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Research article

Thermal insulation impact on overheating vulnerability reduction in Mediterranean dwellings

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A R T I C L E I N F O

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A B S T R A C T

Heat waves are expected to increase the use of air conditioning (AC), deriving in higher energy consumption. This research aims to determine whether thermal insulation is an effective retrofit strategy for tackling overheating. Four occupied dwellings in southern Spain were monitored: two houses built prior to any thermal criteria and two with current thermal standards. Thermal comfort is assessed considering adaptive models and user patterns for the operation of AC and natural ventilation. Results show that a high level of insulation combined with a proper use of night-time natural ventilation can increase thermal comfort hours under heat waves, lasting 2–5 times longer than in poorly-insulated houses and with up to 2 °C temperature difference at nights. Long-term effectiveness of insulation under extreme heat presents a better thermal performance, especially in intermediate floors. Yet, the activation of AC usually occurs with indoor temperatures of 27–31 °C, regardless of the envelope's solution.

1. Introduction

It is generally believed that in the coming decades global warming will derive in more extreme weather events [1]. In southern Europe, the consequences of climate change will include heat events of an increased frequency, magnitude and duration, with a 5 to 10 factor increased probability of severe heatwaves in a 40-year projection [2]. In fact, southern Europe is considered to be more vulnerable to global warming than northern regions [3], with the Mediterranean basin suffering more than other areas [4].

Several studies have demonstrated that extremely hot weather conditions will have adverse impacts on global environmental quality and health conditions, even increasing mortality ratios [5]. In fact, a 1 °C increase in maximum outdoor temperature above 29.4 °C increases mortality risk by 3% in the Mediterranean region [6]. In developed regions, between 25 and 40% of carbon dioxide emissions due to energy-related anthropogenic activities are caused by buildings [7]. In this sector, climate change will noticeably deteriorate indoor ambient and thermal comfort conditions [8], paying particular attention to night-time hot periods [9]. Hence, promoting energy efficiency in buildings is key to achieving a low-carbon economy and mitigating the effects of climate change [10], which will lead to both decreased heating energy demand and increased cooling needs in the Mediterranean area, as some studies have

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found [11].

This increase in temperatures will lead to householders choosing to install air conditioning (AC) devices to counter global warming [12]. However, as most of the existing residential buildings were built prior to thermal criteria regulations [13], the dwellings which are most vulnerable in energy and thermal terms may be unable to cover the increasingly high energy costs. This in turn would lead to fuel poverty [14], which is currently estimated around 32.1–43.8% in Spain [15], primarily due to the fact that vulnerable homes require energy consumption above the average in order to satisfy their energy needs [16]. Moreover, a temperature rise of 1.1 °C in summer increases electricity consumption by almost 2% in Spain [17]. Thus, vulnerable householders living in low thermal quality dwellings and under low environmental standards are seriously at risk of overheating.

To improve energy efficiency in buildings and achieve adequate indoor environmental conditions under heat waves and future climate change scenarios, several mitigation and adaptive technologies could be implemented. However, given the low resources of householders [18] and the existence of public stakeholders' retrofit programmes [19] passive solutions are normally adopted in Mediterranean vulnerable dwellings.

In existing buildings, the retrofit actions currently being promoted to confront the temperature increase mainly focus on improving thermal response and air-tightness [20]. In other words, the thermal resistance and capacity of buildings are being improved. In the Mediterranean region specifically the most common passive retrofit strategies include replacing windows with ones with higher energy efficiency and adding thermal insulation to walls, roof and floors [21]. Other effective techniques to combat overheating during heat waves are modifications in solar short-wave reflective properties of external layers of the envelope and the incorporation of solar radiation shading systems or natural ventilation. Furthermore, vulnerability to high temperatures in residential buildings is reduced through the implementation of efficient mechanical ventilation systems, which play a major role in overheating reduction [22], despite being a significant invasive action.

For instance, Porrit et al. [23] found that coating vertical envelopes with high performance solar reflective paint was a noticeably efficient measure to reduce the number of degree hours over 26 °C during heat waves by 50–60%. Lassandro and Di Turi [24] assessed several façade retrofitting solutions (external insulation, phase change materials, green wall) for reducing climate change effects during summer in the Mediterranean summer climate. These authors reported a reduction in indoor operative temperatures of around 1.63%, 1.67% and 2.54% respectively for the aforementioned façades. De Masi et al. [25] analysed the influence of window replacement, thermal insulation in walls, green roof and external shading systems applied to a residential building in Benevento (Italy) under projections of climate change. According to these authors, considering only the first two retrofit solutions did not provide resilience, but including the remaining solutions resulted in a cooling demand reduction of up to 33% in some climate scenarios. Simões et al. [26] evaluated the impact on heating and cooling demand of Trombe walls combined with shading devices in Mediterranean residential buildings, stating that for southern locations the combination of these solutions with night-time ventilation reduced cooling demands by 35%.

Despite the high costs, passive cooling through cool and green roofs and façades also result in significant improvements in the energy performance of Mediterranean buildings. Zinzi and Agnoli [27] carried out a comparative analysis of the performance of cool and green roofs in residential buildings to mitigate extremely hot temperatures, assessing several parameters that affect final energy performance. In a subsequent study, Zinzi [28] evaluated the potential of cool façades for energy performance and indoor thermal comfort, reporting an average indoor temperature reduction of up to 1.1 °C in cool-façade buildings during summer. Fokaidesa et al. [29] monitored a highly-insulated passive house in Cyprus and established that night-time natural ventilation allowed a reduction of 1.4 °C in indoor air temperatures. Similarly, Santamouris et al. [30] studied the impact of natural ventilation on the cooling needs of approximately 200 dwellings in Greece under high outdoor temperatures and concluded that the benefits of night-time ventilation increase depending on cooling demand. The study of a super-insulated residential building in Italy by Stazi et al. [31] showed that combining envelopes with no inner mass and mechanical ventilation with free-cooling reduced overheating and decreased discomfort hours by 6%. Van Hoff et al. [32] recommend the application of green roofs as a solution for decreasing overheating hours or promoting natural ventilation below a certain indoor-outdoor temperature threshold. However, these authors also suggested implementing natural ventilation and installing building shading systems in well-insulated houses, since an inadequate increase in thermal resistance in the envelope can also lead to higher numbers of overheating hours. The same conclusion was reached by Masoso and Grobler [33] when varying the wall insulation thickness and cooling-set point temperature of a building located in Botswana, a region with a hot climate.

Furthermore, occupancy and operation patterns have a measurable influence on thermal discomfort, along with the subsequent health risks of exposure to high indoor temperatures [34]. Research in the Mediterranean context considering the role of occupants and their thermal adaptability [35] through the free operation of natural ventilation systems is still limited [20]. Most of the research conducted so far has revolved around the impact of climate change on energy-related aspects and subsequent carbon dioxide emissions [36], with less consideration given to thermal comfort in vulnerable dwellings which cannot financially afford the continuous use of active systems [11]. Central European models tend to neutralize to the maximum heat exchange with outdoor environments, under a conception of static thermal analysis, where thermal comfort is managed through seasonal cycle strategies. On the contrary, in the Mediterranean area, where dwellings normally lack thermal building systems and, thus, their energy consumption is quite low, thermal analysis considers daily variations on the thermal flow. The regulation of these variations usually corresponds mainly to users, rather than to constructive robustness of the thermal envelope. And, thus, depends on the level of tolerance and socio-cultural conditions [37].

In this line, this paper presents an assessment of the adaptive thermal comfort vulnerability of dwellings in southern Spain (Mediterranean climate), with the aim of assessing the influence of constructive robustness and users interaction on thermal comfort under overheating episodes and heat wave periods. To do so, four dwellings are used as case studies and monitored with high resolution equipment to obtain on-site measurements for several environmental and energy data. Unlike other studies carried out so far, in this research the dwellings are simultaneously compared under the same outdoor weather conditions, evaluating two well-insulated dwellings, built after the implementation of the current thermal and energy criteria standards, in comparison with another two dwellings built prior to the establishment of any thermal criteria. The novelty of this study is that the thermal assessment is carried out on a daily basis considering the thermal flow variation due to the users' interaction with the building. Furthermore, thermal comfort conditions are assessed considering an updated adaptive thermal model (applicable to hot summer climates), also assessing the operation of natural ventilation through windows and the activation of cooling systems. Additionally, in contrast to similar studies, as this is a long-term monitoring campaign, this work examines the environmental performance of these case studies during the recent heat wave experienced in the city of Seville in June 2022, with maximum outdoor air temperatures of 43 °C.

This research is structured in four sections. Section 1 resumes the Introduction. Section 2 describes the weather conditions and case study considered, as well as the monitoring system and the calculation method and parameters. The analysis and discussion of results are included in section 3. Finally, the last section, presents the main conclusions of this work.

2. Materials and methods

The methodology followed in this research consists of on-site monitoring of four dwellings located in Seville in southern Spain (Mediterranean climate) in order to conduct a descriptive statistical analysis of their indoor thermal performance, adaptive thermal comfort and intensity of use of cooling systems during hot summer periods. The four case studies are simultaneously compared under the same outdoor weather conditions during a summer month (1 to 31 August 2021), as well as during an extreme heat wave period (6 to 19 June 2022), on an hourly basis, including both occupied and unoccupied days. Specifically, two out of the four dwellings were built prior to the first energy standard establishing thermal criteria for buildings (NBE CT-79) [38] and are compared with the remaining two dwellings, built after the implementation of the current Spanish Building Technical Code (CTE) [39] which set out stricter thermal criteria.

2.1. Climatic conditions

All the dwellings monitored are located in Seville (37° 23′ N, 5° 58' W), a city with a Mediterranean climate (Csa) according to the updated Köppen classification [40]. Fig. 1 shows the average monthly temperature of Seville, as well as the maximum and minimum average daily temperatures for the whole year [41]. The average annual temperature is close to 20 °C and the average summer temperature is approximately of 30 °C. It can be observed that the average minimum daily temperature is 13 °C and average maximum temperatures are close to 25 °C. Relative humidity is also included in the graph, being generally between 40 and 75%, with average annual values of 59%. Also, the average annual rainfall is 539 mm and the average number of hours of sunshine per month is 243. In other words, Seville has a Mediterranean climate, with mild winters and dry and warm summers.

For the assessment of ambient and thermal conditions in each dwelling during hot summers, two periods are monitored. Firstly, measurements are recorded during a summer month in southern Spain, 01 to 31 August 2021, in an hourly resolution. Then, a specific heat wave period, 06 to 19 June 2022, is assessed in detail, also on an hourly basis. The main thermal characteristics of each period analysed are summarized in Table 1, indicating the average (T_{avg}), maximum (T_{max}) and minimum (T_{min}) outdoor temperatures, both during daytime (8:00–22:00) and night-time (22:00–8:00).

2.2. Case studies

The location of the sampling dwellings which have been monitored is represented in Fig. 2. Dwellings 1 and 2 (D01 and D02) are located in the northeast of the city, in the surrounding area and at 7 km distance from the city centre. Dwellings 3 and 4 (D03 and D04) are ubicated in the south of the city, also in the surroundings and at 6 km from the city centre. It can be seen that all selected cases are

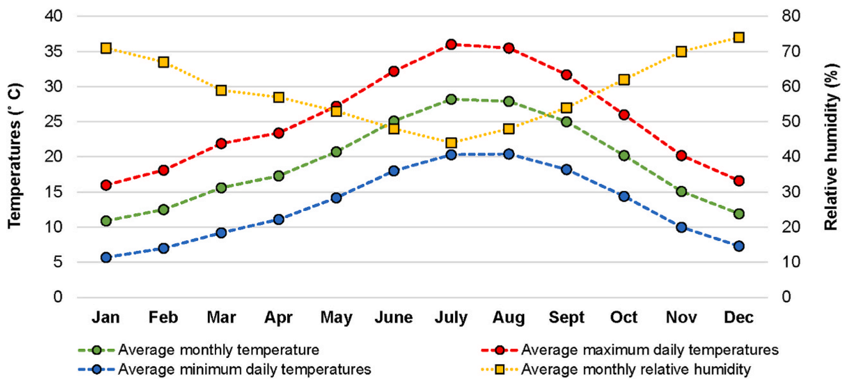


Fig. 1. Main climatic conditions of Seville. Elaboration by the authors based on AEMET's data [41].

Table 1
Main thermal characteristics of the summer periods analysed.

Description	T_{avg} (Daytime)	T_{max} (Daytime)	T_{min} (Daytime)	T_{avg} (Night-time)	T_{max} (Night-time)	T_{min} (Night-time)
01-31/08/2021	32.3	45.3	20.0	25.8	38.3	19.8
06-19/06/2022	33.3	43.0	20.1	26.6	37.2	19.5

Note: Daytime = 8:00 to 22:00; Night-time = 22:00 to 8:00.

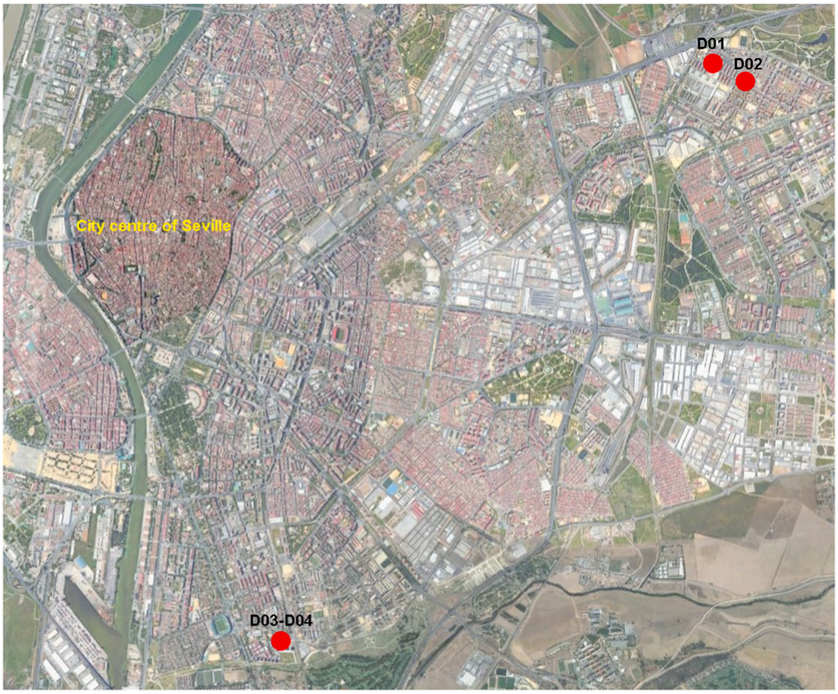


Fig. 2. Location of the monitored dwellings in the city of Seville. Elaboration by the authors. Source image: © google earth.

included in a similar urban area with residential buildings, with analogous planned urban developments and close to extensive urban parks. For this reason, the surrounding environments are considered to be similar.

Fig. 3(a–d) shows the floor plans of the monitored dwellings. Dwelling 1 (D01) is a top-floor flat in an H-block of a residential urban neighbourhood on the northeast side of the city. This flat, built in 1971, has undergone a retrofit process to incorporate thermal insulation, but only in the living room roof. Natural cross-ventilation occurs through single-glazed sliding windows with aluminium frames (no thermal bridge break). The building envelope is a 23 cm brick wall with no air chamber and no thermal insulation. The cooling system consists of two air-conditioner splits, one in the living room and the other in the main bedroom. This flat is occupied by a young couple.

The second case study (D02) is an intermediate floor of a 6-floor H-block, also located in the northeast of Seville. As this block was built in 1972 there is no thermal insulation in the building envelope. The vertical envelope is a 23 cm massive brick wall (no air chamber). Natural cross-ventilation occurs through single-glazed sliding windows with aluminium frames (with thermal bridge break). There is a single split air-conditioner unit installed in the living room. This flat is occupied by a middle-aged couple.

Dwellings 3 and 4 (D03 and D04) are fifth- and top-floor flats, respectively, in a tower block located in the south of the city. As it was built in 2019, the building envelope is well-insulated: 11.5 cm brick wall with 30 mm air chamber and thermal insulation based on 40 mm PUR (polyurethane) + 50 mm MW. Natural cross-ventilation occurs through casement windows with double glazing with chamber (6-12-6) and aluminium frames with thermal bridge break. The cooling system consists of centralized air-conditioning with air ducts throughout the entire flat except for the kitchen and bathrooms. Each of these flats is occupied by a young couple with a baby.

All of the flats have solar radiation shading systems based on external roller blinds, freely controlled by users. None of the dwellings have mechanical ventilation systems.

2.3. Monitoring system

Several air ambient variables and energy aspects were monitored in order to assess the thermal performance and occupation patterns of the dwellings. Indoor air temperature (°C), relative humidity (%) and CO_2 levels (ppm) were measured inside the living

Fig. 3. Floor plans of the four monitored dwellings in Seville: (a) D01, (b) D03, (c) D02 and (d) D04. Sensor locations in the monitored rooms are indicated in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

room and a bedroom of each dwelling at 10-min intervals, which were later averaged to an hourly resolution. The monitoring system installed was the MICA from inBiot solutions, a single smart device that incorporates all the aforementioned sensors. Measurements are stored in the unit and later transferred to a cloud server thanks to its Wi-Fi connectivity, where data can be downloaded into a .csv file. Real-time data can also be visualized through the online platform, easily accessed via any smart device. Likewise, energy consumption due to the air-conditioning cooling systems (kWh) is monitored in the dwellings through the engage hub kit from energy. A sensor and transmitter is installed in the electric panel and connected to the engage hub, so that real-time consumption can be seen through a smart device and consumption reports can be downloaded into a .csv file.

Table 2 shows the main technical characteristics of the sensors used for monitoring the dwellings. Only the living room and the main bedroom of each dwelling were monitored (Fig. 4(a, b)), due to limitations imposed by the users. The location of the sensors in the rooms can be seen in Fig. 3(a–d) above.

Regarding outdoor weather conditions, a local weather station, installed in the vicinity of the buildings, was used to obtain outdoor

Table 2
Main characteristics of the sensors installed in the dwellings.

Sensor description	Location[a]	Model	Measurement rank	Accuracy
Air temperature	D01, D02, D03, D04 (LR, BR)	MICA (inBiot)	0 … +90 °C	±0.5 °C
CO_2 levels	D01, D02, D03, D04 (LR, BR)		0 … 5000 ppm	±(50 + 5.0%) ppm
Relative humidity	D01, D02, D03, D04 (LR, BR)		0 … 100%	±2%
Energy consumption (Air conditioner)	D02, D03, D04	Engage hub kit (efergy)	50 mA-120A/phase	±2%

[a] LR and BR: refers to living room and main bedroom, respectively.

air temperatures (°C), relative humidity (%) and carbon dioxide levels (ppm). The main characteristics of the outdoor sensors are presented in Table 3.

2.4. Assessment of adaptive thermal comfort and indoor air quality

Thermal comfort conditions in the four case studies were analysed through on-site measurements and according to the updated adaptive thermal comfort model proposed by Barbadilla et al. [42]. This model is based on the adaptive model established in EN 16798-1:2019 [43], which is applicable to buildings under free-running conditions (no HVAC systems), with low metabolic rates and where users can freely control window operation and modify clothing levels. The EN 16798-1:2019 model considers a metabolic rate of 1.0–1.3 met and a thermal resistance of 0.5 clo and 1.0 clo in summer and winter, respectively. The adaptive thermal comfort temperature (T_c) is calculated from the running mean dry outdoor temperature for today (T_o), which depends on the daily mean dry outdoor temperature for the previous 1–7 days (T_{o1}–T_{o7}) (Equations (1) and (2)). For a normal level of expectations with a PPD < 10%, the adaptive comfort band is set at +3 °C and −4 °C (upper and lower comfort limits from the T_{com}).

$$T_c = 0.33 \times T_o + 18.8, \tag{1}$$

$$T_o = (T_{o1} + 0.8\ T_{o2} + 0.6\ T_{o3} + 0.5\ T_{o4} + 0.4\ T_{o5} + 0.3\ T_{o6} + 0.2\ T_{o7})/3.8, \tag{2}$$

However, this model can only be applied if outdoor running temperatures are between 10 °C and 30 °C. Thus, Barbadilla et al. [42] proposed an alternative adaptive thermal model for hybrid buildings, that is to say, buildings with intermittent use of air conditioning (AC) systems and natural ventilation through windows, and located in the Mediterranean climate. In this study, the adaptive thermal comfort temperature (T_{cb}) is obtained from Equation (3):

$$T_{cb} = 0.24 \times T_o + 19.3, \tag{3}$$

In this research, the adaptive mixed mode thermal comfort with a temperature interval of ±2.5 °C and 90% of satisfied occupants (PPD <10%) has been considered. The reason for this is that the mixed mode presents better suitability for evaluating thermal comfort in hot summer climates in southern Spain, according to previous research conducted in the Mediterranean area [44]. The aforementioned research concluded that directly using the EN 16798-1:2019 in hot Mediterranean climates would imply comfort conditions with indoor temperatures above 31 °C, which does not represent real perception of users.

3. Results

Firstly, in Figs. 5–8, the hourly evolution of the air temperature has been analysed for all four case studies (D01-D04), focusing on the June 2022 heat wave. The periods in which indoor temperature is outside the comfort band (labelled as ‘discomfort’), the AC system is switched on, or the windows are open for natural ventilation have been marked. The periods in which the dwellings are unoccupied and thermal comfort has not been evaluated have also been indicated.

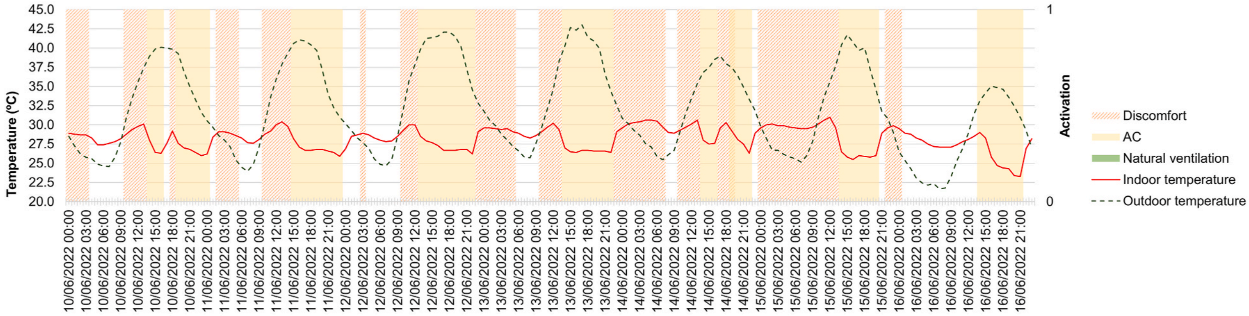
3.1. User patterns: activation of the AC system and operation of natural ventilation

In dwelling 1 (D01, Fig. 5(a, b)), there is intensive use of the AC system in the living room during the day (between 1 and 10 p.m.), with a set point temperature of approximately 26 °C. However, the use of the AC in the bedroom is much more occasional (only on the two hottest days of the heat wave), for a couple of hours before going to sleep. With this sporadic use, a very occasional drop in indoor temperature is achieved. Therefore, as soon as the AC is turned off, the bedroom is back in discomfort conditions. In dwelling 2 (D02, Fig. 6(a, b)), the use of the AC system in the living room almost only occurs on the days that the heat wave coincides with the weekend

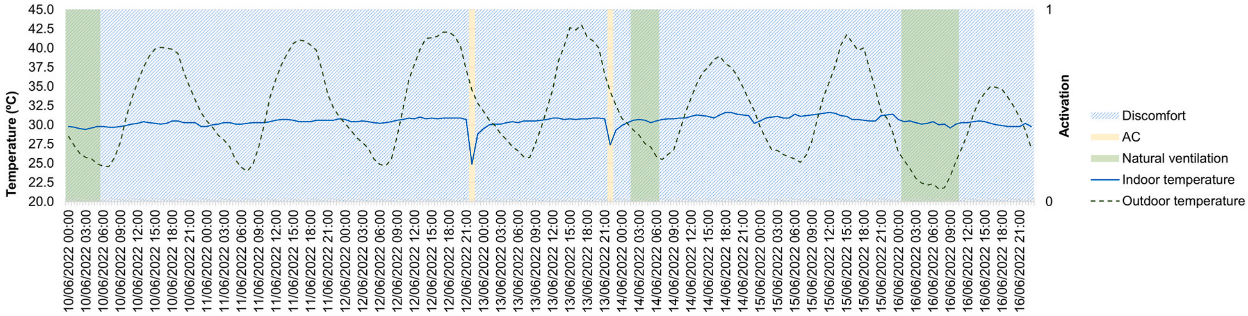
Fig. 4. Sensors installed in the dwellings for monitoring indoor air ambient variables. Example in: (a) living room and (b) bedroom of dwelling 3 (D03).

Table 3
Main characteristics of the outdoor sensors located in a local weather station.

Type of sensor	Model	Measurement range	Accuracy
Air temperature (AT) and relative humidity (RH)	Vaisala HMP110	From −40 to +60 °C From 0 to 100%	±0.5 °C (from +10 to +30 °C) ±0.6 °C (from −40 to +60 °C) ±3% (from 0 to 90%) ±5% (from 90 to 100%)
CO_2 levels	Vaisala GMP222	From 0 to 5000 ppm	±2.0%



(a)



(b)

Fig. 5. Hourly evolution of indoor air temperature, outdoor air temperature, discomfort, AC use, and natural ventilation in dwelling 1 (D01): (a) living room and (b) bedroom.

(higher occupancy in the dwelling), during the central hours of the day (between 1 and 9 p.m.), with a variable set point temperature between 25 and 26 °C. In this case, there is no AC system in the bedroom. In dwelling 3 (D03, Fig. 7(a, b)), occasional use of the centralized AC system is observed, during afternoon time slots (between 2 and 3 p.m., or 4 and 7 p.m.), with a set point temperature of approximately 25.5 °C. In dwelling 4 (D04, Fig. 8(a, b)), a smart system with independent thermostats for each room is installed. This central system analyses the information, establishes the working point of the production equipment and regulates the emission equipment, starting it up automatically to reach the ideal temperature for each room. For this reason, a repetitive pattern in the use of the AC system in the living room is not detected, with intermittent power cycles that sometimes last only a couple of hours. AC use in the bedroom is more sporadic. The set temperature is also variable, between 23 and 25 °C in the living room and 26.5–27.5 °C in the bedroom.

Regarding night-time natural ventilation, in D01 (Fig. 5(a, b)) it is not frequent during the heat wave, even though outdoor temperatures are lower than indoor ones. The windows are only open on nights when the outdoor temperature falls below 24 °C, but the ventilation rate is insufficient to dissipate the heat and make indoor temperatures fall to the level of outdoor ones. In D02 (Fig. 6b), a repetitive pattern for night-time natural ventilation is detected in the bedroom, resulting in a reduction of up to 1.5 °C in indoor temperatures. However, during the hottest days of the heat wave, the ventilation rate is insufficient to ensure comfort conditions. In D03 (Fig. 7(a, b)), where night-time natural ventilation is also frequent, the rate in the bedroom is even lower than in D02, because the window was open but the roller blind was 90% closed, causing almost imperceptible variations in indoor temperature. In the living room, the size of the windows and the opening of the roller blinds result in higher ventilation rates that make indoor temperatures fall closer to outdoor ones. In D04 (Fig. 8(a, b)), natural night-time ventilation is also frequent, except for the day with the highest night-time outdoor temperature, when the AC is switched on before going to sleep and the windows are kept closed. As in the other cases, the ventilation rate is not high enough to ensure indoor minimum temperatures are close to the outdoor ones.

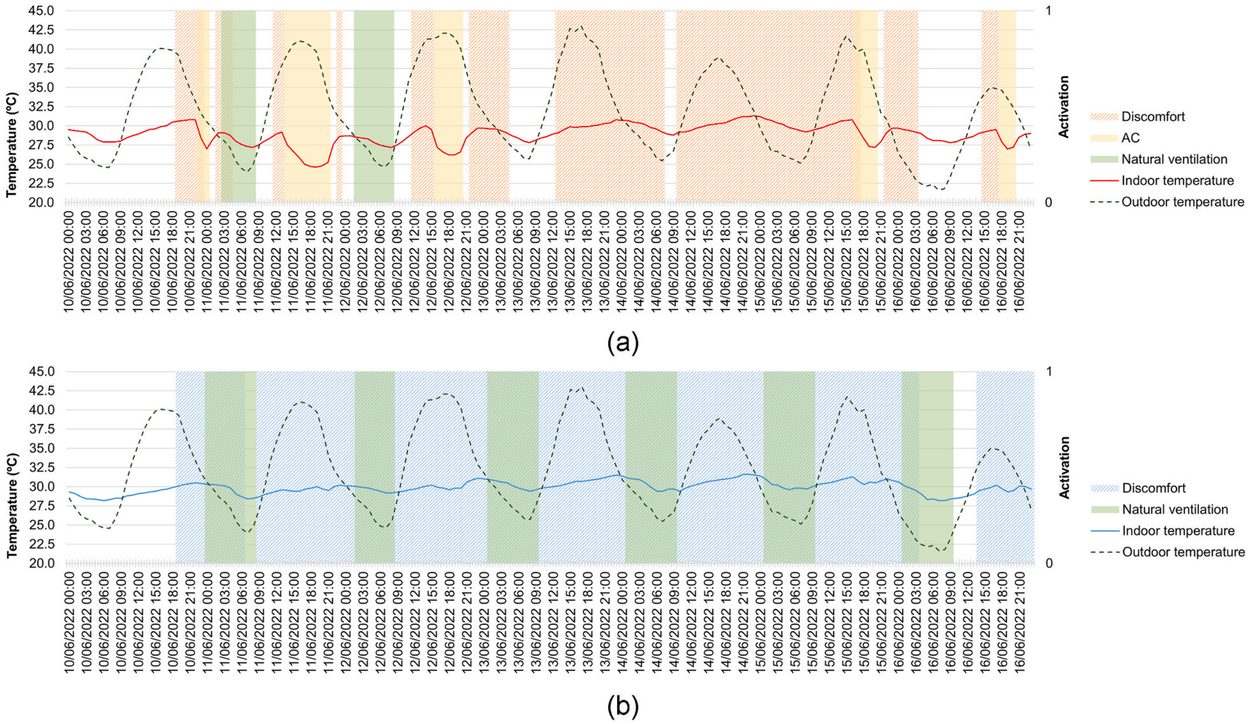


Fig. 6. Hourly evolution of indoor air temperature, outdoor air temperature, discomfort, AC use, and natural ventilation in dwelling 2 (D02): (a) living room and (b) bedroom.

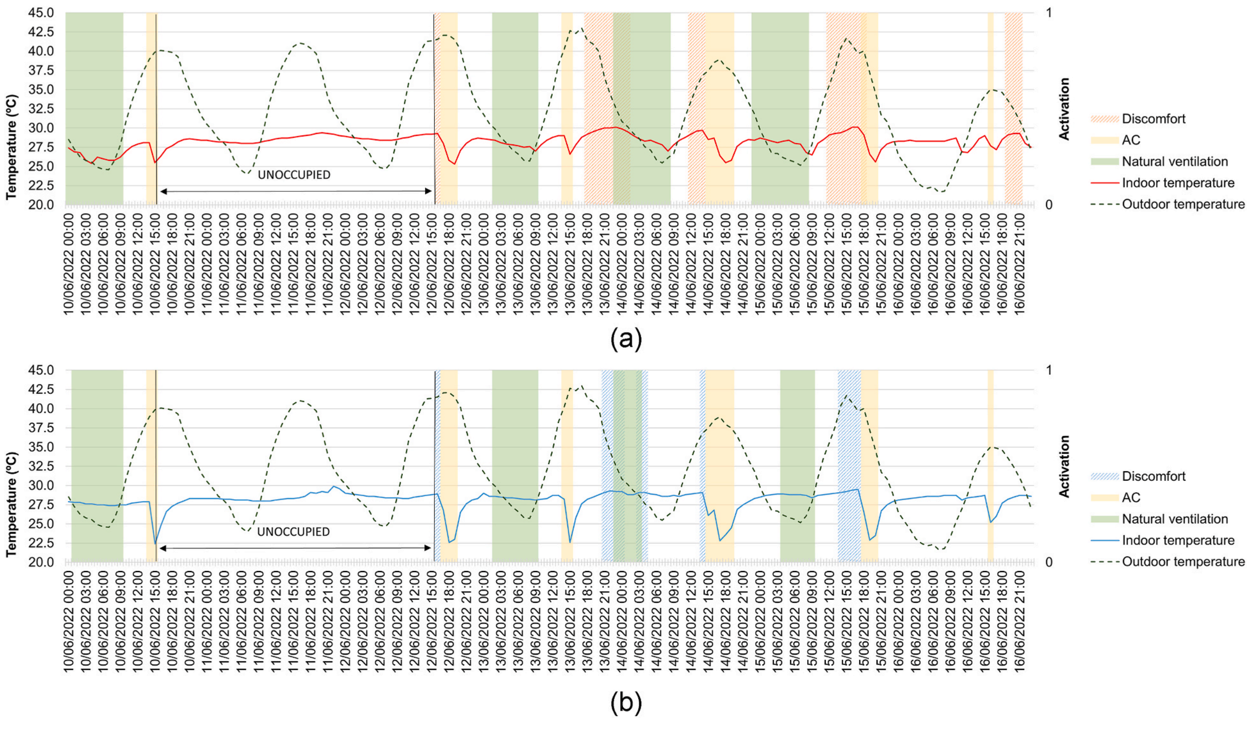


Fig. 7. Hourly evolution of indoor air temperature, outdoor air temperature, discomfort, AC use, and natural ventilation in dwelling 3 (D03): (a) living room and (b) bedroom.

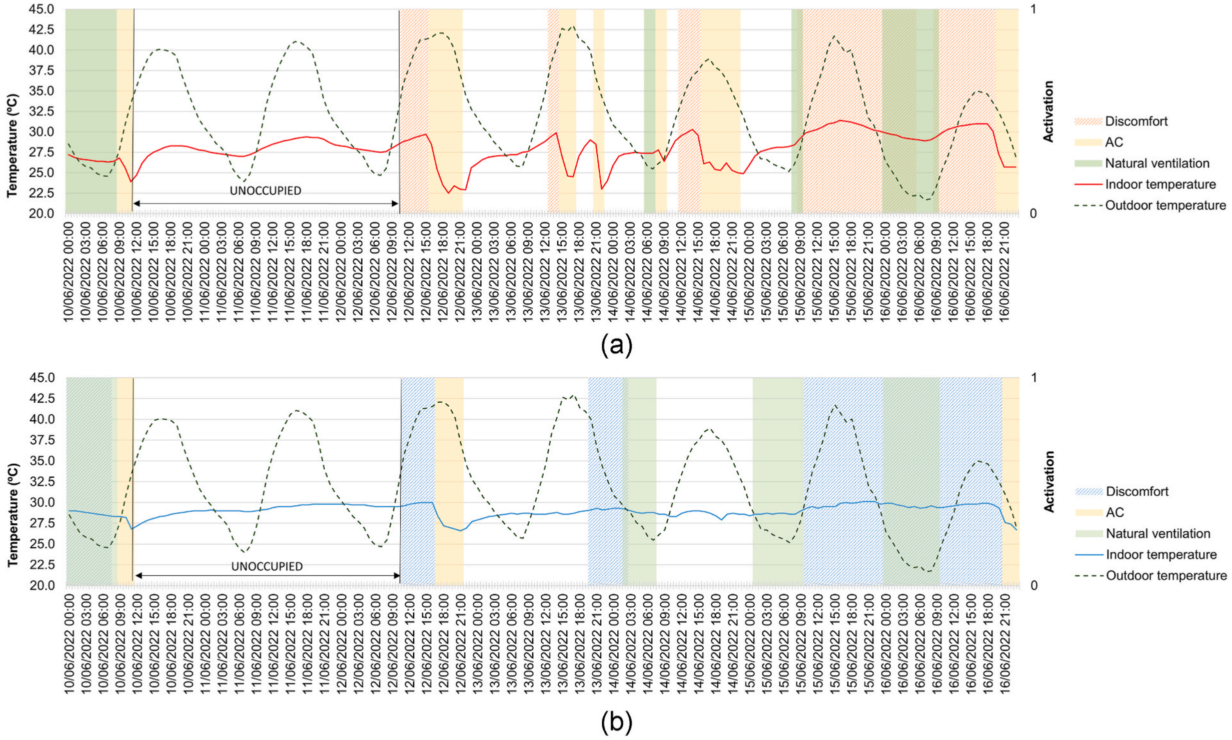


Fig. 8. Hourly evolution of indoor air temperature, outdoor air temperature, discomfort, AC use, and natural ventilation in dwelling 4 (D04): (a) living room and (b) bedroom.

3.2. Assessment of indoor temperatures

When free-running indoor temperatures in D01 are analysed (Fig. 5(a, b)), it is observed that in the living room there is only around 0.5 °C less than in the bedroom during the day, while during the night this difference is around 2 °C less. This is because during the day the uninsulated bedroom roof gains much more heat than the insulated living room one, and this heat is transferred to the bedroom during the night, given the thermal inertia of the concrete floor. In D02 (Fig. 6(a, b)), both monitored rooms behave very similarly under free-running conditions since they have the same orientation and constructive conditions. These indoor temperatures are close to those in the living room of D01 (room with insulated roof, being the same building as D02). If free-running indoor temperatures in D03 are analysed (Fig. 7(a, b)), it is observed that they are generally 1 °C below those of D02 (which is the other case study on an intermediate floor). In D04 (Fig. 8(a, b)), the free-running indoor temperatures of the bedroom remain almost 1 °C higher than in D03 (top-floor of the same building as D04). The behaviour of the living room in D04 is more variable, with slightly higher temperatures than in D03 during the day due to the greater solar gain through the roof, but with similar temperatures at night.

The indoor temperature of the hour before the activation of the AC system has been evaluated in all four case studies in order to test the users' heat tolerance. In D01, it is between 27.5 °C and 30 °C in the living room, and 31 °C in the bedroom. Despite being the same users, tolerances are different depending on the use of the room. In D02, indoor temperature is between 29 °C and 31 °C, with a higher heat tolerance than D01 users. In D03, it is between 27.5 °C and 30 °C, like in D01. Finally, in D04 it is between 26.5 and 29.5 °C, the lowest heat tolerance in the case studies due to the automatic activation of the smart AC system.

In addition, the time that thermal comfort lasts in these dwellings from the point when the AC system is turned off has been assessed. It is worth recalling that D01 and D02 were built before the implementation of any thermal and energy criteria standards, while D03 and D04 were built after the establishment of current thermal criteria. D01 remains in thermal comfort conditions for less than 1 h during the hottest days of the heat wave (minimum outdoor temperatures above 25 °C), and for a maximum of 3 h the rest of the days. In D02, comfort conditions are also less than 1 h during the heat wave, but almost all night if combined with natural ventilation on not-so extreme days. In D03 and D04, thermal comfort conditions last between 2 and 5 h during the day, and generally the whole night (more than 12 h) in combination with natural ventilation.

3.3. Evaluation of thermal comfort

This analysis of the periods monitored was completed with evaluations and graphical representations of the percentage of hours of: AC system use (periods in which the dwellings are in comfort conditions thanks to the use of active systems); discomfort in free-running conditions, and comfort conditions with no activation of AC systems (free-running). As stated in Table 3, the monitored periods selected for the study were: a typical summer month, from 01 to 31 August 2021 (Fig. 9(a, b)), and the heat wave period, from 06 to 19 June 2022 (Fig. 10(a, b)). In the whole month of August 2021, D01 and D04 were the cases with the highest AC use in the living room. The results of D01, with thermal insulation in the roof and frequent use of the AC, show the best behaviour, since 65% of the hours are within the comfort band without the need to activate the AC. In this regard, D03 and D04 have similar behaviour, although D04 has more comfort hours thanks to greater use of the AC. The living room in D02, with moderate use of the AC (6% of the hours), has 52% of comfort hours in free-running conditions. The bedroom in D01 displays the worst behaviour by far (the non-insulated roof releases heat during the night and does not allow indoor temperatures to decrease, while use of AC and natural ventilation is very limited), with 78% discomfort hours. The bedroom in D02, with no AC system, performs notably better than that of D01, as the dwelling is on an intermediate floor with intensive use of natural night-time ventilation. The behaviour of the D03 bedroom is slightly better than that of D04 (percentage of comfort hours without active systems is 4% higher), since the percentage of discomfort hours in D04 is lower but at the expense of more than double hours of AC use.

However, if the analysis focuses on the heat wave period (Fig. 10(a, b)) both the living room and the bedroom of D03 are clearly the ones with the best performance, with 79 and 86% of comfort hours without AC, respectively. This is followed by D04 (more exposed to solar radiation as it is located on the last floor), with 54 and 61% of comfort hours without active systems. In the specific case of the living room results, the use of AC is more intensive (21% of the hours). D01 and D02 display similar behaviour, with slightly less than 50% of the hours in comfort without active systems. D01 has fewer discomfort hours than D02, thanks to more intensive use of AC (24% vs. 10%). In the bedrooms, in periods with extreme temperatures, both D01 and D02 perform quite poorly, with only 14% and 28% of comfort hours respectively, and no use of AC systems. D02 behaves slightly better due to a more adequate use of natural ventilation.

4. Discussion

4.1. General discussion of the main results obtained

Previous results show that the use of AC in the dwellings normally occurs when indoor temperatures exceed 27–31 °C, despite of the building's thermal envelope. Thus, the activation of AC systems is significantly influenced by the user profile, as well as the operation of natural ventilation. In relation to the assessment of thermal comfort, it can be observed that the performance of poorly-insulated dwellings during hot summers is worsen by an inadequate use of night-time ventilation and a limited used of AC systems. Yet, poorly-insulated dwellings may present a slightly better thermal performance when implementing an intensive use of natural night-time ventilation, which is quite significant for dwellings being on an intermediate floor. During extreme heat periods, the exposure of dwellings to direct solar radiation plays a key role in the thermal comfort assessment, leading to a worse thermal performance of dwellings located on the last floor. Moreover, during extreme weather events, the use of night-time ventilation increases in those dwellings that reach the highest percentage of comfort hours. Also, there is a clearly and intensive increase in the use of AC systems, which indicates a lower heat tolerance of users during extremely hot periods.

Generally, it is also interesting to highlight that despite of considering a more adapted comfort method to the Mediterranean climate than the EN 16798-1:2019 [43] standard, the percentage of discomfort hours is much higher than recommended in all cases. For example, the current Spanish regulation [39] establishes a maximum of 4% for discomfort hours for new buildings.

4.2. Results comparison with similar studies

The results obtained show that the implementation of thermal insulation in dwellings and the adequate use of night-time natural ventilation can lead to a noticeable reduction in indoor temperatures. However, as stated by Barbosa et al. [20] for Lisbon (Portugal), with mild Mediterranean climate (Csa and Csb Köppen's classification) [40], even though these strategies can significantly reduce vulnerability, they may not be sufficient during extreme hot events. In fact, in the presented study, the manual activation of AC systems by users was normally addressed when indoor temperatures reached 27–31 °C. Equally, on extremely hot days the activation of the AC system before the sleep period was preferred to the implementation of natural ventilation. Similarly, Guerrero-Delgado et al. [45] stated during a study conducted on social housing in Jaén (Spain), located in the Mediterranean area (Csa Köppen's classification) [40], that thermal insulation implemented in roofs is not sufficient to maintain thermal comfort conditions in summer and that other solutions, such as double skin ventilated roofs, should be also considered. Also, Rodrigues and Fernandes [46] carried out a study on overheating risks in residential buildings considering 16 Mediterranean locations (Valencia, Málaga, Marseille, Naples, Tunis, Algiers or Athens, among others). These authors reported a significant increase in cooling demands for 2050 climate projection and concluded that using ideal U-values in the envelope (optimized thermal insulation thickness) may combat overheating under future scenarios.

During overheating periods, thermal insulation does not always reduce cooling demand, as concluded by Masoso and Grobler [33] in the city of Gaborone (Botsuana), with a more dessert climate (Bsh Köppen's classification) [40]. This can be observed in the use of the AC system: even though the percentage of comfort hours during the heat wave is generally higher in the dwellings built after demanding thermal criteria requirements (D03 and D04), the percentage of use of the AC system is quite similar to the un-insulated or poorly-insulated dwellings (D01-D02), when the location of the dwelling within the building is considered. The same conclusion was reported by Curado and Freitas [47], who analysed a residential building located in several Mediterranean cities, such as Seville or Faro. These authors demonstrated that incorporating thermal insulation in facades is not sufficient to passively guarantee thermal comfort, being necessary to punctually activate also cooling systems in buildings.

Another interesting fact, as concluded by Consoli et al. [48], for a residential building in Catania (Italy) with Csa Mediterranean

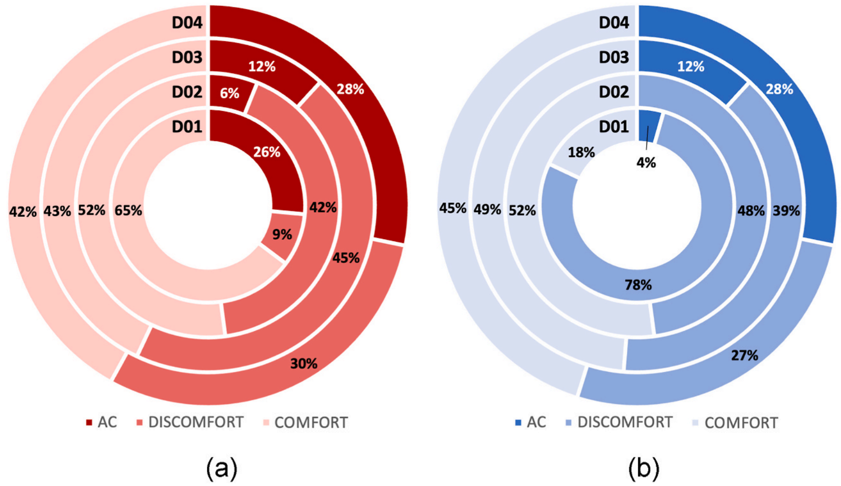


Fig. 9. Percentage of hours of use of the AC system, discomfort hours, and free-running comfort hours during a typical summer month (01 to 31 August 2021) in: (a) living room and (b) bedroom of dwellings D01, D02, D03 and D04.

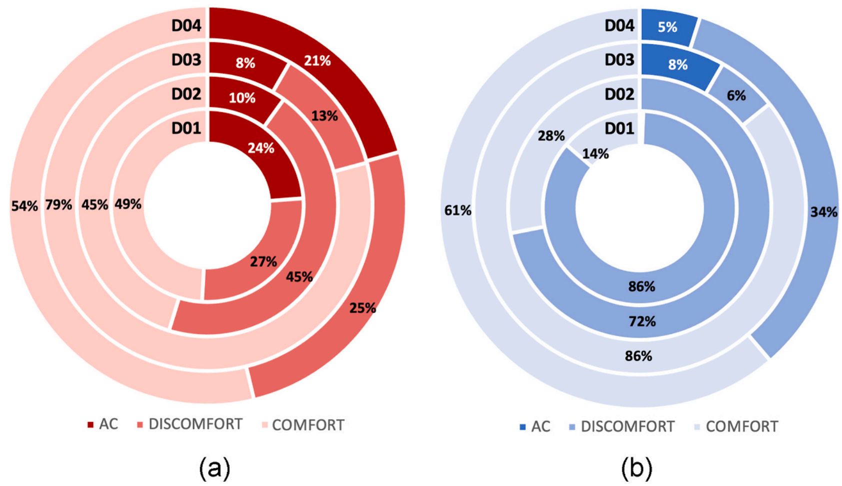


Fig. 10. Percentage of hours of use of the AC system, discomfort hours, and free-running comfort hours during a heat wave period (06 to 19 June 2022) in: (a) living room and (b) bedroom of dwellings D01, D02, D03 and D04.

Köppen's classification [40], and Sharifi et al. [49], for a house in Adelaide (Australia), also with Mediterranean Csa climate according to Köppen's classification) [40], is that due to solar radiation gains top-floor rooms, especially insulated ones, suffer more from discomfort during daytime than those in intermediate-floor dwellings.

4.3. Strengths and limitations. Future research

This text has provided a simultaneous comparison of indoor thermal performance, adaptive thermal comfort and intensity of use of cooling systems of four Mediterranean dwellings during a severe summer and an extremely hot heat wave. It should be highlighted that two dwellings built prior to extensive energy-criteria regulations have been contrasted with two dwellings built after the implementation of more demanding energy requirements. In addition, these dwellings have been analysed during both occupied and unoccupied periods. Thus, in contrast to similar studies, occupation patterns, AC operational aspects and users' interaction with the building have been taken into consideration in the thermal assessment, as have free-running conditions.

Additionally, the methodology used in this research is totally applicable to any city and climate. Yet, results obtained may only be extrapolated to places with similar climate conditions, referring to warm climates with dry summers and mild winters. It has to be also born in mind that the results reported are significantly biased due to the influence of users, thus, dwellings with similar use patterns may only be contrasted.

Nevertheless, it has not been possible to include into the study subjective data on the users' perception and adaptability though surveys, as users did not consent to these. Moreover, only two rooms in each house were monitored (living room and one bedroom) and the main bedroom could not be used for monitoring in all the cases. Furthermore, outdoor weather data were obtained from a local weather station, since outdoor variables could not be monitored in the dwellings. Given the energy-efficiency differences between the AC systems installed in all four dwellings, no direct comparison on energy consumption was possible. Hence, a comparison of the percentage of hours of use of the AC systems was conducted instead.

Future research should investigate the users' thermal perception and vulnerability to combat extremely hot periods. Incorporating a greater number of cases to the study would make it possible to analyse similar operation patterns of users in the dwellings during a typical heat wave, and this in turn would provide interesting conclusions for a better comparison between poorly and well-insulated dwellings. When long-term monitoring methods are implemented the number of case studies is conditioned by the sensors available.

5. Conclusions

Four occupied Mediterranean dwellings (two poorly-insulated and two well-insulated) located in southern Spain have been monitored and simultaneously compared under a heatwave event and a summer month in order to assess their indoor thermal performance and evaluate the effectiveness of insulation to combat indoor overheating. The main conclusions of this study can be summarized as follows:

- Set point temperature of the AC is normally manually fixed at 25–26 °C, regardless of the dwelling's thermal envelope. AC is usually turn on with indoor temperatures around 27–31 °C, with no noticeable differences between poorly- and well-insulated dwellings. When considering the most frequently occupied room (living room), the highest percentage of use hours of AC is found in the top-floor dwellings, regardless of thermal insulation. Well-insulated dwellings only report fewer hours of use of AC during heat wave temperatures and more comfort hours. Yet, differences with poorly-insulated houses are barely noticeable.
- During heat waves, once the AC is turned off, thermal comfort conditions may last 2 to 5 times longer in well-insulated dwellings than in poorly-insulated houses.
- Night-time natural ventilation helps to maintain comfort hours during longer periods, especially in intermediate-floor and well-insulated dwellings.
- Insulated roofs noticeably reduce solar gains, leading to a temperature difference up to 0.5 °C during daytime, and prevent heat transferring at night, minimising indoor air temperatures by up to 2 °C.
- Even though the long-term effectiveness of thermal insulation under light summers is noticeably diluted, a better thermal response is shown under extreme heat, especially in intermediate-floor dwellings.
- In general, using optimized thermal insulation thickness combined with adequate night-time ventilation strategies is vital to improve thermal comfort, especially under extreme hot and heatwave conditions.

Author contribution statement

Carmen María Calama-González, Rocío Escandón, Alicia Alonso, Rafael Suárez, Ángel Luis León-Rodríguez, Ana Sánchez-Ostiz Gutiérrez, Ainhoa Arriazu-Ramos, Aurora Monge-Barrio: Conceived and designed the experiments; Performed the experiments; Analysed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

The authors do not have permission to share data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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