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Characterization of Indoor Temperature and Humidity in Low-income Residences over a Year in Seoul, Korea

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ABSTRACT

People spend the majority of their time in indoor environments. Maintaining adequate indoor temperature and humidity is necessary to support health and improve quality of life. However, people with low incomes can be vulnerable because they may not be able to use effective cooling and heating systems in their homes. In this study, the indoor temperature and humidity in low-income residences over a year in Seoul, Korea was characterized. Indoor temperature and humidity were measured in three types of homes (12 rooftop residences, 16 basement residences, and 18 public rental apartments) occupied by low-income residents. Both differed significantly among the three types of residence, particularly during the summer and winter seasons. A regression model between indoor and outdoor temperature detected a heating threshold at 3.9°C for rooftop residences, 9.9°C for basement residences, and 17.1°C for public rental apartments. During tropical nights and cold-wave advisory days, rooftop residences showed the most extreme indoor temperatures. This study demonstrates that people living in rooftop residences could be at risk from extreme hot and cold conditions.

Key words: Indoor temperature, Indoor relative humidity, Residential type, Season, Low income residence

1. INTRODUCTION

Indoor temperature and humidity conditions are critical to public health because people in industrialized countries generally spend more than 90% of their time in indoor environments (Hppe and Martinac, 1998). Heat and cold stress in home environments are particularly important to examine. In New York, 80% of heat stroke morbidity during the summer of 2007 was attributed to heat exposure at home (NYC, 2013). A similar situation was observed in France; half of all heat stroke fatalities occurred inside homes during the 2003 heat wave (Fouillet *et al*., 2006). Similarly, there are an estimated 30,000-60,000 fatalities in the United Kingdom and 1,500-2,000 fatalities in Ireland due to low residential temperatures each winter (Clinch and Healy, 2000). Low relative humidity (less than 30%) has been associated with dryness of skin, throat, and mucous membranes, and sensory irritation of the eyes (Reinikainen and Jaakkola, 2003; Sato *et al*., 2003). High relative humidity in indoor environments may also affect air quality (Fang *et al*., 1998) and induce the growth of mold, causing respiratory allergies and discomfort (Bornehag *et al*., 2004). Therefore, the maintenance of adequate indoor temperature and humidity levels in homes is necessary to achieve comfortable thermal conditions, protect human health, and improve quality of life.

Low-income households may not have adequate indoor environments. Chartered Institution of Building Service Engineers (CIBSE) recommends 25°C and 24°C as acceptable indoor temperatures for living areas and bedrooms, respectively, during warm weather (CIBSE, 2006). Therefore, use of an air conditioning (AC) unit is the strongest protective factor against heat-related deaths. However, individuals with low incomes may not have AC units in their homes and may thus be vulnerable to high temperatures during the summer months (Naughton *et al*., 2002). In low-income households in Greece, indoor temperatures consistently exceed 30°C during heat waves. One study reported that 216 continuous hourly indoor temperatures were over 30°C; in very-low-income households, indoor temperatures were above 33°C over 6 continuous days (Sakka *et al*., 2012). To maintain adequate health during the winter months, several studies have suggested an indoor temperature of between 18°C and 24°C (WHO, 2007; DEFRA, 2004; Healy and Clinch, 2002a). However, approximately 15-25% of the low-income population of southern Europe and Ireland are unable to afford the expenses associated with this suggested temperature level (Eurofound, 2003). For example, 29% of indoor temperatures in low-income households in southern Europe are lower than 18°C and 10.8% of indoor temperatures in low-income households in Ireland are below 18°C (Healy and Clinch, 2002b).

Indoor temperature and humidity have been investigated for the general population (Bae and Chun, 2009) including in public buildings in Korea (Yeom *et al*., 2014; Yang *et al*., 2009). In general residences of Korea, indoor temperatures during summer and winter were 27.5±2.0°C and 23.9±1.6°C, respectively and indoor relative humidity during summer and winter were 59.5±9.7% and 31.6±7.7%, respectively (Bae and Chun, 2009). These factors have also been investigated in low-income housing during short periods of the summer or winter in other countries (Santamouris *et al*., 2014; Sakka *et al*., 2012; Oreszczyn *et al*., 2006) but not in Korea. In addition, to appropriately assess the effects of indoor temperature and humidity conditions on one's daily life, it is essential to monitor these factors over the long term, ideally over the course of 1 year. Therefore, we characterized the indoor temperature and humidity in various types of low-income residences over 1 year in Seoul, Korea.

2. METHODS

2. 1 Study Population

About 2% (207,736 people) of the population of Seoul, Korea, were within income brackets below the minimum cost of living; such persons relied on the National Basic Livelihood Security System (NBLSS) for living expenses (Seoul Statistics, 2014). For the purposes of this study, a low-income residence was defined as a home containing NBLSS beneficiaries who survived on an income under the minimum cost of living or had near-poor status with an income less than 1.2 times the minimum cost of living. The participants were conveniently selected from the NBLSS list in one of the 25 districts in Seoul by social workers. According to NBLSS list in a selected district, low-income group generally lived in three types of residence such as rooftop residences, basement residences, and public rental apartments. These three types of residence could represent general low-income residences in Korea. A total of 13 rooftop residences, 16 basement residences, and 18 public rental apartments were selected for this study. One data logger placed in a rooftop residence malfunctioned and did not save the temperature and humidity data; these data were excluded from further analysis. There were 46 low-income residences in the final dataset. In four rooftop residences and one basement residence, the residents moved during the study period. Only the temperature and humidity data prior to their move were included. A short questionnaire was used to collect information about the type of residence, heating system, cooling system, use of dehumidifier, age of residence, number of preschool children living in the residence, and maintenance work performed during the study period.

2. 2 Indoor Temperature and Humidity Measurements and Outdoor Weather Data

Indoor temperature and relative humidity were measured using a UX-100-003 or U10 temperature and relative humidity data logger (Onset, Cape Cod, MA, USA). The UX-100-003 data logger has a temperature accuracy of ±0.21°C from 0°C to 50°C and a relative humidity accuracy of ±3.5% from 25% to 85% over the range of 15°C to 45°C or ±5% from 25% to 95% over the range of 5°C to 55°C. The U10 data logger has a temperature accuracy of ±4.0°C from 0°C to 40°C and a relative humidity accuracy of ±3.5% from 25% to 85%. The data logger was set up to record temperature and relative humidity every 30 min. The measurements were conducted from November 2013 to October 2014. A data logger was placed in a representative location in all residences such as living room or bedroom. The position selected was away from the immediate influence of the AC unit, dehumidifier, gas stove, heater, doors, windows, and direct sunlight. The hourly outdoor temperature and relative humidity were obtained from the Korea Meteorological Administration. Absolute humidity was calculated as follows:

$$A\,(g/m^3) = C \cdot P_w / T$$

where C = constant 2.16679 gK/J, P_w = vapor pressure in Pa, and T is temperature in K.

2. 3 Data Analysis

Monthly average indoor and outdoor temperature, relative humidity, and absolute humidity were used to describe the pattern of annual temperature and humidity. To compare the indoor temperature and humidity among the types of residence, an analysis of variance (ANOVA) was performed for every month. Daily average values were classified by type of residence during the four seasons. In addition, piecewise linear regression models were used to determine the threshold point where the correlation between indoor and outdoor temperature was significantly changed. The piecewise regression model was based on the significant zero-crossing method (SiZer) (Sonderegger *et al*., 2009).

A particular focus was placed on values during extreme weather events, such as tropical nights and cold-wave advisories. A tropical night was defined as a night following a day when the lowest hourly outdoor temperature was higher than 25°C. Five tropical nights occurred during July and August 2014. A cold-wave advisory was defined as a period when the lowest outdoor temperature was lower than -12°C over 2 days or when there were marked differences in the temperature in the morning and during the night. Over the study period, a cold-wave advisory was issued for 3 days in January 2014. To determine the residential characteristics during tropical nights and cold-wave advisory days, the variation in indoor temperature was compared to that of normal days and temporal profiles of hourly indoor temperatures were produced for each type of residence. All statistical analyses were performed using Predictive Analytics Software (PASW) Statistics (version 21.0; SPSS Inc., Chicago, IL, USA), and R version 3.0.2 (R Foundation for Statistical Computing, Vienna, Austria) was used for piecewise regression modeling, with all graphs drawn in SigmaPlot 10.0 (Systat Software Inc., San Jose, CA, USA).

Table 1. Indoor climate characteristics by residence type of 46 low-income residences in Seoul, Korea.

	Characteristics	N
Rooftop residence (N=12)		
Heating system	Central heating	0
	Other heating	12
Cooling system	Air conditioning	2
	Natural ventilation	10
Age of residence	Under 20 years	1
	Over 20 years	6
	No answer	5
Basement residence (N=16)		
Heating system	Central heating	0
	Other heating	16
Cooling system	Air conditioning	3
	Natural ventilation	13
Age of residence	Under 20 years	1
	Over 20 years	9
	No answer	6
Public rental residence (N=18)		
Heating system	Central heating	10
	Other heating	8
Cooling system	Air conditioning	6
	Natural ventilation	12
Age of residence	Under 20 years	8
	Over 20 years	10
	No answer	0

3. RESULTS

3.1 Residential Characteristics

The characteristics of 46 low-income residences are shown in Table 1. Ten residences (23.7%) had central heating systems; these were all public rental apartments. Two rooftop residences, three basement residences, and six public rental apartments had AC units. A rooftop residence, a basement residence, and 8 public rental apartments were built less than 20 years ago. Six rooftop residences, 9 basement residences and 10 public rental apartments were built over 20 years. Five rooftop residences and 6 basement residences did not provide the age of their residences. None of the residences used a dehumidifier, were remodeled, or included residents that were preschool children.

3.2 Indoor and Outdoor Temperature and Humidity throughout the Year

The monthly average indoor and outdoor temperature, relative humidity, and absolute humidity from 16 November 2013 to 26 October 2014 are shown in Fig. 1. The values displayed seasonal patterns, with highs during summer and lows during winter. The lowest and highest monthly average indoor temperatures were 19.3°C in January and 29.5°C in July, respectively. The lowest and highest monthly outdoor temperatures were −0.6°C in January and 26.2°C in July, respectively. Indoor temperatures were significantly higher than outdoor temperature in every month ($p<0.01$).

The lowest and highest monthly average indoor relative humidity were 40.3% in February and 59.7% in August, respectively. The lowest and highest monthly outdoor relative humidity were 50.2% in January and 77.4% in August, respectively. Relative humidity was significantly lower indoors than outdoors in every month ($p<0.0001$). The lowest and highest monthly average indoor absolute humidity were 6.6 g/m^3 in January and 17.2 g/m^3 in July. The lowest and highest monthly outdoor absolute humidity were 2.4 g/m^3 in January and 18.2 g/m^3 in July. Unlike temperature and relative humidity, the indoor and outdoor absolute humidity were not significantly different ($p=0.22$).

3.3 Comparison of Indoor Temperature and Humidity by Type of Residence

The daily average indoor temperature and humidity conditions by type of residence are shown in Fig. 2. The daily average indoor temperature differed significantly by type of residence ($p<0.01$) in every month. The indoor temperature was significantly higher in public rental apartments than in the other types of residence from November to June ($p<0.05$), except in March and May; it was significantly lower in basement residences than in other residences from November to

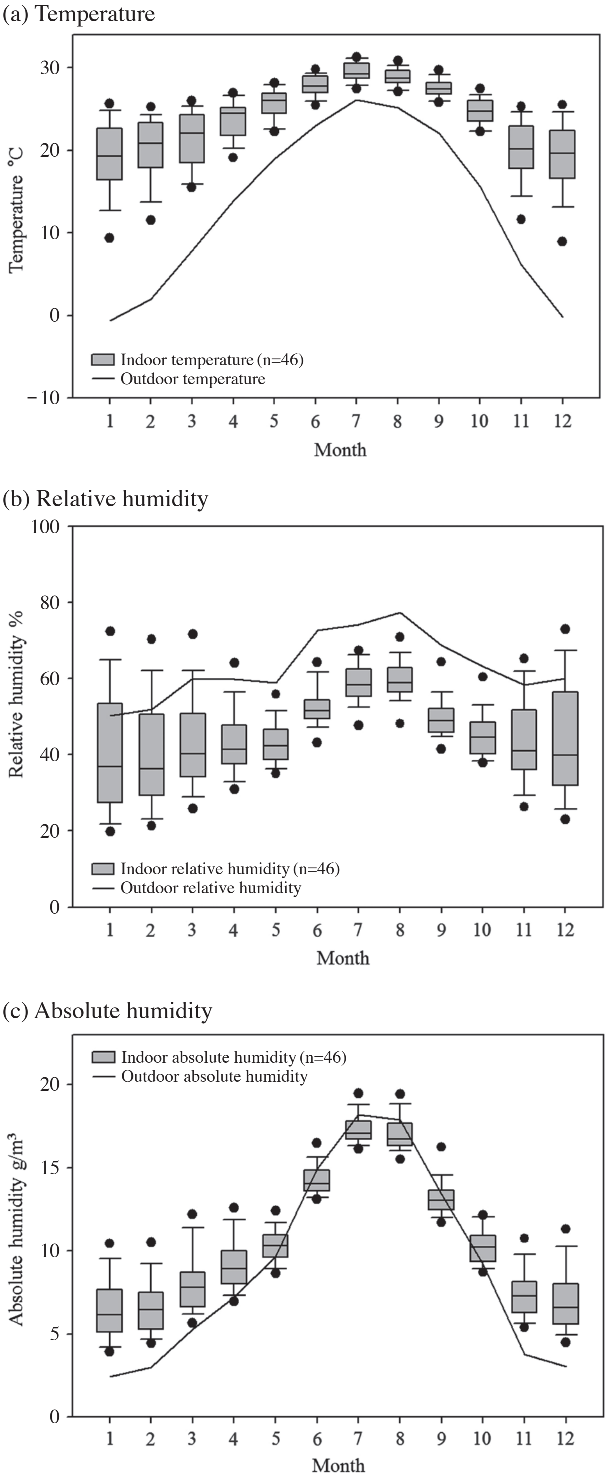

Fig. 1. Monthly average indoor (a) temperature, (b) relative humidity, and (c) absolute humidity.

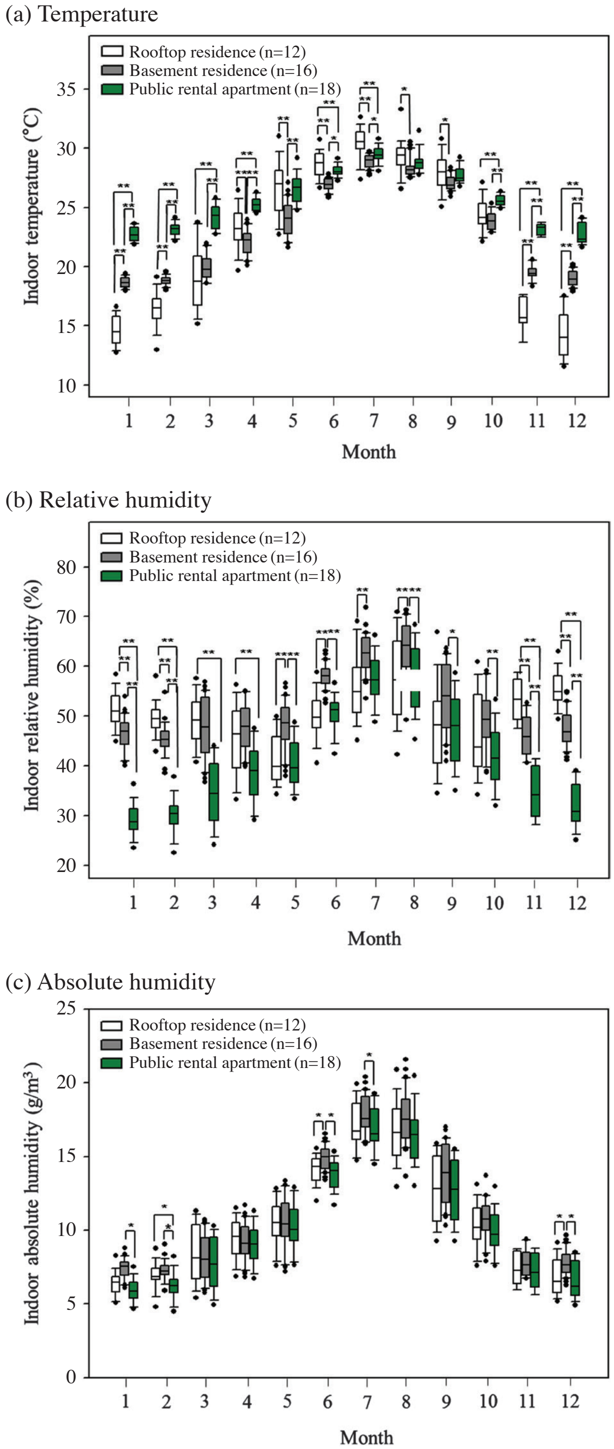

Fig. 2. Comparison of the daily average indoor temperature, relative humidity, and absolute humidity by residential type in each month (*$p<0.05$, **$p<0.0001$) Nov 2013 to Oct 2014 in Seoul, Korea.

March ($p<0.0001$).

The daily average indoor relative humidity differed significantly among the types of residence ($p<0.05$) in every month. It was higher in rooftop residences and significantly lower in public rental apartments than in other residences, from November to February ($p < 0.0001$). The daily average indoor absolute humidity significantly differed among residences in January, February, June, July, and December.

3.4 Relationship between Indoor and Outdoor Temperature and Humidity

A piecewise regression model was used to identify the threshold point of temperature by residence type (Fig. 3). When daily average outdoor temperatures were over 3.9°C for rooftop residences, 9.9°C for basement residences, and 17.1°C for public rental apartments, there was a strong linear correlation with the daily average indoor temperature. When the outdoor temperature was below the threshold point for each residential type, the relationship was weak. Seasonal changes in each parameter are shown in Fig. 4; the patterns did not differ among types of residence in summer. In spring and autumn, there were slight differences among residences. However, in winter, there were significant differences in temperature (highest in public rental apartments) and relative humidity (highest in rooftop residences). Absolute humidity did not differ by residence.

3.5 Indoor Temperature during Extreme Weather Conditions by Type of Residence

Regarding tropical nights, the difference in hourly average indoor temperatures between such nights in July and the whole month of July was significant for each type of residence ($p < 0.0001$) (Fig. 5). The values during tropical nights and the whole month of July were 32.1 ± 1.5°C and 30.5 ± 1.9°C in rooftop residences, 29.5 ± 0.4°C and 28.9 ± 0.6°C in basement residences, and 30.4 ± 0.6°C and 29.5 ± 0.8°C in public rental apartments, respectively (Fig. 5).

Fig. 6 shows the hourly average indoor temperatures for 5 consecutive days in July. The first 3 days were not tropical nights, with temperatures of 25.0°C, 26.5°C, and 26.6°C. The following 2 days were tropical nights with temperatures of 28.5°C and 28.7°C. The indoor temperature in basement residences and public rental apartments did not follow the pattern of outdoor temperatures. Indoor temperatures in rooftop residences displayed a similar pattern to the outdoor temperatures during both tropical and non-tropical nights. Indoor temperatures in public rental apartments exceeded 30°C during tropical nights. In rooftop residences, the indoor temperature reached up to 35°C.

Regarding cold waves, the difference in the hourly average indoor temperatures between cold-wave advisory days and the whole month of January was significant only in rooftop residences ($p < 0.0001$) (Fig. 7). The temperature during cold-advisory days and for the whole month of January were 13.9 ± 1.6°C and $14.6 \pm$

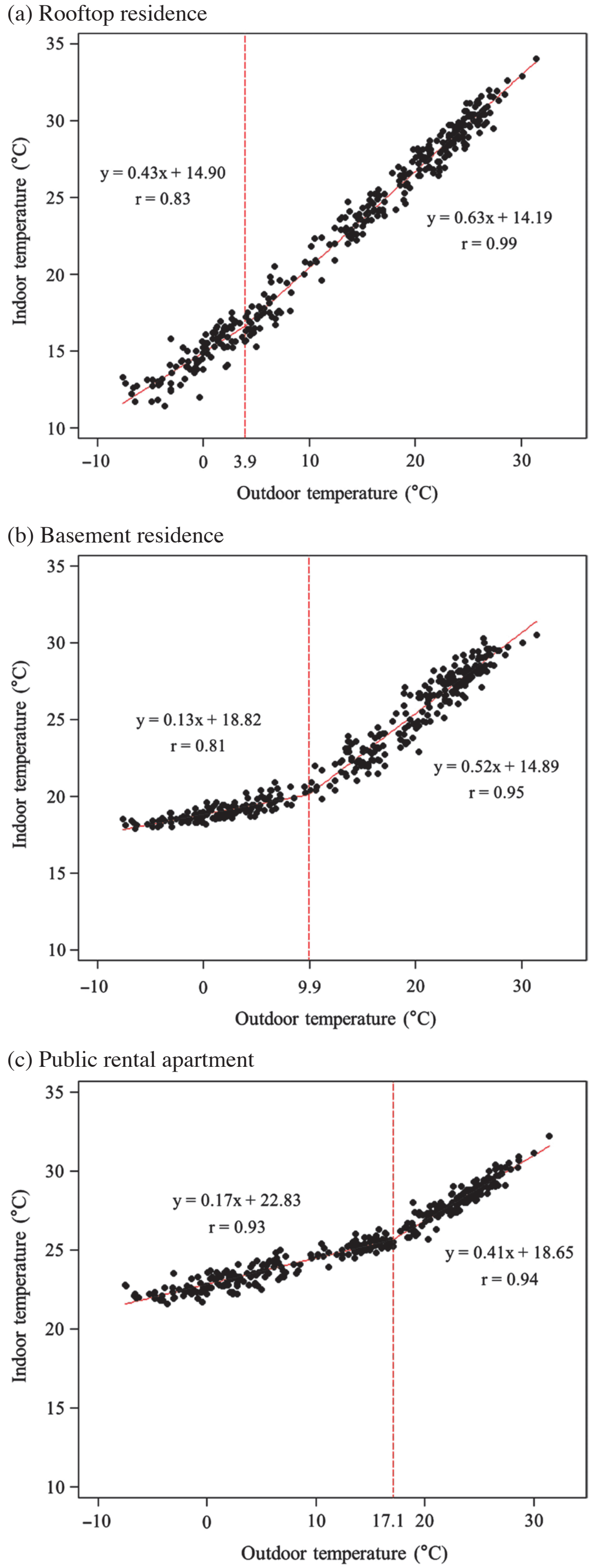

Fig. 3. Determination of the threshold point from the relationship between indoor and outdoor temperatures.

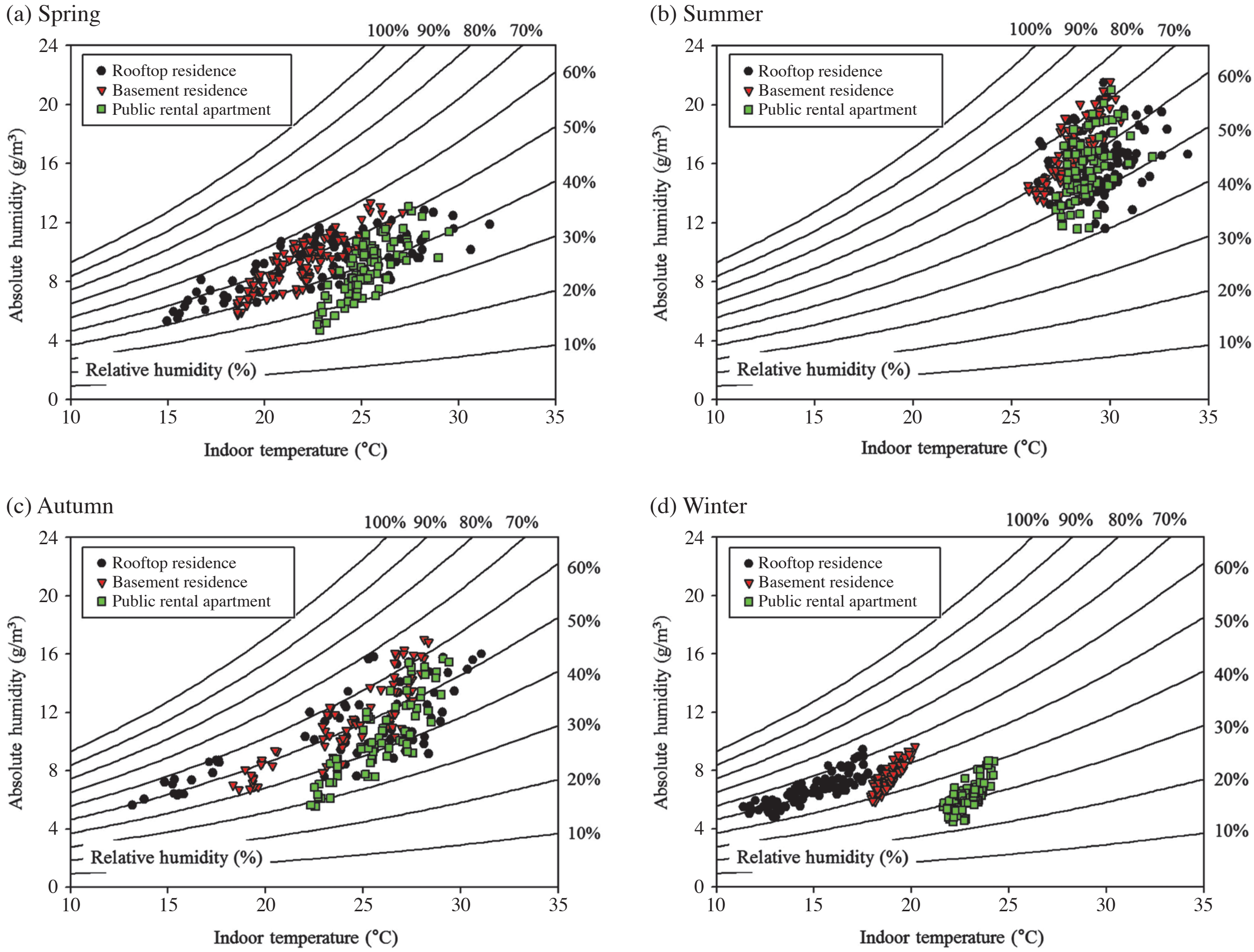

Fig. 4. Correlation between indoor and outdoor temperatures in three types of residence occupied by low-income residents during four seasons.

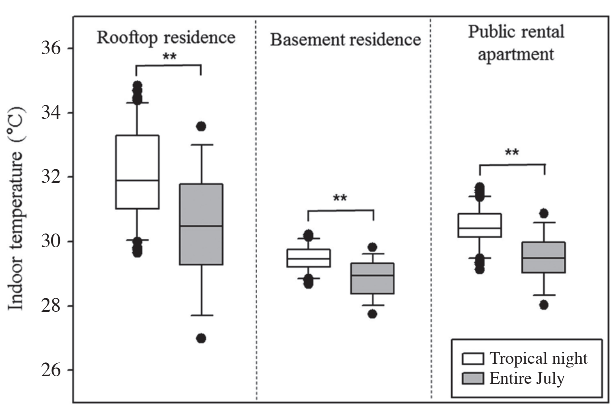

Fig. 5. Variation in the hourly average indoor temperature during three tropical nights in July and during the whole month of July in different types of residence (* $p<0.05$, ** $p<0.0001$).

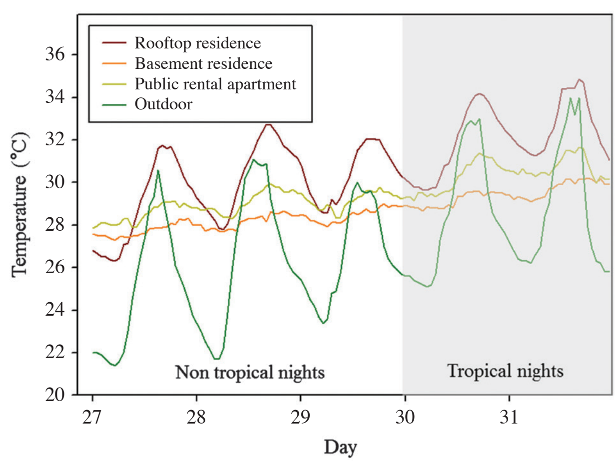

Fig. 6. Temporal profiles of hourly indoor temperature on non-tropical nights and tropical nights in different types of residence.

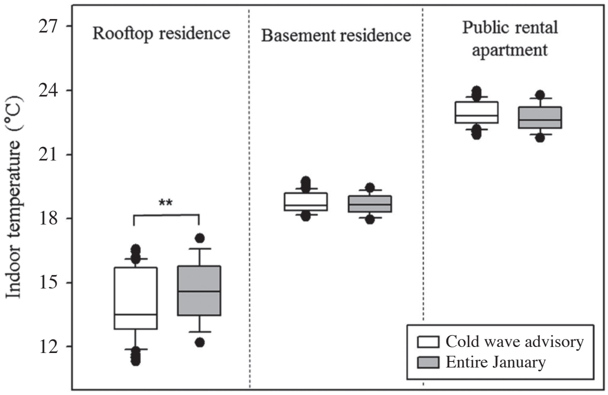

Fig. 7. Variation in the hourly average indoor temperature during cold-wave days (8-10 Jan) and during the whole month of January in different types of residence. (* $p < 0.05$, ** $p < 0.0001$).

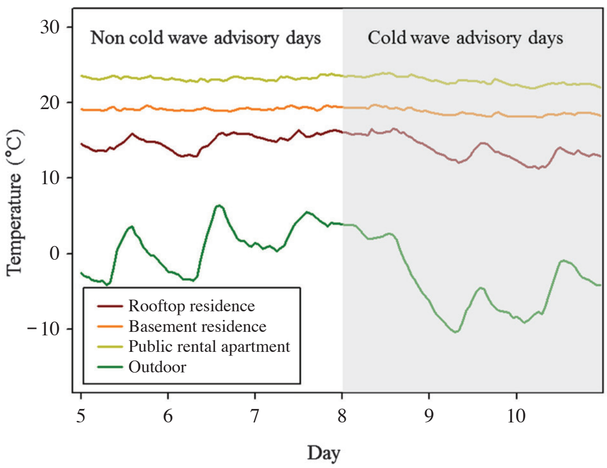

Fig. 8. Temporal profiles of hourly indoor temperature on both non-cold-wave advisory days and cold-wave advisory days in different types of residence.

1.5°C for rooftop residences, 18.7±0.5°C and 18.7±0.5°C for basement residences, and 22.9±0.6°C and 22.7±0.6°C for public rental apartments (Fig. 7).

Fig. 8 shows the hourly average indoor temperatures for 5 consecutive days in January. The first 3 days were not cold-wave advisory days, and the outdoor temperatures were −0.8°C, 0.8°C, and 3.0°C, respectively. The following 3 days were advisory days, with outdoor temperatures of 0.5°C, −7.8°C, and −4.7°C, respectively. The lowest hourly average indoor temperature throughout this study was recorded from rooftop residences, whose temperature showed a pattern similar to the outdoor temperature. In contrast, the indoor temperatures in basement residences and public rental apartments were stable, regardless of the outdoor temperature.

4. DISCUSSION

The percentage of residence with AC units may be associated with residential income. In a previous Korean survey, 67.6% of residences in Korea had AC units (Statistics Korea, 2013). However, only 23.9% had AC units in this study population. The difference by residential income was similar to data reported from Greece, where AC units were installed in 48% of low-income households and 69% of high-income households (Santamouris *et al.*, 2007).

Monthly average temperatures were significantly higher indoors than outdoors, while indoor relative humidity was significantly lower than outdoors. However, monthly average absolute humidity was not significantly different indoors and outdoors. These findings are similar to those of a previous study where indoor temperature, relative humidity, and absolute humidity were measured over a 1-year period in residences in Boston, United States. The daily average indoor temperature and relative humidity were 21.4°C and 46.4% respectively, while the corresponding values outdoors were 13.1°C and 64.8%. However, daily average indoor and outdoor absolute humidity were 8.9 and 8.2 g/m^3 (Nguyen *et al.*, 2014). In two types of middle-income residence (apartment and detached house) in Korea, indoor temperature and relative humidity were measured over a year (Yeom *et al.*, 2014). The ranges of monthly average indoor temperature were from 22.3 to 29.3°C for apartments and from 20.3 to 30.1°C for detached houses. The lowest monthly averages of indoor temperature were higher than the low income residences in this study. It might indicate that people in middle-income residences used heating system more frequently than low-income residences.

The values of all parameters differed among the three types of residence, particularly during summer and winter. Among residences, the indoor temperatures in rooftop residences were the highest during the summer and the lowest during the winter. Because such homes are located on the tops of buildings, they are more affected by outdoor conditions. Moreover, poor insulation or construction material of building envelopes may also influence the indoor temperature in such houses (Santamouris *et al.*, 2014, 2007). The indoor relative humidity and absolute humidity in basement residences were highest during the summer. Because basement residences are located underground, they have limited sunlight and ventilation. The indoor temperatures in public rental apartments were higher than in the other types of residence during months when heating was required. The relative humidity in such apartments was lowest during these same heating months.

Differences in indoor temperature and relative humidity in the three types of low-income residences may be due to the type of residence, ventilation, and heating and cooling systems in place. When indoor temperatures were measured over a 1-year period in four types of residence in the United Kingdom, the indoor temperature of terraced houses was lower than that of the other residences investigated (Yohanis and Mondol, 2010). Ventilation may have a greater effect on indoor temperature and humidity than a house's building materials (Kalamees *et al*., 2009). For example, the ventilation rate was significantly higher in multifamily houses than in detached houses in both Norwegian and Swedish studies (Bornehag *et al*., 2005; Øie *et al*., 1998). Studies to determine the ventilation rate in various types of residence in Korea are needed.

The heating systems in rooftop residences, basement residences, and public rental apartments might be used when the outdoor temperature was below 3.9°C, 9.9°C, and 17.1°C, respectively. In a previous study on the general population in Korea, the heating point was determined to be 15°C (Yeom *et al*., 2014), which is higher than in rooftop and basement residences in this study. The findings of this and previous studies demonstrated that low-income residences might be vulnerable to cold conditions. The reason why the heating point in public rental apartments was highest of the three types of residence was that 10 of the 18 public rental apartments used a central heating system. Similar results were observed in China. When measurements were made in nine cities in China during a short period, high indoor temperatures were observed in households using a central heating system (Zhang and Yoshino, 2010). However, cooling threshold was not found in this study. Since people living in low-income-residences did not use AC units during summer, the correlation between indoor and outdoor temperatures were not significantly changed. It demonstrated people living in low-income residences could not control indoor temperature during summer.

In a previous Korean study, it was reported that people turned on their AC units when the indoor temperature was 30°C and turned the units off at 26.9°C (Bae and Chun, 2009). In 2005, the Japanese government recommended an AC unit start up temperature of 28°C until the beginning of September (Roaf *et al*., 2010). However, in this study, the indoor temperature in rooftop residences continuously exceeded 30°C during tropical nights. People living in rooftop residences did not have or operate AC units during the study period. Moreover, living in a poor-quality house with a low residential income can increase the likelihood of experiencing adverse indoor environmental conditions that cause health issues during hot summers (Conti *et al*., 2007; Haines *et al*., 2006).

In this study, hourly average indoor temperatures in rooftop residences were significantly different between winter and cold-wave advisory days. Furthermore, the pattern of hourly average indoor temperatures in rooftop residences was similar to the hourly outdoor temperature pattern during the winter, including cold-wave advisory days. This indicates that people living in rooftop residences did not operate heating systems over the course of the whole winter. A study conducted in low-income residences in Greece also found large differences between indoor temperatures during the winter; on very cold days there were high levels of variation in indoor temperatures (Santamouris *et al*., 2014). People living in low-income residences have an increased likelihood of experiencing adverse indoor environmental conditions that cause health issues during cold winters (Santamouris *et al*., 2014; Eurofound, 2003).

This study has a few limitations. This study was conducted in small number of each type of residences. When this study was designed, more than 60 residences (20 rooftop residences, 20 basement residences, and 20 public rental apartments) were expected to participate. However, many occupants in low-income residences were reluctant to show their poor living conditions to researchers. And some participants moved during the study period. Therefore, we were unable to recruit the expected number of residences. Two slightly different data logger models (UX-100 and U10, Onset, Cape Cod, MA, USA) were used. Since they have slightly different accuracies, use of different models may cause some potential bias. However, use of the two models was evenly distributed to three types of residences. Thirty nine UX-100-003 data logger models (9 rooftop residences, 15 basement residences, and 15 public rental apartments) and Seven U10 data logger models (3 rooftop residences, a basement residence, and 3 public rental apartments) were used in this study. Although the manufacturer did not provide accuracy in RH below 25%, actual measurements in winter were often below 25% (KMA, 2015). The data in such dry condition may not be accurate. It should be noted that many low income residences can be suffered from very dry conditions in winter.

This study could not evaluate effects of heating system, cooling system and age of residence to indoor temperature and humidity. In order to determine the effect of heating and cooling systems, energy use information is needed. Although presence of heating and cooling systems and age of residence were collected, people living in low-income residents did not want to provide information. Since they usually rented their residences, some of them did not know the exact age of residence. In future study, data of heating and cooling systems usage should be collected continuously.

5. CONCLUSION

Indoor temperature and relative humidity differ by type of residence in low-income residences in Seoul, Korea. In rooftop residences, the indoor temperature is highest during summer and lowest during winter, with a high level of variation. In the basement residences, the indoor humidity is the highest during summer. In the public rental apartment, the indoor relative humidity is the lowest during winter. The residents of low-income residences in this study were unable to control their indoor temperature and humidity during the summer and winter. Therefore, people living in low-income residences could be at risk from extreme hot and cold conditions. The results highlight the urgent need for improved management of indoor temperature and humidity in low-income residences throughout the year.

AUTHORS' CONTRIBUTION

All authors contributed equally in the preparation of this manuscript.

DECLARATION OF CONFLICTING INTERESTS

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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