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SUMMERTIME OVERHEATING OF BEDROOMS IN NORTH ARGENTINA
VERANO SOBRECALENTAMIENTO DE DORMITÓRIOS EN EL NORTE DE ARGENTINA

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ABSTRACT
Purpose and objective: the general purpose is to contribute to fill the gap of information related to the thermal condition of sleeping environment in Latin America. The specific objective is to evaluate the thermal conditions of bedrooms during nighttime in three family houses in Salta City, Argentina, during January 2023 including a heat wave episode.

Methodology/Approach: air indoor temperature and humidity were registered at 15-minute intervals with HOBO data-loggers, in three houses. Thermal comfort during sleeping was evaluated through the modified PMV-PPD model of Lan *et al.* (2018), which considers the body part in contact with the bed.

Findings: temperatures exceeded 26°C in the non-conditioned house. The bedroom with AC showed better thermal performance, with 5% of the hours exceeding 26°C. Only 12% of the hours in the non-conditioned house were in comfort, and 40-42% in the conditioned ones. About 60-85% of the hours were categorized as “slightly warm”, and up to 24% as “warm”. Ceiling fan was estimated to reduce the discomfort hours by about 44%.

Research Limitation/implication: data were measured over a single month (January) and one single heatwave event. Low number of monitored houses makes difficult to generalize the results.

Originality/Value of paper: this study brings new information about sleeping conditions and comfort in Latin America. It should be understood as a case study that opens a discussion on overheating risks of bedrooms in this region.

KEYWORD: heatwave, sleeping comfort, night PMV.

RESUMEN

Propósito y objetivo: el propósito general es contribuir con información relacionada con las condiciones térmicas de dormitorios en Latinoamérica. El objetivo específico es evaluar las condiciones térmicas de dormitorios en tres viviendas en Salta, Argentina, durante enero de 2023 que incluyó una ola de calor.

Metodología: se registraron temperatura y humedad del aire cada 15 minutos con data-loggers HOBO, en tres dormitorios. El confort térmico nocturno se evaluó mediante el modelo PMV-PPD modificado de Lan et al. (2018), que considera la fracción del cuerpo en contacto con la cama.

Resultados: las temperaturas superaron 26°C en la casa sin acondicionamiento. El dormitorio con AC presentó mejor desempeño, con 5% de las horas superando 26°C. Sólo 12% de las horas en la casa no acondicionada estuvo confortable, y 40-42% en las acondicionadas. 60-85% de las horas fueron “ligeramente cálidas” y 24% “cálidas”. Se estimó que el ventilador de techo reduce el disconfort en 44%.

Limitaciones/implicancias de la investigación: los datos se midieron durante un solo mes (enero) y una única ola de calor. El bajo número de viviendas monitoreadas dificulta la generalización de los resultados.

Originalidad/Valor del artículo: se aporta nueva información sobre las condiciones térmicas y de confort de dormitorios en América Latina. Es un estudio de caso que abre una discusión sobre los riesgos de sobrecalentamiento de los dormitorios en esta región.

PALABRAS CLAVE: ola de calor, confort durante el sueño, PMV nocturno

1. INTRODUCTION

Argentina has experienced air temperature increases since the 1960s due to climate change, with an average increase of 0.5°C between 1960–2010 that was observed in the majority of non-Patagonia areas and more than 1°C in the Patagonia region (BarrosGC *et al.*, 2014). Extreme temperatures in the east and north of the country were also observed to increase, as well as the occurrence of more frequent heat waves and a reduction in frosts (3CN, 2015). For the rest of the 21st century, hot weather events in Argentina are expected to increase and intensify due to climate change, with mean annual temperatures projected to rise on average by +1.6°C by the 2050s and by 3.3°C by the end of the century under a high emissions scenario (Representative Concentration Pathway RCP 8.5, which corresponds to a warming scenario commonly referred to as "business as usual") (World Bank, 2021). High temperatures, analyzed in terms of the number of days above 25 degrees, are expected to rise significantly. Semi-arid regions of Argentina will continue to experience temperature spikes over the summer months, with the greatest warming expected to occur in the northwest region (Fig. 1), where Salta city is located (3CN, 2015). Fig. 1 also shows the observed annual average air temperature of Salta Province, where an increasing trend has been observed since the 1960s. Fig. 1 also shows the projected change of the annual average air temperature for future scenarios of projected socioeconomic global changes provided by the World Climate Research Programme (WCRP) for the Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change, that are known as Shared Socioeconomic Pathways (SSP) (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, where the final number corresponds to the expected level of radiative forcing in the year 2100, ranging from 1.9 up to 8.5 W/m^2). Fig. 1 shows an increase up to 5°C at the end of the century for the worst SSP5-8.5 scenario (very high greenhouse emissions, with CO_2 emissions triple by 2075). Recent research on the future heat waves for Salta city estimated an increase in the number of waves with a noticeable acceleration from 2040 to the end of the century (Flores Larsen and Filippín, 2023). In 2031-2060 this amount will multiply by 4 and in 2071-2100 10 times more waves will occur than in the base period 1991-2020. Rising temperatures and extreme heat conditions will result in significant implications for human and animal health, as well as agriculture, water resources, and biodiversity.

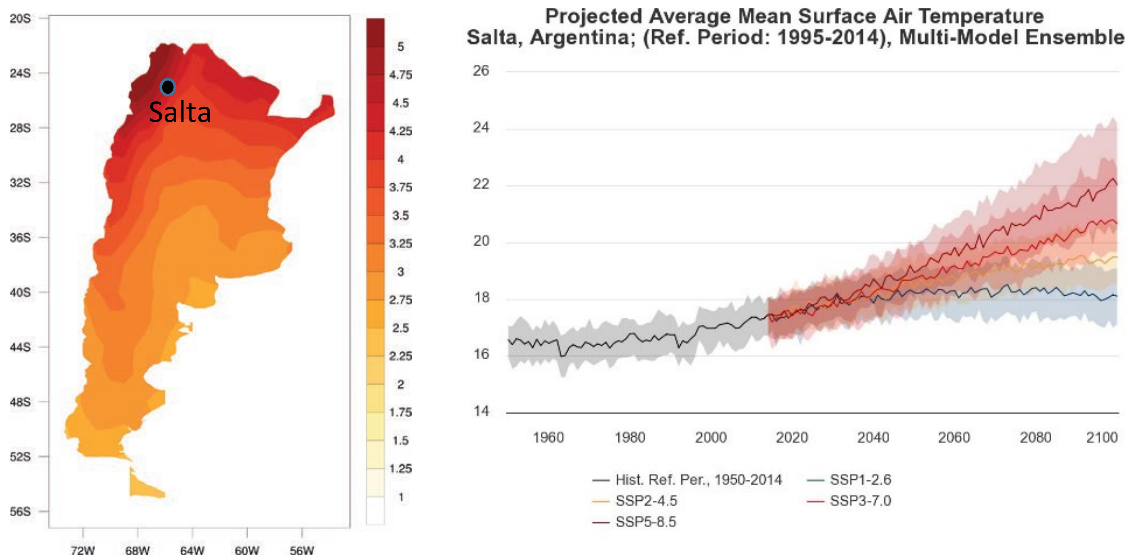


Fig. 1. Left: CMIP5 multi-model ensemble projected change (32 Global Climate Models) in annual temperature by 2080–2099 (right), relative to 1986–2005 baseline under RCP8.5 (CCKP, 2021). Right: CMIP5 multi-model ensemble projected change (32 Global Climate Models) in annual average mean surface air temperature for Salta Province, Argentina (Reference period: 1995-2014).

Among human health and comfort impacts, indoor overheating is one of the critical issues in the spotlight of current research, as people spend more than 90% of their time inside built environments. Thermal air conditions affecting sleep are of particular interest because high temperatures during the night may strongly affect sleep quality, increase wakefulness and disturbance, reduce sleep time, and affect the recovery time during the night that is needed to deal with heat during the day (Ebi *et al.*, 2021; Lan *et al.*, 2014; Xu *et al.,* 2021). Furthermore, heat stress during the night negatively affects people's mental capacities and threatens psychological and physical health (Beckmann *et al.*, 2023; Wong *et al.*, 2018; Wang *et al.*, 2020; Okamoto-Mizuno and Mizuno, 2012). During sleep, body thermoregulation is reduced as lower core body temperature is required (Lee and Shaman, 2017; Xu and Lian, 2023). A pioneering study showed that, during the second night of sleeping in a hot environment, sleep quality is already poor, with subjects sleeping restlessly and less efficiently (Di Nisi *et al.*, 1989). This underlines the need to focus research on night-time temperatures during hot periods and heat waves.

Threshold temperatures for night sleeping and overheating metrics are nowadays under development and study, so there are several indexes proposed in the literature (Havenith and Fiala, 2016). When health risk from overheating is the main objective, the World Health Organization's general threshold of 24 °C is widely used. The Heat Index (NWS, 2023), Humidex (MSC, 2023), and standard effective temperature SET (Ji *et al.*, 2022) are also well-established indexes related to the human body perception and its thermos-physiological response under heat stress conditions. Building overheating metrics are also numerous. The CIBSE (Chartered Institution of Building Services Engineers) guidelines are a very spread method for measuring overheating risk in buildings (CIBSE, 2021). It suggests that temperature in bedrooms should not exceed 26 °C for >1% of the annual occupied hours because sleep quality drops for temperatures above 24 °C. This threshold has been used by several authors, who assumed an occupancy of bedrooms from 23:00 to 7:00 (Hacker *et al.*, 2008, Beizaee *et al.*, 2013, Ade and Rehm, 2022). To consider the adaptation of building occupants to warm climates, particularly in free-running (not air-conditioned) and naturally ventilated buildings, CIBSE has adopted the adaptive thermal model to define thermal comfort and design overheating criteria, a guidance known as TM52. It incorporates a three-criteria methodology with a Pass/Fail Criteria, where rooms or dwelling are categorized as 'overheated' when failing two criteria. However, the CIBSE criteria is built upon a dataset primarily from temperate European cities, and therefore its applicability in countries outside Europe is questionable (Kim *et al.*, 2023). For example, a recent study of the cited authors in 162 dwellings in Australia concluded that the 26°C threshold could be too stringent to apply to naturally ventilated homes in subtropical regions of Australia and that sleep thermal comfort and sleep quality remained unaffected well beyond this limit. In fact, the threshold depends on the age and health conditions of occupants, among other factors. For instance, peak sleep efficiency across children is observed at about 22-23°C (Hinnant *et al.*, 2023). In Germany, Beckmann *et al.* (2021) analyzed survey data of subjective heat stress during night-time from 427 private households. They found a significant difference in subjective heat stress among different groups, with thresholds of 24.8 °C (people living alone) and 26.7 °C (people with chronic disease). Furthermore, in addition to these thresholds, two main indicators are commonly used for sleeping thermal comfort evaluation: thermal comfort vote (TCV) and Predicted Mean Vote/Percentage of Dissatisfaction (PMV/PPD). TCV is generally obtained from questionnaires in experiments with subject participation, and PMV is generally used for model derivation (Xi and Lian, 2023) with some assumptions for sleeping evaluation. PMV categorizes the thermal sensation on a seven-point scale from cold (−3) to hot (+3), where PMV equal to zero represents thermal neutrality. Because conventional thermal comfort models may not be able to predict and assess the optimal environment conditions for humans in sleep (i.e., the bedding system was found to have a significant influence on the thermal neutral temperature), researchers proposed modifying the PMV model. Thus, the PMV model was adapted for sleeping people by Lin and Deng (2008a) who considered the bedding system together with clothing, and more recently by Lan *et al.* (2018) who distinguished in the thermal balance the body parts in contact with the bed, and those in contact with air chamber. This last model was used in the present research.

Besides heat stress thresholds, overheating levels in bedrooms and the strategies to manage hot environments are currently attracting considerable interest from researchers. In the United States, Lee and Shaman (2017) assessed summertime bedroom thermal satisfaction and heat-coping strategies among 706 New York City residents during the 2015 summer through questionnaire surveys. They found that air conditioning (AC) was the preferred heat-coping strategy and it was significantly associated with greater bedroom thermal satisfaction; however, setting AC to a lower temperature provided no additional benefit. Electric fan use and window opening were deemed ineffective for cooling by many respondents. In central England, Morey *et al.*, 2020 investigated overheating in 122 social housing dwellings. Their results showed that bedrooms were more likely to overheat than living rooms, with 42% of bedrooms exceeding 5% of occupied hours over 24 °C, and 40% exceeding 1% of occupied hours over 26 °C. Furthermore, a study during the hot summer of 2018 in England concluded that over 4 million bedrooms were deemed overheated (Lomas *et al.,* 2021). Hence, the scale of the overheating problem in bedrooms is not fully understood, even though night-time temperatures in bedrooms could be higher than those recorded in the daytime during heatwaves (Emmit, 2023; Lomas, 2021). An alternative is to provide safe havens, a cool retreat for sleeping when the main bedroom overheats during hot weather (Drury *et al.*, 2021). In Honduras, with a tropical climate, a study of twelve monitored dwellings evidenced frequent occurrences of overheating in both apartments and single-family housing (Gamero-Salinas *et al.*, 2020).

As shown, sleep thermal comfort is strongly related to the thermal environment conditions. Between the main affecting factors, the air temperature and humidity are relevant. During heat waves, environmental conditions can lead to unhealthy situations during the night if AC is not available. Low socioeconomic households are more likely to suffer overheating due to poor building design and construction quality, high occupant density, and affordability issues around installing, operating, and maintaining AC (Taylor *et al.*, 2023). In conclusion, thermal comfort studies in sleeping environments are limited and field data is still scarce. Moreover, scientific investigation of overheating is geographically skewed toward the Northern Hemisphere. A literature survey by Chen (2019) indicates that about 80% of research articles on the topic of residential overheating published over the last three decades or so were from either the UK or adjacent European countries. In Latin America, there has been little research into the thermal condition of the sleeping environment. This paper is a contribution towards filling the gap of information about monitored thermal summer conditions in bedrooms in the region.

In this context, the main objective of our research is to evaluate the thermal conditions of bedrooms during nighttime, their comfort, and health risk levels in summer. The paper describes the main findings of the thermal behavior of three houses in Salta city, in the Northwest region of Argentina, during a summer month (January 2023) that included a heat wave episode. The article is organized as follows. Section 2 (Materials and Methods) describes the climate and location of the studied houses and their main characteristics, the monitoring equipment, and the methodology for the thermal and comfort analysis of the bedrooms, including the PMV method modified for sleeping. Section 3 (Results) shows the main results of the monitored period, the meteorological conditions during January 2023, the main characteristics of the heat wave that occurred during that month, the thermal behavior (air temperature and relative humidity) of the bedrooms, and the comfort levels during the study period. Finally, Section 4 (Conclusions) draws the main findings, limitations, and conclusions of this research.

2. MATERIALS AND METHODS

2.1. Climate and heat wave detection

The study was carried out in the city of Salta, in the Northwest region of Argentina (24°47′18″S 65°24′38″O, 1152m o.s.l), whose climate is classified as Cwa (temperate, dry winter-hot summer) in the Köppen-Geiger climate classification. The main climatic variables in summer are shown in Fig. 2. January is characterized by a maximum, mean, and minimum monthly average air temperature of 27.7°C, 21.5°C, and 16.8°C, respectively (average 1991-2020). During January 2023, these values were 30.2, 23.1, and 15.8°C, showing higher maximum and average temperatures when compared with normal 1991-2020 baseline values. Outdoor meteorological conditions were registered at 15-minute time intervals with a Davies Vantage Pro2 meteorological station at INENCO-National University of Salta campus (LEB, 2023), at about 6.6 km (H1), 2.1 km (H2), and 1.7 km (H3) respectively, of the monitored houses. Air temperature and relative humidity, solar irradiance on a horizontal surface, air pressure, wind velocity, and direction were registered for the monitored period.

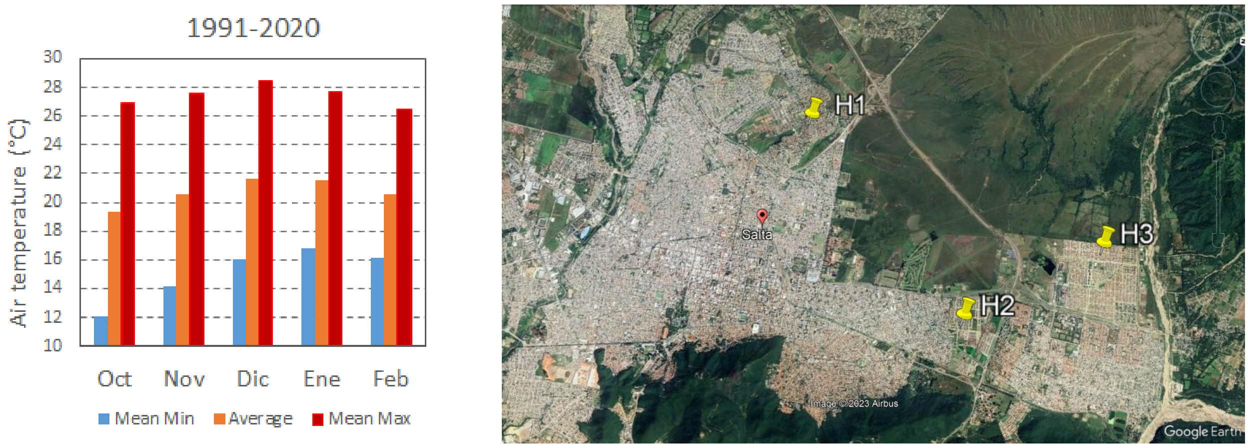


Fig. 2. Left: Monthly mean air temperature in the cooling season for Salta City (Source: National Meteorological Service, WMO 87047). Right: location of the three measured houses in Salta city during January 2023. Source: GoogleEarth.

In Argentina, the National Meteorological Service (SMN) defines the occurrence of a heat wave when the maximum and minimum temperatures exceed or equal, for at least 3 consecutive days and simultaneously, the threshold values that depend on each locality (percentile 90 of the warm semester October-March) and they are calculated for the period 1961-2010 by SMN. A previous study demonstrated that this definition is not completely adequate to study indoor overheating in buildings (Flores Larsen *et al.*, 2022). The definition provided by Ouzeau's method is used instead (Ouzeau *et al.*, 2016), which is currently used by the Météo-France meteorological service to detect heat waves. The method compares the average daily temperature with three thresholds S_{pic} (the threshold that defines that a heat wave is occurring), S_{deb} (the threshold that defines the beginning and ending of the heatwave), and S_{int} (the threshold that interrupts or joins two consecutive heatwaves). These thresholdsmust be previously calculated as the 99.5th, 97.5th, and 95th percentiles, respectively, of the distribution of the observed daily mean temperature of the location of interest over 30 years. A heat wave is then defined as a period of at least three consecutive days with the average daily temperature above the initial threshold S_{deb}, with at least one day with the average daily temperature exceeding the maximum heat threshold S_{pic}. The wave ends if the average temperature drops below S_{int} even for a single day. For Salta city, the thresholds are 24°C (S_{int}), 24.7°C (S_{deb}) y 26.2°C (S_{pic}). Thus, a heatwave is detected when the average daily temperature is higher than 24.7°C during (at least) three days and higher than 26.2°C for at least one of those days. This method was applied to the data measured in January 2023 to detect the occurrence of heat waves and characterize their duration, severity, and intensity.

2.2. Measurements of air indoor conditions in bedrooms

Simultaneous measurements of air indoor temperature and relative humidity were carried out in bedrooms of three family houses (H1, H2, H3) located in different parts of the city (Fig. 2), in neighborhoods of low-rise houses, during January 2023. The three bedrooms are placed on the first floor of the houses and the geometry, windows' size and materials, and envelope layout, are shown in Table 1. Air temperature and relative humidity were registered at 15-minute intervals with HOBO data loggers (models U12-013, U100-003, and U10-003; 12-bit resolution, accuracy: ± 0.35°C, ±2.5% from 10% to 90% RH) (ONSET, 2023). The data loggers were installed at the bedroom levels in the three spaces, protected from direct solar radiation and air cooling equipment. Only bedroom B1 has mechanical cooling; while B2 and B3 rely on night ventilation to cool the spaces. As bedrooms are occupied at nighttime, we analyzed both, the whole daily period, and the occupied period, which was assumed as 23 PM-7AM.

Bedroom Name	**B1**	**B2**	**B3**
House N°	H1	H2	H3
N° and age of occupants	2 adults	1 adult	0 (Jan 1-20) 3 kids (Jan 20-31)
Location	First floor	First floor	First floor
Floor Area (m^2)	20 m^2	4m x 3.5m	12.4 m^2 (3.4m x 3.65m)
Bedroom volume (m^3)	48 m^3	36.4	31.6 m^3
Ceiling height (m)	2.4 m	2.60 m	2.55 m
Cooling system	- AC (split, setpoint=25°C, air flow: 550 m^3/h) - Night one-side ventilation	- Ceiling fan - Night one-side ventilation (partial aperture – 10% of total area)	- No ventilation (Jan 1-20, house closed during summer holidays) - Night cross ventilation (Jan 20-31)
Window size & material	2.6 m^2 DHG 4+6+4 with black-out curtain and exterior eave for shading	Glassdoor: 2.40m x 2.20m DHG glazing 4+6+4 with black-out curtain	Glassdoor: 1.60m x 2m Window: 0.80m x 1.5m Simple glazing (Clear 3mm) with black-out curtain
Window Orientation	West (287°)	North (0°)	North (0°) – Glassdoor East (90°) – Window
Exterior Walls	Massive brick wall (0.30m)	Massive brick wall (0.30m)	Hollow brick wall (0.18m thick)
Roof layout	Tile roof, thermal insulation (0.05m thick of expanded polystyrene), wood board, air chamber, thermal insulation (0.10m thick of glass wool), and gypsum board ceiling	Metal sheet, air chamber, glass wool (0.10m), and gypsum board ceiling	Metal sheet with polyurethane foam (0.025m thick) air chamber, glass wool (0.10m), and gypsum board ceiling
Bedding layout	Bed+mattress+sheet+ half-slip sleepwear		

Table 1. Main characteristics of the monitored bedrooms B1, B2, and B3.

2.3. Comfort evaluation

There is a common agreement on using the overheating threshold of 26°C for night sleeping and several studies suggest using additional comfort indicators such as PMV-PPD (Predicted Mean Vote/Predicted Percentage Dissatisfied), which is among the most recognized thermal comfort models. While the PMV model predicts thermal sensation well in buildings with HVAC systems, field studies in warm climates in buildings without air-conditioning have shown that it predicts a warmer thermal sensation than the occupants actually feel (Fanger and Toftum, 2002; Brager and de Dear, 1998). Some suggested explanations are that openable windows in naturally ventilated buildings should provide a higher level of personal control than in air-conditioned buildings, and that the expectations of the occupants in warm climates are lower because they would judge a given warm environment as less severe and less unacceptable than would people who are used to air-conditioning.

Fanger and Toftum proposed to use an expectancy factor, *e*, to be multiplied with PMV to reach the mean thermal sensation vote of the occupants of the actual non-air-conditioned building in a warm climate. The factor *e* is estimated to vary between 1 and 0.5. It is 1 for air-conditioned buildings. For non-air-conditioned buildings, e depends on the duration of the warm weather over the year and whether such buildings can be compared with many others in the region that are air-conditioned.

As shown, PMV and PPD values are useful indicators because they allow considering the sleeping situation through the metabolic rate and clothing insulation. It was developed using principles of heat balance and experimental data collected in a controlled climate chamber under steady-state conditions. Standard thermal comfort surveys ask subjects about their thermal sensation on a seven-point scale (+3: *Hot*, +2: *Warm*, +1: *Slightly warm*, 0: *Neutral*, -1: *Slightly cool*, -2: *Cool*, -3: *Cold*). Fanger's equations are used to calculate the predicted mean vote (PMV) of a group of subjects for a particular combination of air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation. However, this conventional thermal comfort model may not be able to predict and assess the optimal environmental conditions for humans in sleep. Hence, based on the PMV model, Lan *et al.* (2018) developed a theoretical thermal comfort model for sleeping people, that divides the human body into two parts - one in contact with a bed and the other not- to describe the heat balance of the body.

The model considers the following assumptions: modified metabolic rate (0.7 met or 40 W/m^2 corresponding to an immobile person during the whole period of sleep, Tsang *et al.,* 2021), body in supine position (a fraction of 0.39 is assumed to be in contact with the mattress), vapor evaporation per surface of the body in contact with a bed is assumed to be reduced to 20% of that if the body does not in contact with bed, no regulatory sweating during sleep, thermal conductivity of the mattress 0.048 W/m^2-K, and mean radiant temperature similar to air temperature. Thus, PMV and PPD can be calculated as (Lan *et al.,* 2018):

$$PMV_{sleep} = 0.0998\left\{40 - \frac{13.41 - 1.519p_a - 0.13T_a}{A_D} - \left[1.875(5.52 - p_a) + \frac{0.61(34.6 - T_a)}{0.155I_{clo} + 1/(f_{clo}h)} + 0.0187(\frac{35.4 - T_a}{d})\right]\right\} \quad (1)$$

$$PPD = 100 - 95\exp(-0.03353PMV^4 - 0.2179PMV^2) \quad (2)$$

where A_D (m^2) is the area of the human body (1.7m^2), I_{clo} (clo) is the clothing insulation of the sleep covering (including the sleepwear and bedding), f_{clo} is the covering area factor, d is the mattress height (0.20m), T_a and p_a are the ambient air temperature (°C) and water vapor pressure (kPa), respectively. The total heat transfer h is calculated as the sum h_r+h_c, where the radiative heat transfer coefficient h_r (W/m^2-K) is assumed as 3.235 (W/m^2-K) and the convective heat transfer coefficient h_c (W/m^2-K) at the body surface depends on air velocity and is calculated as:

$$h_c = \begin{cases} 2.7 + 8.7v^{0.67} & for\ 0.15 < v < 1.5 \\ 5.1 & for\ 0 \le v \le 0.15 \end{cases} \quad (3)$$

We used this model with an expectancy factor *e*=1 because Salta has only brief periods of warm weather during the summer (suggested expectancy factor may be 0.9–1, Fanger and Toftum, 2002). Furthermore, one monitored bedroom was air-conditioned, the second one was closed, and the third one did not open windows for night ventilation.

Finally, the *comfort zone* for sleeping is defined by the combinations of the six parameters for which the PMV is within the recommended limits which are slightly different in various international standards, as shown in Table 2 (Xu and Lian, 2023). In ISO and CEN standards, Category I is recommended for spaces occupied by very sensitive and fragile persons with special requirements (very young children, elderly, ill), Category II is suitable for most new buildings and renovations, Category III is suitable for existing buildings, and Category IV are values other than above; acceptable for only part of year.

Standards	Category level	Allowable PMV ranges	Allowable PPD ranges (%)
ISO 7730	I	-0.2 < PMV < 0.2	< 6
	II	-0.5 < PMV < 0.5	< 10
	III	-0.7 < PMV < 0.7	< 15
CEN 15251	I	-0.2 < PMV < 0.2	< 6
	II	-0.5 < PMV < 0.5	< 10
	III	-0.7 < PMV < 0.7	< 15
	IV	PMV < - 0.7 or PMV > 0.7	> 15
ASHRAE 55	-	-0.5 < PMV < 0.5	< 10

Table 2: PMV/PPD ranges for sleeping thermal comfort: Source: Xu and Lian (2023).

In this paper we defined the comfort zone according to Category III of the standards ISO 7730 and CEN 15251, as it is the category suggested for existing buildings. Thus, the indoor environment is considered in thermal comfort when -0.7 < PMV < 0.7 and PPD < 15%.

Eqs. (1) - (3) were used in a Python script to calculate PMV and PPD hourly values and characterize the thermal sensation of the bedrooms' occupants during the nights of January 2023. Air temperature and relative humidity were obtained from measurements. Water vapor pressure was calculated from the air temperature through known thermodynamic equations (i.e., $p_a = 0.133322exp[20.386 - 5132/(T_a + 273.15)]$). The clothing insulation I_{clo} was considered as 0.6 clo (summer blanket), and f_{clo} was obtained from Lin and Deng (2008b), considering a covering of body surface area of 59.1% (bottom part of the body). The air velocity was considered as 0.1 m/s in B1 and B3, and 0.6 m/s in B2 (the limit value suggested for bedrooms, Lan *et al.*, 2018) due to the use of a ceiling fan.

3. RESULTS

3.1. Meteorological conditions and heatwaves during January 2023

The summer of 2022-2023 broke national records in several regions of Argentina and it led to large-scale power outages, wildfires, and drought, and it is estimated to have led to an increase in heat-related deaths (Rivera *et al.*, 2023). Particularly, the average air temperature in January 2023 established a new record of high temperatures (SMN, 2023). With a difference of +1.6°C with respect to the period 1981-2010, this January 2023 displaced January 2022 from the ranking of warmest January for Argentina since 1961. As previously explained, there is a clear tendency of increased temperature that is affecting the country, especially in the summer months.

In Salta, the air temperature and humidity, solar irradiance on the horizontal surface, and wind velocity during January 2023 are shown in Fig. 3. The period included sunny days with high solar irradiance (>1000 W/m^2). The monthly mean temperature was 23.1°C (a deviation of +0.8°C with respect to the 1991-2020 baseline), with maximum (absolute) values that reached 34.7°C. As shown, there were 13 days with maximum air temperature exceeding 30°C. Minimum air temperatures oscillated between 13.8°C and 19.7°C. These values are enough low to consider using night ventilation, but they are counteracted by very low wind speed during the night that reduced the ventilation potential.

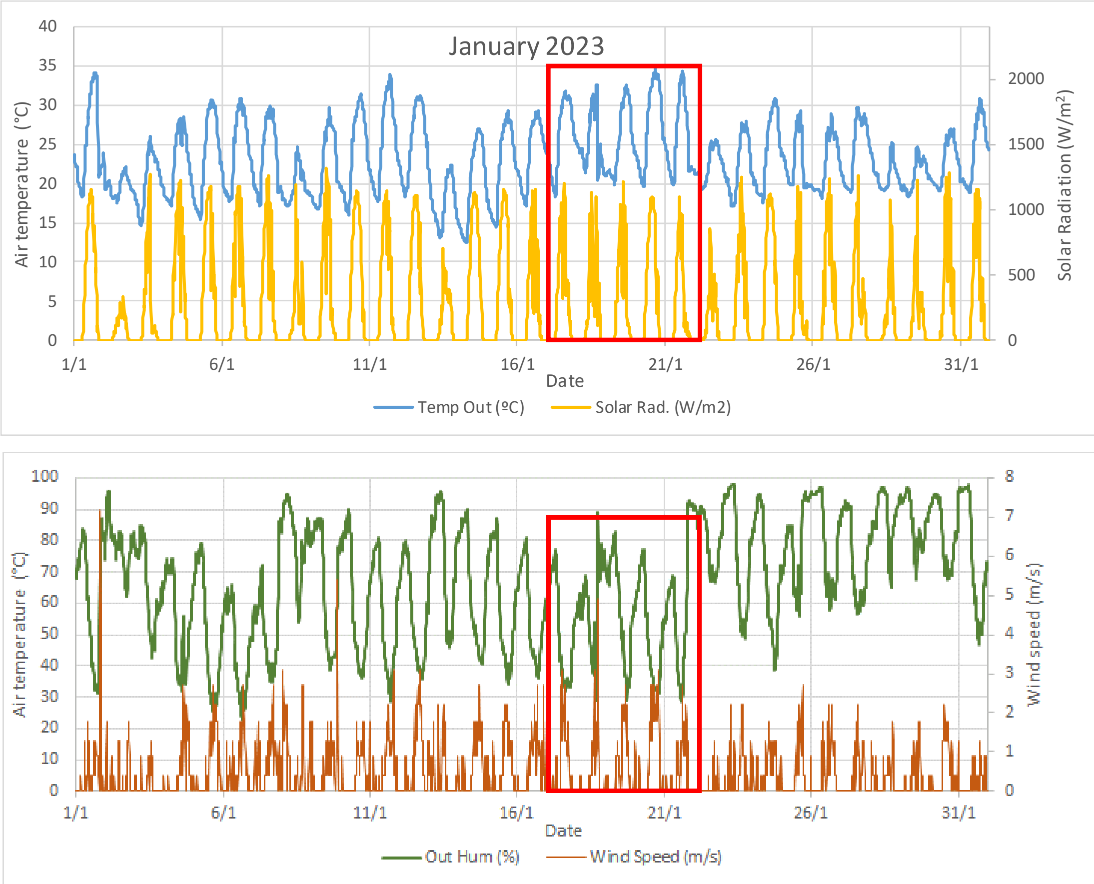


Fig. 3. Air temperature and global solar irradiance on a horizontal surface (top), relative humidity, and wind velocity (bottom) for January 2023 in Salta city. In red, is the heatwave period. Data was provided by the meteorological station of the INENCO-National University of Salta (LEB, 2023).

According to Ouzeau's method, for Salta City, the thresholds are 24°C (S_{int}), 24.7°C (S_{deb}) y 26.2°C (S_{pic}), a heat wave with a duration of 5 days was detected, starting on January 17th (red rectangle in Fig. 3). Fig. 4 shows the air temperature, global solar irradiance on a horizontal surface, and wind speed during the heat wave. Air temperature oscillated between 18.2°C and 34.7°C (average of 26.0°C during the heatwave), with relative humidity between 30% and 80%. Wind velocity was around 2.2 m/s from midday until the afternoon, and it was calm during the nights. This low air velocity affected the efficiency of natural night ventilation. The days were partially clouded with maximum solar irradiance values of about 1100 W/m^2. It is possible to compare this 2023 heatwave with previous ones. Previous research (Flores Larsen and Filippín, 2023) analyzed the heat waves that occurred in the period 2010-2023 and showed that 21 heatwaves occurred during the cooling season (between October and February), shown in Fig. 4, with durations between 3 and 7 days, maxima temperatures between 33.1 and 39.3°C, and severities between 1.3 and 7.8 (represented by the bubble size). The heatwave selected for this study (January 17-21, 2023) lasted 5 days, with a maximum temperature of 34.7°C and global severity of 4.5. Thus, it can be described as the sixth most severe of the period 2010-2023, and the fourth longest one.

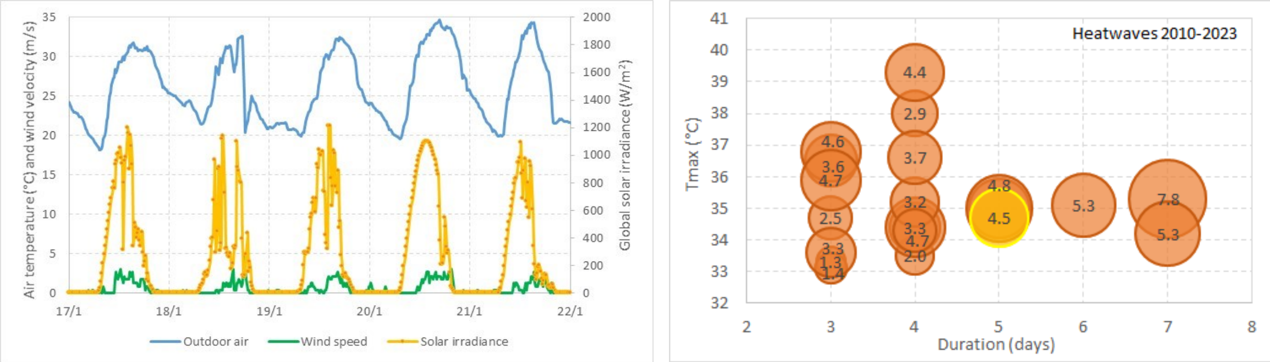
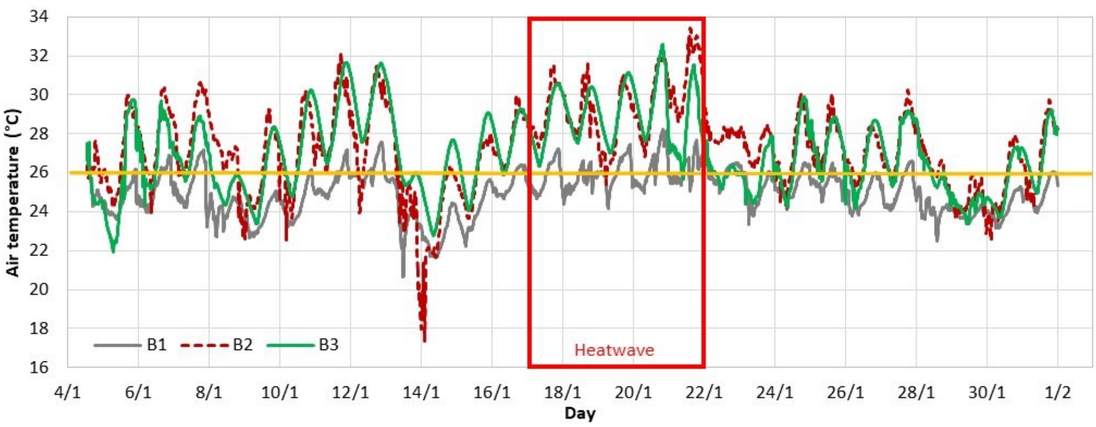


Fig. 4: left: meteorological conditions during the heat wave on January 17th, 2023. Right: heatwaves detected in the period 2010-2023 in Salta city, according to Ouzeau's method. The vertical axis shows the maximum temperature reached during the heatwave, and the bubble size indicates the severity of the heatwave, as defined by the method. The January 2023 heatwave is shown in yellow.

3.2. Indoor conditions in bedrooms

The monitored indoor air temperature and relative humidity in the three bedrooms during January 2023 are shown in Fig 5. About 73% of the hours exceeded the threshold of 26°C in bedroom B2, 65% in B3, and 20% in B1. The best performance corresponds to B1 due to the use of air conditioning during the night and to an envelope with higher quality (DGH and insulation in the roof). Furthermore, during eight nights, the air temperature at the beginning of the sleeping period was higher than 30°C in B3, a very detrimental thermal situation that not only could cause sleeping disturbance but also could lead to severe health problems. Thus, the three bedrooms in this study can be counted as overheated, no matter which of the identified thresholds (24°C or 26°C) is used.

Fig. 6 focuses on the occupancy period (23 PM-7 PM) when the percentages of hours exceeding 26°C are 66% (B2), 63% (B3), and 5% (B1). It is evident in B1 the use of mechanical air conditioning that lowered the air temperature. In the case of B2 and B3, it is concluded that night ventilation was not useful at all because B2 (with natural ventilation) and B3 (without natural ventilation) showed similar behavior. As mentioned in the previous section, the reason is the low air velocity during the night, which affected the efficiency of natural ventilation. The average temperatures during the night in the three bedrooms were 26.6°C (B2 and B3) and 24.7°C (B1).



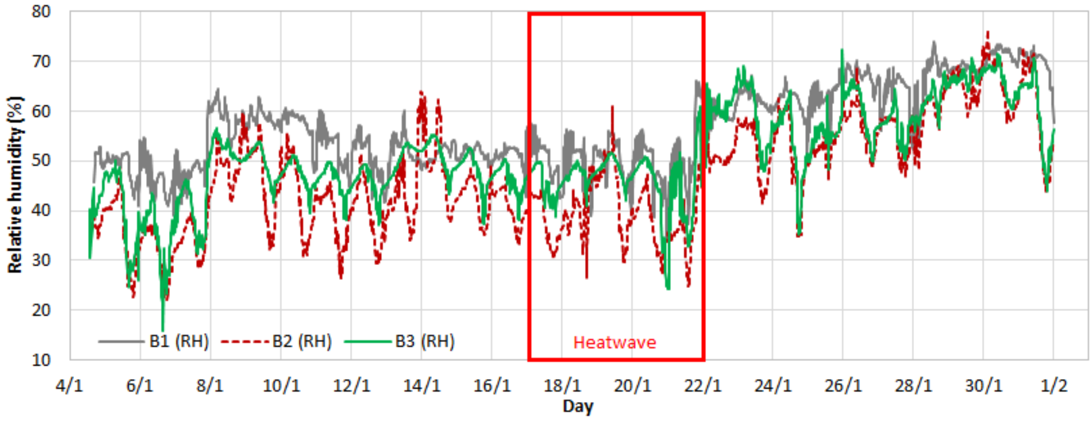


Fig. 5. Indoor air temperatures (top) and relative humidity (bottom) in the three bedrooms (B1, B2, and B3) during January 2023.

The analysis of the relative humidity shows an oscillation between 25% and 70%, with the highest values occurring during the night hours. During the heat wave period, the average relative humidity during the night was about 51% (for bedroom B1), 41% (for B2), and 47% (for B3). These relatively low values favor the heat perception to be more acceptable for the occupants, in comparison with higher humidity values.

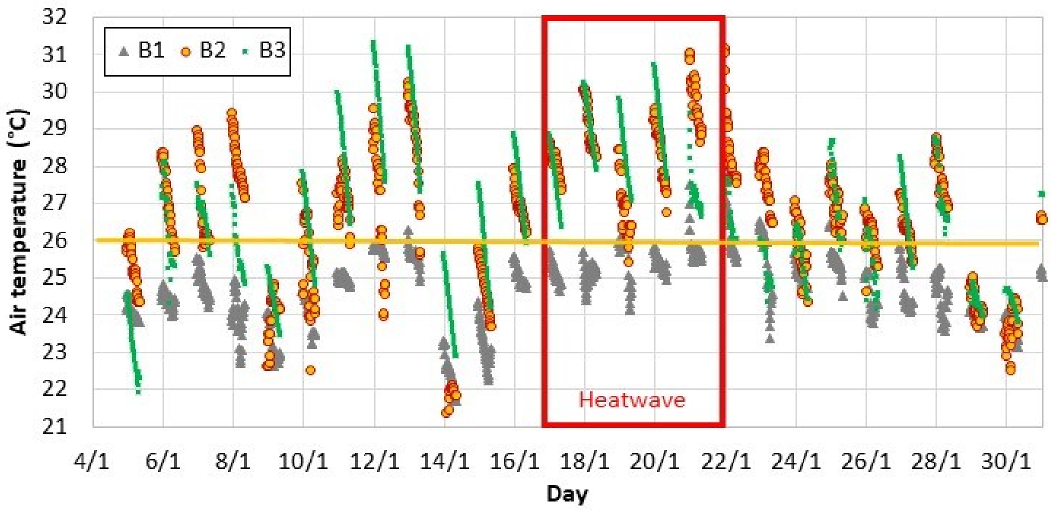


Fig. 6: indoor air temperature in the three bedrooms during the nights (23 PM-7 AM).

Finally, the analysis is focused on the heatwave days, from Jan 17 to Jan 21. The average night temperatures in the bedrooms during the heatwave in January 2023 were 25.4, 28.5, and 28.3 °C, for B1, B2, and B3, respectively, with standard deviations of 1.0, 2.1, and 1.9 °C, respectively. Only B1 was below the threshold of 26°C, because of the use of air conditioning equipment. The percentage when indoor temperatures in bedrooms exceeded 26°C was about 12%, 99%, and 100%, respectively, of the total night hours. It is worth noting that indoor overheating started before (1-2 days) and continued after (up to 7 days) the occurrence of heat waves, depending on building construction and operation of windows, shading devices, and air conditioning equipment.

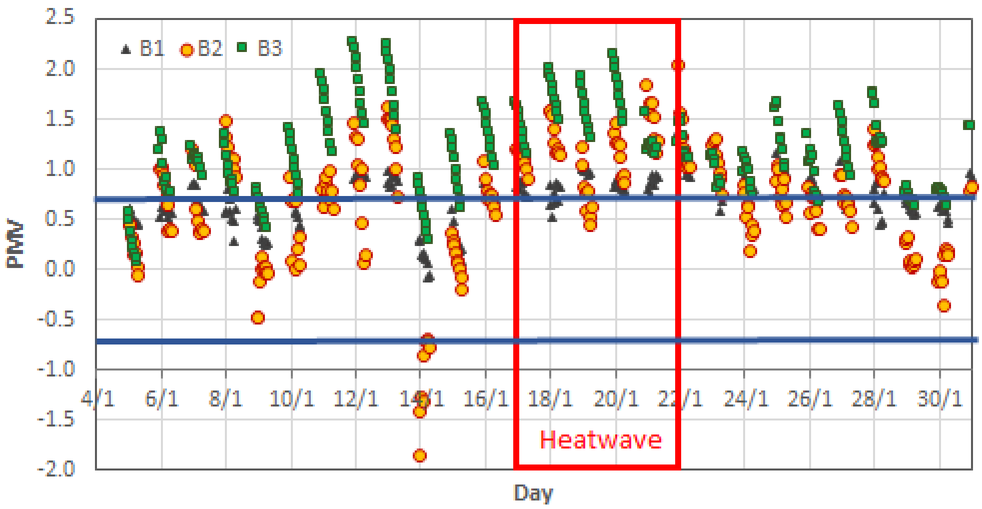
3.3 Comfort levels in the bedrooms

The results of the calculations of the Predicted Mean Vote (PMV) and the Percentage of Dissatisfied People (PPD) in the night period 23 PM-7 AM are shown in Fig. 7 for the three bedrooms. As previously explained, the indoor environment is considered in comfort (Category III of standards ISO 7730 and CEN 15251, see Table 2) when -0.7 < PMV < 0.7 and PPD < 15%. Thus, the percentage of hours that B1, B2, and B3 are in comfort are about 42%, 40%, and 12%, respectively. These values of comfort occur mainly in the last hours of the nighttime. As expected, the best performing is B1 (the bedroom with air conditioning), followed by B2 (the bedroom with ceiling fan) and B3 (the bedroom closed for 20 days).

The effect of the ceiling fan on the perceived thermal sensation is evidenced through the comparison of B2 and B3 on January 24th, when the air temperature and relative humidity of both bedrooms were very similar (Fig. 5). However, the PMV and PPD values are different, with higher values for B3 (without ceiling fan, 100% of the hours outside the comfort range) than for B2 (with ceiling fan, 44% of the hours in comfort). Thus, the use of the ceiling fan reduced the discomfort hours by 44%.

The analysis focused on the heatwave days shows that the average PMV values were 0.8, 1.2, and 1.6. Bedroom 3 presented values in the *Warm* category. The values indicate that the three bedrooms present overheating during the heatwaves, with a maximum Percentage of Dissatisfied People about 25%, 80%, and 82% for B1, B2, and B3, respectively. These values are in agreement with those of Fig. 7: the higher the percentage of dissatisfied people, the lower the percentage of hours in comfort.

The number of hours in the comfort range Category III during the monitoring period is shown for each night hour in Fig. 8 together with the frequency of occurrence of PMV. As expected, the number of hours in comfort is higher for the last hours of the sleeping period. The highest comfort hours during the first hours of the night are achieved in B1 and B2, due to the use of mechanical cooling (AC and fan ceiling), while in B3 there is no comfort in this period. This overheating in B3 during the first hours of sleeping could cause difficulties getting to sleep or an increase in sleep disruptions. Fig. 8 also shows the percentages of night hours in each PMV range. In the case of B1, with maximum values of PMV between 0.6 and 1.0, the use of AC causes a more narrowed distribution with a strong decrease after 1.0. On the opposite, B2 and B3 present a more flattened frequency distribution with values exceeding 1.5, the limit of *the Warm* category.



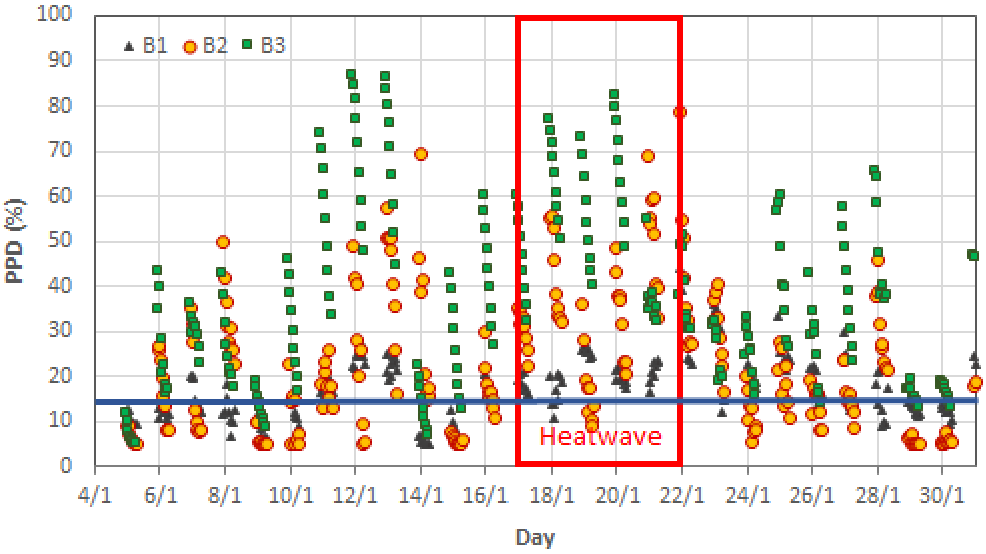


Fig. 7: PMV and PPD for sleeping in the three bedrooms during the nighttime (23 PM-7 AM). Horizontal lines in blue correspond to the limits of ±0.7 in PMV (and 15% in PPD), of Category III of standards ISO 7730 and CEN 15251 (Table 2).

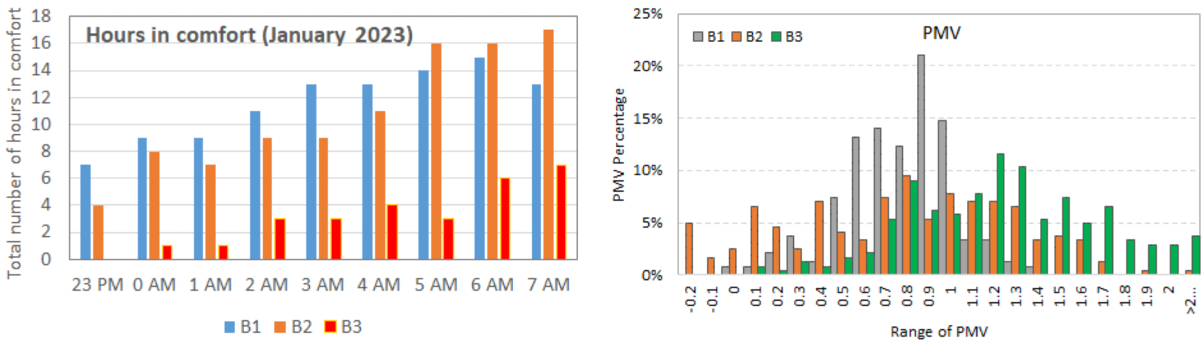


Fig. 8. Number of hours in the comfort range Category III during the monitoring period, for each night hour (left) and percentage of occurrence of PMV for the hours of January 2023 in the night period (right).

4. CONCLUSIONS

Nocturnal bedroom temperatures play a key role in the recovery of the human body during heat events. In this paper, we present the results of three monitored bedrooms during January 2023 in Salta City. The period included a heat wave that lasted 5 days where the maximum temperature reached 34.7°C. In the monitored bedrooms, night air temperatures largely exceeded 26°C when thermal environment cooling relied only on natural ventilation and shading. The bedroom with AC showed better thermal performance, with 5% of the night hours exceeding 26°C. Usage cost of AC was still a major concern and the reason for the set point selection. The comfort PMV-PPD analysis during the sleeping period makes evident that neutral conditions were achieved only for 12% of the hours in the non-conditioned house, and 40-42% in the conditioned ones, while for all houses 60-85% of the hours were categorized as “slightly warm”, and 0%-5% were categorized as “warm” (houses with conventional cooling) and 24% (for the house without cooling). Natural ventilation was not enough efficient due to the low wind velocities during the night. This situation could be improved by forced ventilation: a ceiling fan was estimated to reduce the discomfort hours by about 44%.

A limitation of this study is that temperature data was measured over a single month (January), whereas many recommendations refer to an amount of overheating time during one year. Furthermore, the temperature was only analyzed for one heatwave during January 2023. This does not lead to an overall picture of the overheating situation in Salta nor to the response to different types of heatwaves that occur in this climate. Another limitation is the low number of houses that were monitored, which makes it difficult to generalize the results to other building typologies. More houses and more prolonged monitoring periods are planned for future research.

Despite the usual acclimatization of the inhabitants to higher temperatures in summer, the indoor temperatures showed that they were heat-stressed most of the night time. In accordance with Beckmann *et al.* (2021), if citizens and society do not perceive heat waves as a risk or feel heat stressed, they do not see the need to adapt, making subjective heat stress crucial for taking measures against overheating. Passive strategies and improving thermal insulation and shading are the more efficient ways to adapt buildings to heat. Because heat waves are a regular occurrence in Argentina, there is an urgent need for improving heat early warning systems, heat emergency plans, building retrofit, urban planning for heat including more green areas, and behavioral change communication to reduce heat impacts now and in the future.

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DECLARATION OF CONTRIBUTIONS TO THE ARTICLE

ROLE	Flores Larsen	Filippin
Conceptualization – Ideas; formulation or evolution of overarching research goals and aims.	X	X
Data curation – Management activities to annotate (produce metadata), scrub data and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later re-use.	X	
Formal analysis – Application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data.	X	X
Funding acquisition - Acquisition of the financial support for the project leading to this publication.		
Investigation – Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection.	X	X
Methodology – Development or design of methodology; creation of models.	X	X
Project administration – Management and coordination responsibility for the research activity planning and execution.		
Resources – Provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools.	X	
Software – Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components.	X	
Supervision – Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team.	X	X
Validation – Verification, whether as a part of the activity or separate, of the overall replication/reproducibility of results/experiments and other research outputs.	X	X
Visualization – Preparation, creation and/or presentation of the published work, specifically visualization/data presentation.	X	X
Writing – original draft – Preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation).	X	
Writing – review & editing – Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre- or post-publication stages.		X