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Published in:
E3S Web of Conferences

DOI:
10.1051/e3sconf/202567201050

Published: 01/01/2025

Document Version
Publisher's PDF, also known as Version of record

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Please cite the original version:
Velashjerdi Farahani, A., Jokisalo, J., & Kosonen, R. (2025). Correlation between indoor and outdoor temperatures during hot summers in Finnish residential buildings. *E3S Web of Conferences*, *672*, Article 01050. https://doi.org/10.1051/e3sconf/202567201050

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Correlation between indoor and outdoor temperatures during hot summers in Finnish residential buildings

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Abstract. As climate change intensifies, heatwaves' impact on residential buildings becomes increasingly significant. This study aims to analyze the overheating risks in Finnish apartment building stock and explore the relationship between indoor and outdoor temperatures during the hot summer of 2021. Through a comprehensive field study in more than 6,000 apartments, the research examined the indoor temperature variations in Finnish apartment building stock during the hot summer of 2021. The findings revealed that almost 50% of the apartments experienced indoor temperatures exceeding 27°C for seven consecutive days. Moreover, the daily average temperature was higher than 27°C when the outdoor average temperature was higher than 21°C. There was a strong correlation between indoor daily maximum or average temperatures and the outdoor 5-day sliding average during short heatwaves. Notably, this correlation weakened in the face of longer heatwaves. This shows the effects of thermal mass in buildings giving occupants time to take proactive actions against heatwaves. The study highlights the increasing impact of heatwaves on Finnish residential buildings that should be considered in the design phase.

1 Introduction

Climate change is evident in the rising global ambient temperature, with Northern countries experiencing a rate about twice as high as the global average increase [1]. This trend is linked to the more frequent occurrence of hot summers and heatwaves [2]. Notably, Finland has witnessed four hot summers in 2010, 2014, 2018, and 2021 [3] during the last decade. A recent study in more than 6000 apartments in Finland showed that the average indoor temperature was higher than 27°C in almost all the apartments and higher than 30°C in one-third of them during the hot summer of 2021 [4].
Because of these changes, there is a growing concern about indoor overheating in non-mechanically cooled apartments in Nordic countries. On the other hand, some field studies focused on the relationship between indoor climate conditions and outdoor weather conditions [5,6]. Therefore, this study aims to assess overheating risks in the residential building stock and investigate the relationship between indoor and outdoor temperatures during the hot summer of 2021.

2 Methods

2.1 Data collection

Data on room air temperatures in apartment buildings was collected in Helsinki, Finland. The data included information on the design year, area, and number of rooms for each apartment. Hourly measurements were taken from mid-May to the end of August 2021 in a total of more than 10000 apartments. To obtain the average room air temperature of each apartment, a temperature sensor was installed in the main corridor of each unit. The measurements were conducted using IoT sensors specifically designed for indoor conditions, capable of measuring temperatures within the range of -40 to +60 °C with an accuracy of ±0.2 °C.

The data analysis was done using Python programming with Jupiter Notebook. The apartments with more than 15% of the time missing data, the apartments with missing data for more than three hours in a row, and the ones with the highest temperature of more than 40 °C and the lowest temperature of less than 18 °C were filtered out. This way, the faults in IoT sensors and the potential unoccupied apartments were avoided to influence the analysis. The apartments with an acceptable amount of data were selected and through linear interpolation and the needed data was processed. Overall, after data cleaning and pre-processing, there were 6057 apartments out of the original 10000, with hourly indoor temperatures from the 15th of May to the 31st of August 2021 in the analysis.

2.2 Buildings' description

The data included information on the design year, area, and number of rooms for each apartment. The apartments were constructed between 1902 and 2016 and had 1 to 6 rooms. The area of these apartments varied from 20 to 232 m^2. Most of the apartments had mechanical ventilation systems. There were no permanently installed cooling devices in the measured apartments. However, there may have been portable cooling devices in the apartments, and occupants may have used openable windows. The shading and orientation of buildings, the exact characteristics of the building envelope, and detailed information on the occupancy were unknown.

2.3 Outdoor weather during the hot summer of 2021

Fig. 1 shows the outdoor daily average, maximum, and minimum temperatures during the summers of 2021. A hot day in Finland is defined as a day with a daily maximum temperature higher than 25°C [3]. Therefore, there were 30 hot days in the summer of 2021, most of them in July (25 days). Moreover, the maximum temperature exceeded 30°C on 7 days. Additionally,

there were 5 days with an average temperature higher than 25°C.
Further, these hot days can be grouped into two heatwaves. One short from 18 to 23 of June, and one long from 3 to 18 of July.

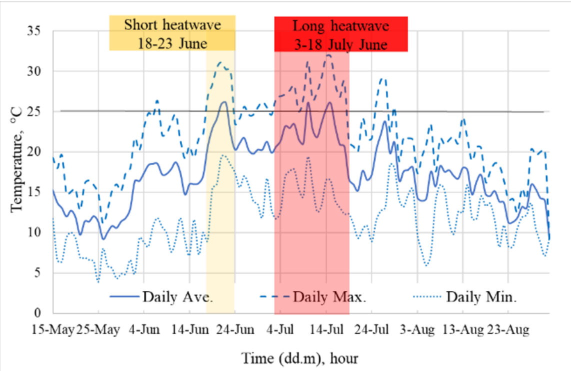

Figure 1. Outdoor temperature during the summer of 2021.

2.4 Indoor temperature assessment criteria

The indoor temperature thresholds used in this study were based on national Finnish building codes and legislations as well as EN standards. Based on the requirements suggested by the Finnish Ministry of the Environment, in the design phase, the maximum allowed design indoor air temperature is 27 °C outside the heating season, and only 150 degree hours above 27 is allowed based on simulation results with Test Reference Year 2012 between June and August [7]. Additionally, 27 □C is the upper limit for thermal comfort, based on class III of the EN Standard 16798 [8]. Based on the requirements of the Finnish Ministry of Health and Social Affairs, in the occupied apartments, the upper limit for the indoor air temperature of 32 °C, is used concerning the health and well-being in all the living spaces [9]. Notably, the 30 □C aligns with the action limit mandated by the Finnish Ministry of Health and Social Affairs for the well-being of elderly people who are cared for [9].

3 Results

3.1 Overheating assessment in the apartments

Analysis showed long-term exposure to overheating in the apartments. Table 1 displays the percentage of apartments where indoor temperatures consistently exceeded the thresholds ranging from 27 to 35 □C for certain periods from 1 to 7 days. Indoor temperatures exceeded 27 □C for a continuous period of 7 days in approximately 50% of the apartments.
Furthermore, the data indicated that indoor temperatures consistently surpassed 30 □C in 8% of apartments for 1 day and in 1% of apartments for 7 days. The percentage of apartments with temperatures above 32 □C for 1 to 7 days was below 1%. It is worth mentioning that 1% of apartments is equal to almost 60 apartments.

Table 1. The share of apartments with indoor temperatures consistently higher than the threshold.

Hourly temperature higher than	Percentage (%) of apartments with						
	1 day	2 days	3 days	4 days	5 days	6 days	7 days
27 °C	84.8	77.9	69.8	61.0	55.1	50.0	46.8
28 °C	59.6	48.8	40.2	32.7	26.2	21.5	19.2
29 °C	28.1	20.9	15.8	11.8	8.8	6.2	5.3
30 °C	8.3	5.5	3.9	2.8	1.9	1.5	1.2
31 °C	1.8	1.3	0.9	0.6	0.3	0.2	0.2
32 °C	0.4	0.3	0.2	0.2	0.1	0.1	0.1
33 °C	0.1	0.1	0.1	0.1	0.1	0.0	0.0
34 °C	0.05	0.05	0.05	0.05	0.05	0.0	0.0
35 °C	0.05	0.03	0.03	0.03	0.03	0.0	0.0

3.2 Indoor temperature variation based on outdoor daily average temperatures

The evaluation of indoor overheating indicated a significant exposure to heat stress in apartments. Solar radiation, outdoor temperature, and internal heat gains can affect indoor temperature and overheating but outdoor temperature is typically related to health risks for vulnerable people. Thus, it is crucial to delve into analyses regarding the impact of outdoor temperatures on indoor conditions. Fig. 2 illustrates the daily average indoor temperatures in the apartments based on the daily average outdoor temperatures during the summer.
As can be seen, when the outdoor daily average temperature reached 21 °C, the mean value of the indoor daily average temperatures was 27 °C. Therefore, during the heatwaves when the outdoor daily average temperature was always above 21 °C (see Fig. 1), a large number of apartments faced average temperatures higher than 27 °C.
Moreover, the outdoor daily average temperature of 26 °C caused the maximum value of indoor daily average temperatures to be higher than 30 °C. Although the period with the outdoor daily average temperature over 26 °C is relatively short (just 5 days), indoor temperatures over 30 °C are crucial from the health point of view for elderly occupants.

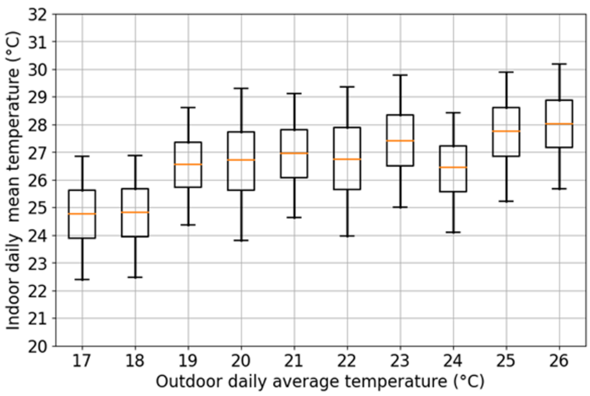

Figure 2. Indoor daily average temperatures versus outdoor daily average temperatures. (Orange lines show the mean values.)

On the other hand, Fig. 3 shows the daily maximum indoor temperatures in the apartments based on the daily average outdoor temperatures during the summer. The outdoor average temperature of 19 °C caused the mean value of indoor maximum temperatures to reach 27 °C. Based on the data in Fig. 1, this can happen even during the cool part of the summer.

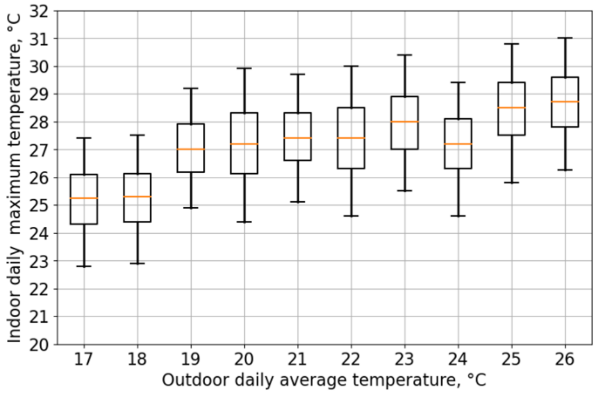

Figure 3. Indoor daily maximum temperatures versus outdoor daily average temperatures. (Orange lines show the mean values.)

3.3 Correlation between indoor and outdoor temperatures

Based on the results, there was a strong linear regression between the indoor daily average temperature and the outdoor average temperature in each apartment during the whole summer, and the heatwaves. To analyze the effects of the thermal mass of the buildings and the time lag of the apartments to react to the outdoor temperature, different sliding averages of the outdoor temperature were calculated: Daily average, and 2 to 9-day sliding averages. It is worth mentioning that this time lag is a factor affected by solar radiation and internal heat gains as well. Fig. 4 shows the variation of Pearson correlation coefficients in the apartments for the whole summer. As the figure shows, although the correlation coefficients are still high between the daily average temperature and indoor daily average temperature, the strongest correlations are between the 5-day sliding average temperatures and indoor daily average temperatures. This shows the effects of weather history and the building's thermal mass on overheating.

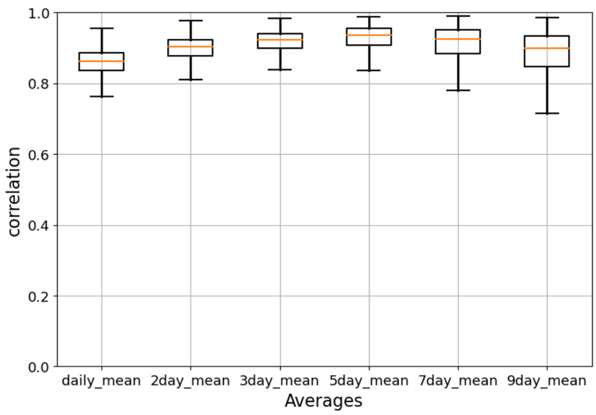

Figure 4. The variation of Pearson correlation coefficients between the different outdoor sliding averages and the indoor daily average temperatures in the apartments for the whole summer.

Fig. 5 shows the variation of Pearson correlation coefficients in the apartments for the short and long heatwaves. During the heatwaves, the correlation between the outdoor daily average temperature and the indoor daily average temperature is weaker than during the summer. However, the strongest correlations are between the 5-day sliding average temperatures and indoor daily average temperatures.

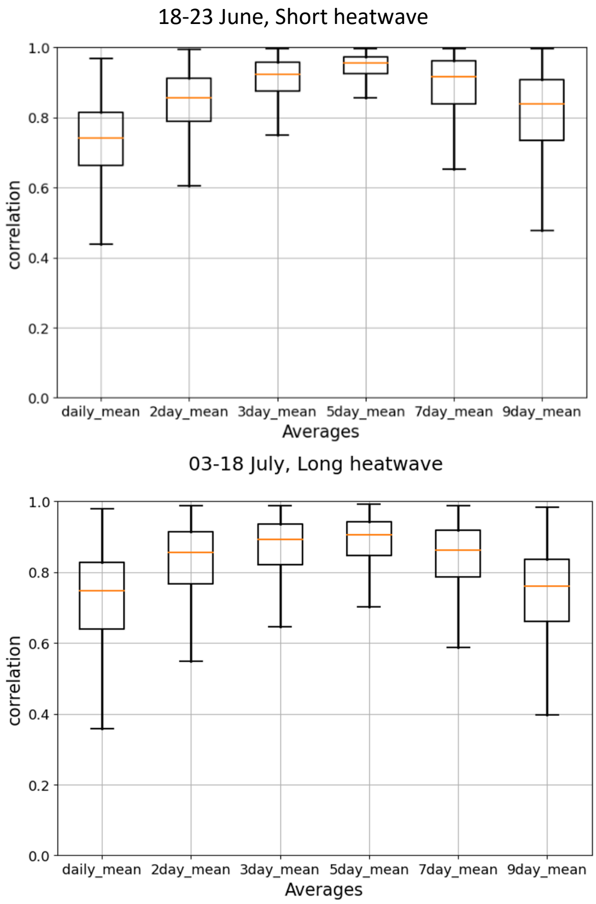

Figure 5. The variation of Pearson correlation coefficients between the different outdoor sliding averages and the indoor daily average temperatures in the apartments for the heatwaves.

Moreover, comparing Fig. 4 and Fig. 5 shows that the correlation was weaker during the heatwaves than during the whole summer. It was weaker during the long heatwave than during the short one. It can reinforce the hypothesis that apartments exhibit a gradual response to high outdoor temperatures, requiring more time for the indoor temperature to reach its peak.

4 Conclusions

This study highlights the escalating significance of heatwaves on residential buildings in Finland, particularly in the context of climate change. The thorough analysis of over 6,000 apartments during the hot summer of 2021 illuminates a concerning trend, with nearly half of the examined residences experiencing indoor temperatures surpassing 27°C for an extended period.

However, it is crucial to understand the potential divergence between these measured conditions and the actual thermal comfort experiences of the residents, highlighting the subjective nature of thermal comfort. The strong correlation observed between indoor and outdoor average temperatures underscores the vulnerability of these buildings to external climate factors. However, the results showed that the strongest correlations were between the outdoor 5-day sliding average and the indoor daily average temperature. This shows the effect of thermal mass and weather history on the indoor overheating issue.

Notably, the weakening correlation during prolonged heatwaves signals a time lag between indoor and outdoor temperatures to reach their peaks providing occupants with an opportunity to take proactive measures to alleviate overheating.

As climate change continues to intensify, these findings emphasize the urgent need for adaptive strategies in building design, construction, and urban planning to mitigate the adverse impacts of hot summers and heatwaves on the well-being of residents and the resilience of housing infrastructure.

Acknowledgments This study is part of the following project: HEATCLIM (Heat and health in the changing climate, Grant Numbers. 329306, 329307) funded by the Academy of Finland within the CLIHE (Climate change and health) program.

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