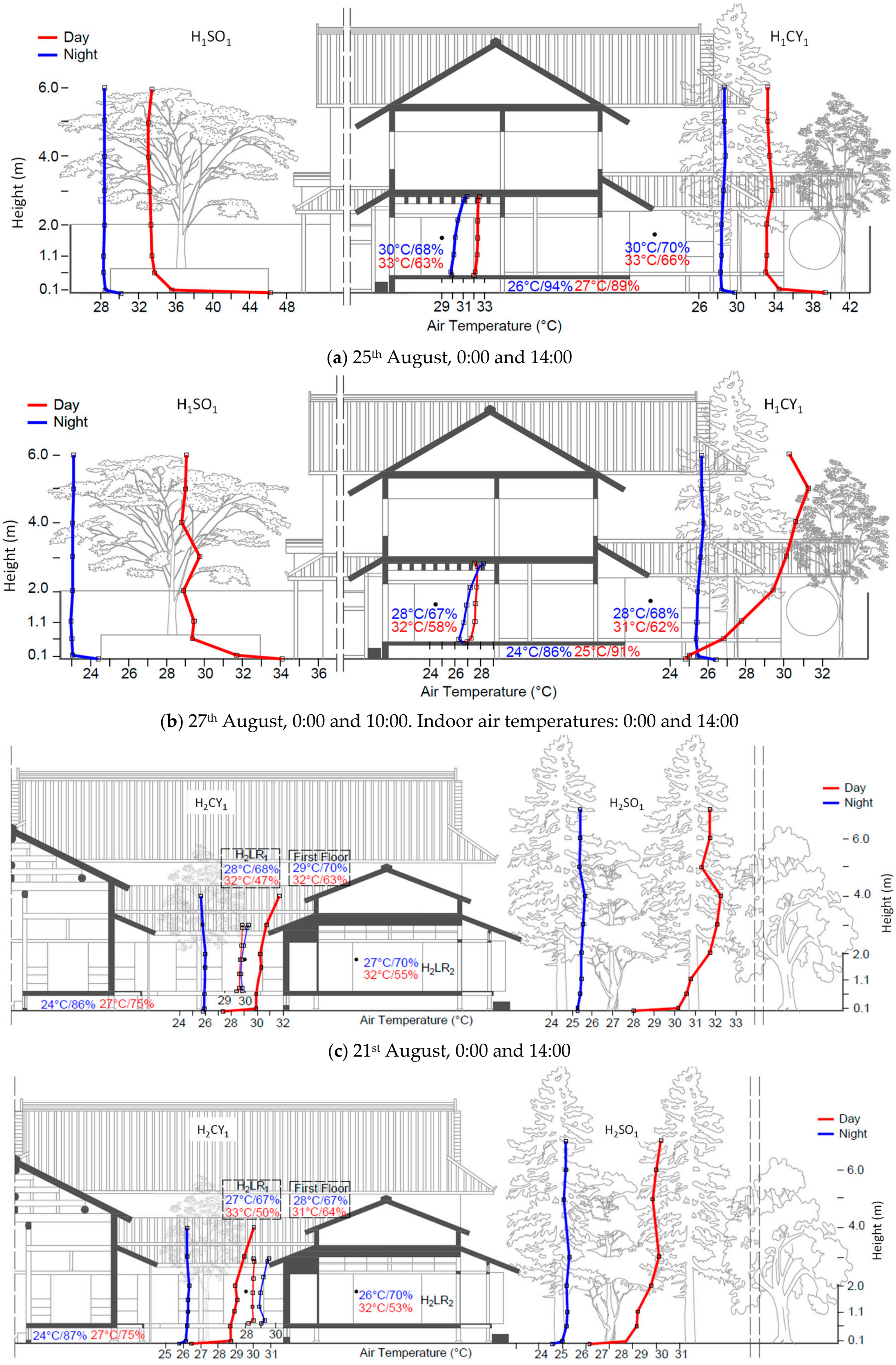
(**a**) (**b**)

Figure 5. Operative Temperature and SET* evaluation. (**a**) H_1LR_1; (**b**) H_2LR_1.

In calculating SET*, the metabolic rate was assumed to be 1.0 met, which is equivalent to seated position. Meanwhile, clothing insulation was estimated to be 0.5 clo, which represents typical clothing worn when the outdoor condition is warm [30]. As indicated in Figure 5, SET* was below 30 °C in H_1LR_1 under open conditions during the daytime, whereas in H_2LR_1, SET* remained above 30 °C during the afternoon. The results imply that the frequent cross-ventilation between H_1SO_1 and H_1CY_1 reduced SET* and improved occupants' thermal comfort by sweat evaporation. In contrast, even though H_2LR_1 had lower air temperature than H_1LR_1, it received low-speed winds, hence the SET* values increased.

3.3. Vertical Distribution of Air Temperature in Living Rooms and Semi-Outdoor Spaces

Figure 6 presents the vertical temperature distribution in the living rooms and semi-outdoor spaces of H_1 and H_2, together with indoor thermal conditions during peak hours. Under the dry conditions, the H_1SO_1 which has a sparsely vegetated surface received more solar radiation than its counterpart (H_1CY_1) which is densely vegetated and has moss-covered ground surface (Figure 6a). The increased surface temperature of H_1SO_1 was 6.5 °C higher than H_1CY_1, while air temperature at 0.1 m above the ground was 1.5 °C higher. Figure 6c shows that during peak hours, both H_2SO_1 and H_2CY_1 had lower surface temperatures of 28.0–27.5 °C, respectively. This is due to the shade provided by the trees and the surrounding walls. During night-time, the air temperature profiles in all the semi-outdoor spaces remained flat. In the living rooms, the ceiling surface temperature followed the indoor ambient temperature and the tatami flooring was slightly cooler at daytime.



(**a**) 25th August, 0:00 and 14:00

(**b**) 27th August, 0:00 and 10:00. Indoor air temperatures: 0:00 and 14:00

(**c**) 21st August, 0:00 and 14:00

(**d**) 19th August, 0:00 and 10:00. Indoor air temperatures: 0:00 and 14:00

Figure 6. Vertical distribution of air temperature in the living rooms and the semi-outdoor spaces in H_1 and H_2, together with indoor thermal conditions during peak hours. (**a**,**b**) Dry; (**c**,**d**) Wet.

3.4. Building Microclimate in the Semi-Outdoor Spaces

Figures 7 and 8 show temporal variations of air temperatures and surface temperatures of semi-outdoor spaces in H_1 and H_2, respectively. In H_1SO_1, the surface temperature rose to 48 °C under clear sky condition and during the proceeding night, it remained higher than the ambient by 2 °C (Figure 7a). Air temperature near the surface at 0.1 m was also affected by radiant heat and under dry conditions, it rose up to 2 °C above ambient air temperature. In H_1SO_2, a high tree shaded the ground during the afternoon and reduced the surface temperature by 10 °C compared to H_1SO_1 (Figure 7b). The air temperature at 0.1 m was 2 °C lower than the outdoors. Overall, a clear relation was noticed between the rise in the surface temperature and the solar radiation received by the semi-outdoor spaces. Meanwhile, in the small courtyard (H_1CY_1) under dry conditions, the surface temperature rose noticeably above ambient temperature and remained 2 °C above the ambient during night-time (Figure 7c). Nevertheless, after spraying water on this space (27th and 28th August), the peak surface temperature was reduced to 36 °C from 50 °C and followed the ambient air temperature during night-time (Figures 7c and 9). Moreover, the air temperature at 0.1 m above ground fell from 26 °C to 23.5 °C and followed the outdoor air temperature during night-time. In contrast to the dry conditions, when the surface temperature increased with solar radiation, under wet conditions, this pattern was broken, and the peak surface temperature was reduced and delayed. This shows that the peak surface temperature can be lowered substantially by spraying water before peak time and its cooling effect is maintained until the night.

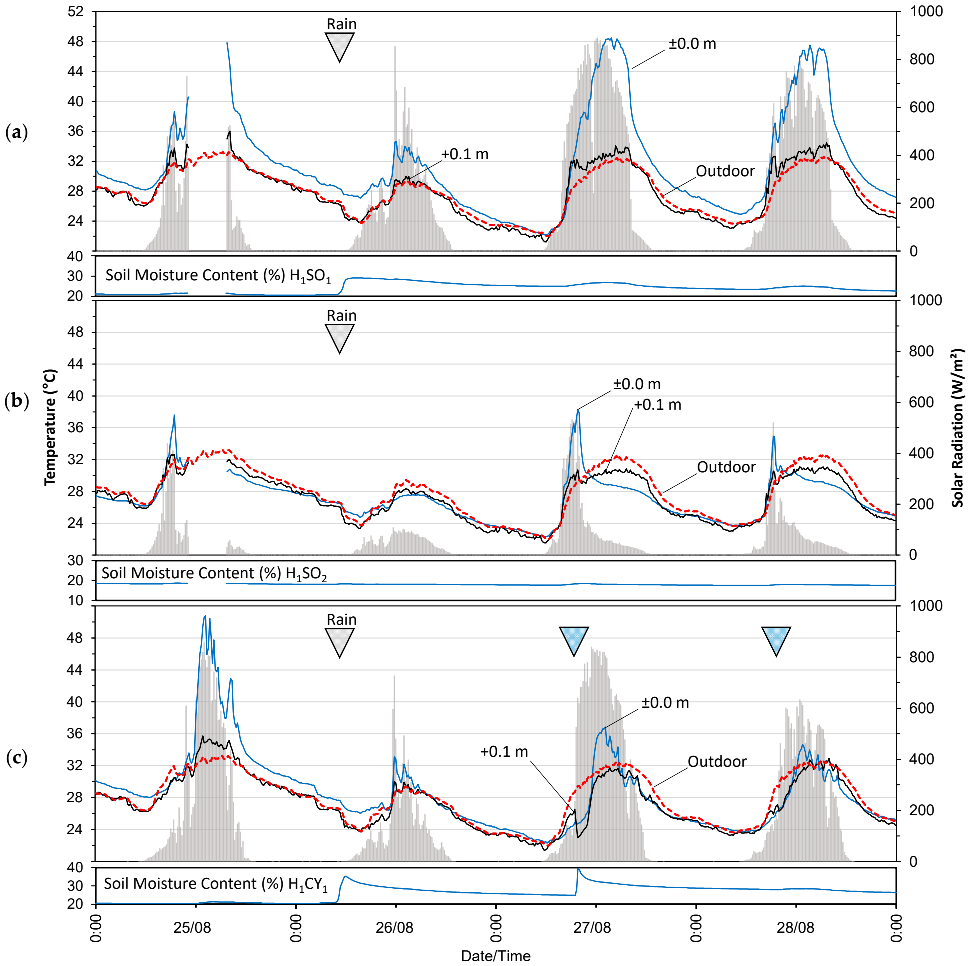


Figure 7. Temporal variations of air temperatures, surface temperatures and soil moisture content of the semi-outdoor spaces in H_1. The blue triangles indicate times of water spraying (**a**) H_1SO_1; (**b**) H_1SO_2; (**c**) H_1CY_1.

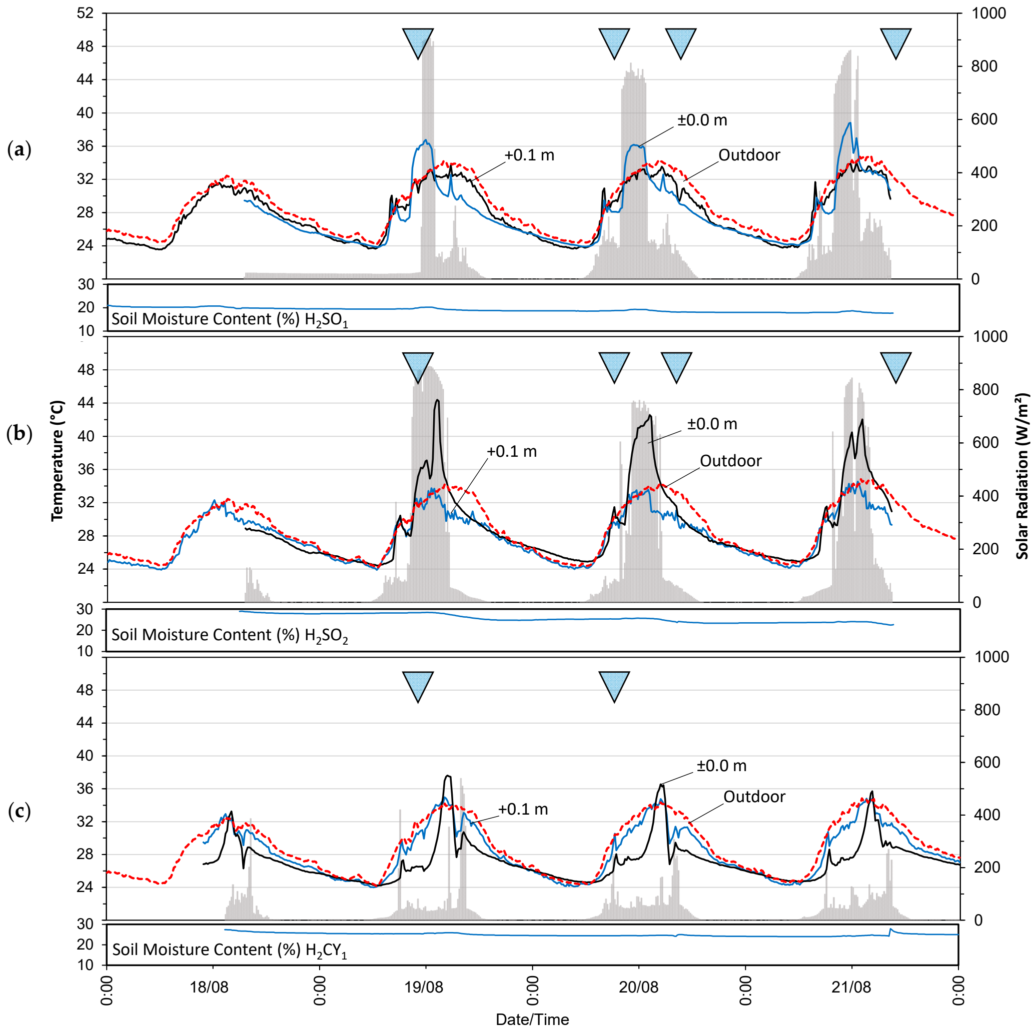


Figure 8. Temporal variations of air temperatures, surface temperatures and soil moisture content of the semi-outdoor spaces in H_2. The blue triangles indicate times of water spraying. (**a**) H_2SO_1; (**b**) H_2CY_1; (**c**) H_2SO_2.

In H_2, on the other hand, all the semi-outdoor spaces were vegetated, and the surfaces received solar radiation unevenly (Figure 8). Hence, an irregular pattern was seen in the surface temperature that also affected the air temperature at 0.1 m above the ground. H_2SO_1 had tall trees and the surface of the semi-outdoor space was not insolated during the morning and afternoon.

Thus, the surface temperature during those times was lower than the ambient temperature (Figure 8a). This space was irrigated before and after peak hours and the results show that when irrigated before noon (19th and 20th August), the peak surface temperature was 3 °C lower than when irrigated in the afternoon (21st August). Moreover, a drop in the air temperature above the ground (0.1 m) was noticed after spraying water in this space (Figure 8a). In H_2CY_1 as well, the surface temperature and the nearby air temperature were below the ambient temperature during the morning and afternoon. H_2SO_2 was insolated during the morning and experienced shady afternoon. During the afternoon, the air temperature near the ground was 4 °C lower than the ambient. A drop in air temperature and surface temperature was observed particularly when water was sprayed during the afternoon of 20th August.

Furthermore, the results of vertical distribution (Figure 6c,d) show that the air was thermally stratified in the small wet courtyard (H_2CY_1) for a short time. The reason is shading and spraying water as seen in Figure 8c. It is confirmed that the effects of shading in lowering the air temperature of the outdoor space is prolonged more than the effects of water spraying. However, Figures 7c and 8 imply that the increase in surface temperature due to the direct incidence of solar radiation can be delayed by spraying water on the ground surface.

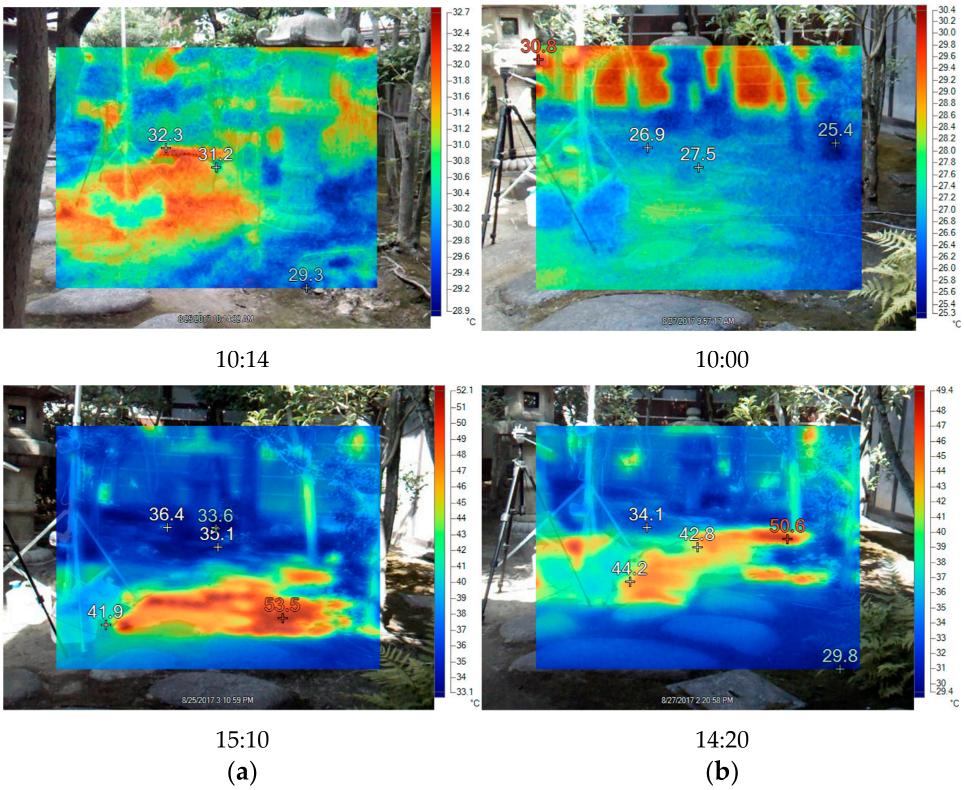


Figure 9. Thermal images of the courtyard H_1CY_1 under dry and wet conditions. (**a**) Dry; (**b**) Wet.

3.5. Interaction of the Semi-Outdoor with Indoor Spaces

As discussed earlier, a major area of the exterior envelope of the Japanese traditional houses can be removed to allow outdoor-indoor air exchange. In other words, the air flowing from the immediate surroundings of the house can affect the indoor thermal conditions. Figure 10 presents the statistical summary of indoor and outdoor air temperatures in various spaces during the fair weather days. As shown, in the high tree-shaded semi-outdoor spaces such as H_1SO_2, H_2SO_1, H_2SO_2 and H_2CY_1, the daytime air temperatures maintained lower than the corresponding outdoors. When these shaded semi-outdoor spaces are located toward the prevailing wind directions, which is from southwest to southeast, the pre-cooled air entered the houses and improved the indoor thermal comfort as shown in Figure 11. The shaded semi-outdoor space, i.e., H_1SO_2, created a cool zone underneath the wide tree crown with tall trunk that did not interrupt the airflow to the surrounding rooms and thus, relatively low air temperatures with breezy conditions were achieved in H_1LR_3 and H_1LR_4. For example, the air speed in H_1LR_3 was noted as 0.7 m/s on average during open window condition while maintaining lower air temperature.

The previous study showed that in the high thermal mass courtyard houses such as the Chinese shophouses, the air was not exchanged between indoor and outdoor during the daytime due to the thermal stratification in the courtyards [3]. Under this closed condition, the ground floor maintained lower air temperature (approx. 4 °C lower than the outdoors) and the courtyards functioned as a cooling source to the surrounding spaces. In other words, the courtyards provided “cool but still” conditions to the indoor spaces [3]. On the other hand, in the traditional Japanese houses with low thermal mass structure, the outdoor air is greatly invited inside the house, thanks to the large sliding openings. In these houses, the semi-outdoor spaces act as thermal buffers for promoting cross-ventilation as well as pre-cooling (however, so large temperature reduction cannot be expected) to provide “warm but breezy” conditions to the adjacent indoor spaces as shown herein.

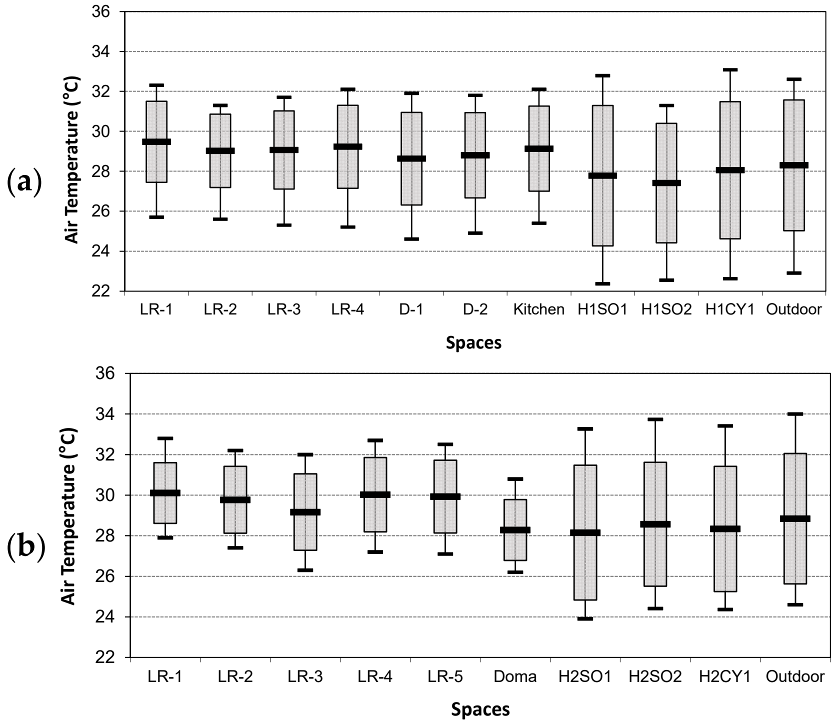


Figure 10. Air temperature comparison. (**a**) H_1; (**b**) H_2.

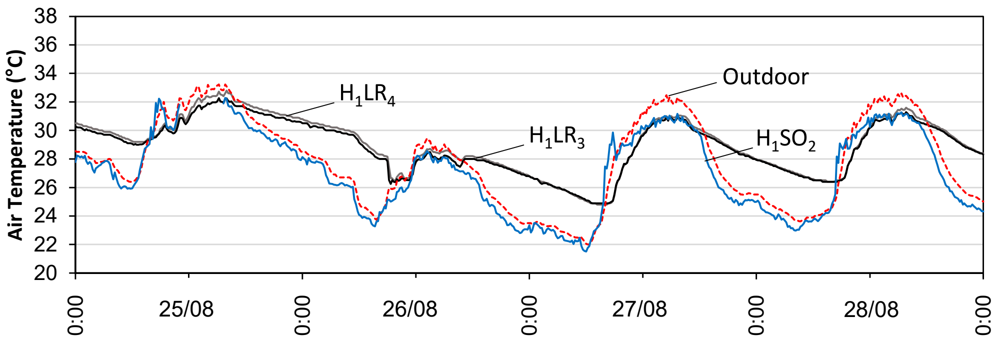


Figure 11. Indoor air temperature and air temperature in the semi-outdoor spaces in H_1.

4. Conclusions

This paper investigated the effects of building microclimate on indoor thermal environment of two traditional Japanese houses with different types and sizes of semi-outdoor spaces through the on-site measurements. The main findings are summarized as follows:

- Basically, the indoor thermal environment followed the outdoor conditions due to the open-plan and the lightweight wooden structure. Nevertheless, the air temperatures of the living rooms in both houses were lower than the corresponding outdoors by approximately 0.5 °C and 2 °C, respectively. It was found that the semi-outdoor spaces acted as thermal buffers for promoting cross-ventilation as well as pre-cooling to provide “warm but breezy” conditions to the connected indoor spaces.
- Vegetation in the semi-outdoor spaces reduced direct exposure to solar radiation and reduced the surface temperature during the day and the proceeding night. Furthermore, the peak

surface temperature was reduced by spraying water before the peak hours and kept the surface temperature as low as the ambient during the proceeding night. This practice reduced the air temperature near the ground and affected until approximately 0.6 m above the ground.

The results of this research highlight the importance of considering the indoor, the semi-outdoor and their interaction, i.e., building microclimate, when designing bioclimatic buildings. Following are some passive cooling recommendations for the new buildings in the hot-humid climates:

- Indoor thermal comfort should be considered from the building microclimate level particularly when designing a naturally ventilated wooden house.
- Tree-shaded semi-outdoor spaces should be oriented toward the prevailing winds and placed near the operable envelope to maximize indoor-outdoor interaction. Tall but wide trees should be planted to provide shade and do not obstruct air flow.
- Harvested rain water should be sprayed in the semi-outdoor spaces particularly before the peak hours to keep the ground surface cool and avoid heat gain from this space.

Further investigations will be conducted in traditional houses in different climates such as a hot-dry climate in the future study. In particular, we will compare the thermal functions of semi-outdoor spaces among various climates.

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