

Comparative Analysis Between Indoor Temperatures of Dwellings at Urban Scale During a Typical and Extreme Summers in a Temperate Climate

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ABSTRACT

This study examines the impact of heatwaves on indoor operative temperatures of dwellings in Pamplona (north of Spain) and presents a comparative analysis of a typical summer and two extreme summers with heatwaves in 2003 and 2022. The assessment was conducted in two neighbourhoods with different urban morphologies and built periods related to different energy regulations in Spain. EnergyPlus was used to simulate each residential typology for 5 months in 8 different orientations and with the constructive characteristics that correspond to its built period. The Urban Weather Generator tool was used to consider the microclimate of each neighbourhood. The results showed that dwellings in the older neighbourhood, located on top floors, with one orientation and with large windows had the highest temperatures. These results are strengthened in extreme hot summers with heatwaves compared to those derived from the typical climate series. The evaluation of indoor temperatures of dwellings in two different climatic situations highlighted the importance of assessing temperatures through summers with heatwaves to analyse dwellings' behaviour to high temperatures, even in temperate climates. The urban approach and temperature analysis in relation to building parameters allowed the identification of dwellings with higher indoor temperatures and the key building parameters (built period, floor level, orientation, window area and number of orientations) for the future objective of designing passive measures to adapt dwellings to warming conditions.

KEYWORDS

Overheating; Microclimate; Heatwaves; Building parameters; Natural cooling.

1 INTRODUCTION

The last Intergovernmental Panel on Climate Change (IPCC) report concludes that global surface temperature has reached 1.1 °C above 1850-1900 in 2011-2020 ([Intergovernmental Panel on Climate Change, 2023](#)). These increasingly higher temperatures are leading to more frequent periods of hot and warm weather, and an increase in the frequency and severity of heatwaves ([Taylor et al., 2023](#)).

Through the last 20 years, there were some events, that illustrate this phenomenon and tendency: a heatwave during August 2003 when 50,000 excess deaths were registered across Europe ([Brücker, 2005](#)); in June 2021, western North America experienced a record-breaking heatwave that caused over 1,000 deaths in Canada and around 500 deaths in the USA ([Thompson et al., 2022](#)); recently, summer 2022 was extremely warm summer characterized by a cascade of heatwaves that caused 110,000 excess deaths across Europe ([Copernicus Climate Change Service \(C3S\), 2022](#); [Vicedo-cabrera & Fischer, 2023](#)) and around 4,500 in Spain ([Tobías, Royé, & Iñiguez, 2023](#)).

The projections for southern Europe warn of more extreme warm temperatures, similar to those currently found in regions of North Africa, and suffer more tropical nights (H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, 2022). Besides, the probability of suffering mega-heatwaves will increase by a factor of 5-10 in the next 40 years in Europe (Barriopedro, Fischer, Luterbacher, Trigo, & García-Herrera, 2011).

The population living in urban areas accounts for 75% of the total in the European Union (Zinzi & Carnielo, 2017). In this context, it is relevant to focus on cities where Urban Heat Island (UHI) can exacerbate the effect of these extreme temperatures, heatwaves (D. Li & Bou-Zeid, 2013) and indoor thermal discomfort in summer (X. Li et al., 2019; Litardo et al., 2020; Meggers et al., 2016; Nakano, Bueno, Norford, & Reinhart, 2015; Zinzi & Carnielo, 2017).

Therefore, the interest in analysing the negative effects of high temperatures on people's health, well-being (World Health Organization, 1990, 2011) and mortality (Pathan, Mavrogianni, Summerfield, Oreszczyn, & Davies, 2017) and studying how to prevent them have increased noticeably in recent years, especially within the cities.

This paper is focused on quantifying and comparing indoor operative temperatures (IOT) of dwellings - during a typical summer (climate series 1980-2010) and two extreme ones with heatwaves (2003 and 2022) - in relation to their built period and building parameters. The assessment was conducted in two neighbourhoods of Pamplona (a city in the north Spain) considering the effect of microclimate.

Specific research aims are the following:

- To quantify the influence of microclimate on indoor operative temperatures in dwellings.
- To compare how indoor operative temperatures of dwellings are strengthened in extreme warm summers in relation to a typical climate series.
- To analyse the influence of different building parameters (built period, floor level, orientation, area of windows and number of orientations) on indoor operative temperatures.

2 METHODS

2.1 Urban context

Pamplona is a city placed in the north of Spain. It has an area of 23.55 km² with a population of 203,081 inhabitants and a population density of 8,472 inhabitants/km² (Instituto Nacional de Estadística, 2021). The city is made up of 14 neighbourhoods.

Two neighbourhoods were selected to develop the study: *Iturrama* (N1) and *Mendillorri* (N2). They are samples of different urbanism: N1 (with 9,242 dwellings and built between 1960-1980) has a high density of buildings (0.31 site coverage ratio) and they are higher (average building height: 25.45 m); in contrast, N2 (with 5,634 dwellings and built between 1990-2006) is less dense (0.17 site coverage ratio) and the buildings are lower (average building height: 10.32 m). Besides, N2 has higher percentage of green spaces (Urban ground covered in grass: 25% in N1 and 47% in N2) as it can be seen in Figure 1.

2.2 Building typologies and energy parameters definition

The building typologies classification is based on the results of the project PrestaRener (SAVIArquitectura, 2016), carried out by the research group SAVIArquitectura and previous projects analysis (Aparicio-Gonzalez, Domingo-Irigoyen, & Sánchez-Ostiz, 2020; Monge-Barrio & Sánchez-Ostiz Gutierrez, 2018). Eleven residential typologies were detected in both

neighbourhoods through a visual work using Google Earth and SITNA software ([Gobierno de Navarra, n.d.-b](#)). Figure 1 shows the residential typologies in neighbourhoods' plans: typologies 11, 12, 13, 14 and 15 refer to dwellings in multi-family buildings grouped in linear blocks; typologies 21 and 22 correspond to dwellings in multi-family buildings grouped in H-blocks; typologies 31, 32 and 34 correspond to dwellings in tower; typologies 51 are single-family dwellings.



Figure 1. Green space and residential typologies graphed in N1 (left) and N2 (right) plans.

N1 and N2 were built in different built periods related to energy requirements in Spain, so their buildings have different building characteristics as they had to comply with their energy regulation requirements for each built period:

- N1 was built before 1979 (*no energy regulation*) when there weren't any energy regulations for buildings.
- N2 was built between 1980-2006 (*CT-79 period*) with the first standard energy regulation in Spain NBE CT-79 ([Ministerio de Obras Públicas y Urbanismo, 1979](#)) which appears after the 1970s energy crisis as in other countries.

Infiltration rates were not regulated in Spain until 2019 (with the Spanish Building Code regulation) so the used values are based on previous studies ([Feijó-Muñoz et al., 2019](#)). There weren't any IAQ regulations in any of the periods and all dwellings are naturally ventilated.

Based on these envelopes' energy requirements for each built period, two types of envelopes were defined for the simulation. The parameters that defined each one are presented in Table 1.

Table 1: Used parameters and values for energy simulations

Built period / Energy regulation	U _{façade} / U _{roof} (W/m ² K)	U _{glass} / U _{frame} (W/m ² K)	Infiltrations (50Pa)	Solar shading system	Ventilation
<i>N1</i> <i>No energy regulation</i>	1.39 ^a / 2.9	5.7 / 8.5	7	Blinds with low reflectivity slats ^b	Calculated natural ventilation: Windows free aperture = 15%
<i>N2</i> <i>CT-79</i>	0.73 ^a / 0.65	3.5 / 8.5	7	Blinds with medium reflectivity slats ^b	1AM- 8AM: 4ren/h 9AM- 12PM: 0ren/h Cracks: medium

^a This value considers the influence of thermal bridges, which worsen the façade transmittance (U) it by 30%.

^b They are considered to be in use (completely down) when solar radiation >150 w/m²

2.3 Climate and Microclimate

Pamplona has a Cfb climate (according to Koppen-Geiger classification), temperate without dry season, "oceanic" type. Three weather files were used for energy simulations: climate series (IWEC2-based in climate series 1980-2010 of ASHRAE ([ASHRAE, 2011](#))) and two extreme warm summers (2003 and 2022 - elaborated with available data from Government of Navarra weather stations ([Gobierno de Navarra, n.d.-a](#))). The year 2003 registered two

heatwaves (20 days in total) the and year 2022 had three heatwaves (41 days in total) (AEMET, 2022). Figure 2 shows a summary of outdoor temperatures for the three summers.

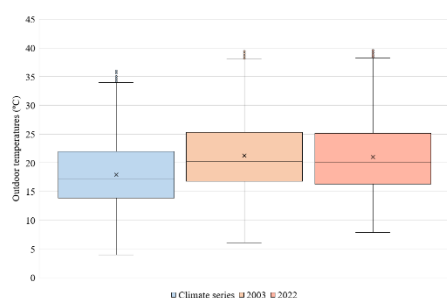


Figure 2. Box-plots showing outdoor temperatures summary for the climate series and the extreme years (2003 and 2022), during the simulation period (May to September).

As the study involves an urban scale, assessing the indoor operative temperature considering the different microclimates through each neighbourhood, was considered fundamental. For this propose, Urban Weather Generator (UWG) software was used (Bueno, Norford, Hidalgo, & Pigeon, 2013).

There are five key parameters to develop the microclimatic files through the UWG (Bueno, Norford, Pigeon, & Britter, 2011; Nakano et al., 2015):

- Urban parameters: Urban area building plan density (*site coverage ratio*); Urban area vertical to horizontal ratio (*facade to site ratio*); *Anthropogenic heat generation* (other than from buildings-traffic).
- Construction parameters: *Albedo* (roofs and soils); *Emissivity* (roofs and soils)

This research did not only consider these key parameters, but also some others more detailed ones: *average building height*, *urban ground covered in grass and trees*, and *vegetation albedo*. The parameters were calculated for the area of each neighbourhood to which a buffer of 50 m perimeter was added (to consider the affection of their surroundings).

2.4 Energy simulation and data analysis

The eleven residential typologies were modelled with their corresponding envelopes' parameters linked to their built period (Table 1). Each model was simulated for 8 different orientations. The considered simulation period was the one established by CIBSE TM-59 (CIBSE, 2013): 1 May - 30 September. The simulations were carried out for the two extreme summer climate files (2003 and 2022) and for the climate series weather file (IWEC2).

For each typology and orientation, results for two dwellings were obtained: one located on an intermediate floor (IF) and the other located on a top floor (TF) under the roof. Each dwelling was considered as a thermal zone because the scale of the research makes it unfeasible to analyse dwellings considering different thermal zones within them (Escandón, Suárez, Alonso, & Mauro, 2022) (f.e: living rooms and bedrooms). To accept this simplification, this work is based on previous studies which indicated that, when rooms do not have an active air conditioning system and the doors of all rooms are usually open (with the consequent circulation of air throughout the house) it is possible to consider the dwellings as one single thermal zone (Escandón, Suárez, & Sendra, 2019).

For each dwelling, the monthly mean operative temperatures, monthly mean maximum operative temperatures and monthly mean minimum operative temperatures were obtained for the simulation period.

Energy simulations were carried out by parameterization of building energy models developed in Design Builder and managed by a Python script (57,601 simulation combinations). Geographic Information System (GIS) was used to adjust the results to the real sample resulting

in a database of 1484 dwellings (N1 and N2) with the results of indoor operative temperature by climate weather file.

3 RESULTS

First of all, mean indoor operative temperatures (IOT) -considering or not microclimate for each neighbourhood-were compared through a TTest: differences between the three climate scenarios were found statistically significant ($p < 0.05$) in both neighbourhoods. It is important to note that the warmer the summer was, the greater this difference was (see Table 2).

Table 2. Differences between mean indoor operative temperatures (°C) considering microclimate or not considering it.

Group	Climate series	2003	2022
N1. base*	23.08 (SD. 1.61)	26.01 (SD. 2.82)	26.64 (SD. 2.00)
N1. microclimate*	23.22 (SD. 1.45)	26.95 (SD. 3.23)	27.94 (SD. 2.00)
N1. Diff.	0.13 (0.15-0.11) $p<0,001$	0.93 (0.97-0.89) $p<0,001$	1.30 (1.32-1.27) $p<0,001$
N2. base**	23.07 (SD. 1.59)	25.90 (SD. 2.73)	26.47 (SD. 1.96)
N2. microclimate**	23.40 (SD. 1.26)	26.96 (SD. 3.17)	27.74 (SD. 1.96)
N2. Diff.	0.32 (0.35-0.30) $p<0,001$	1.06 (1.11-1.01) $p<0,001$	1.30 (1.33-1.26) $p<0,001$

Based on these results, the following analyses were carried out considering the effect of microclimate in the three climate scenarios.

The mean indoor operative temperature resulted from the simulation with the climate series (1980-2010, IWEC2) and those obtained for extreme ones (2003 and 2022) showed an average difference of 4.1°C between means (1980-2010 mean: 23.6°C; 2003 mean: 27.3°C; 2022 mean: 28.1°C). This difference was even greater when only considering the three warmest months (June-August), reaching an average difference of 5.3°C between means (1980-2010 mean: 24.5°C; 2003 mean: 29.8°C; 2022 mean: 29.9°C).

If the limit of 26°C-established by the CIBSE TM-59 for bedrooms ([CIBSE TM59, 2017](#))- was considered, the n indoor operative temperature in summers with heatwaves exceeded this threshold (especially when only considering the three warmest months), while the mean indoor operative temperature derived from the simulation with the climate series was below it (see Figure 3).

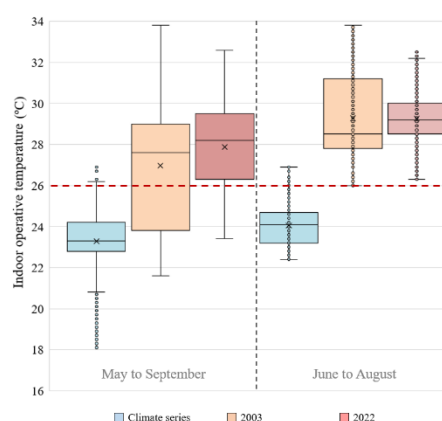


Figure 3. Box-plots showing the differences between indoor operative temperatures for the climate series and the extreme years (2003 and 2022), during all the simulation period (left) and during the warmest months (right). Monthly mean temperatures per group data.

A multilevel mixed-effects linear regression was developed to relate the dependent variable (IOT, °C) and the five independent variables analysed (built period, floor level, orientation, window area and number of orientations). This analysis was carried out for mean, maximum

and minimum temperatures. The most relevant results were found in the mean maximum temperatures (Table 3).

Table 3. Adjusted* monthly mean maximum indoor operative temperatures (°C) according to different building parameters.

Parameters**	Climate series		2003		2022		p value
	Beta Coef.	[95% Conf. Interval]	Beta Coef.	[95% Conf. Interval]	Beta Coef.	[95% Conf. Interval]	
Built period							
No regulation (N1)	0 (Ref.)		0 (Ref.)		0 (Ref.)		
CT-79 (N2)	+0.20	(+0.18 to +0.21)	-0.17	(-0.19 to -0.16)	-0.37	(-0.38 to -0.35)	<0.001
Floor level							
Top floor	0 (Ref.)		0 (Ref.)		0 (Ref.)		
Intermediate floor	+0.31	(+0.29 to +0.32)	-0.20	(-0.22 to -0.18)	-0.40	(-0.42 to -0.37)	<0.001
Orientation							
N/ NE / NW	0 (Ref.)		0 (Ref.)		0 (Ref.)		
S / SW / W	+0.20	(+0.19 to +0.21)	+0.38	(+0.37 to +0.40)	+0.44	(+0.42 to +0.46)	<0.001
E / SE	+0.13	(+0.11 to +0.14)	+0.06	(+0.05 to +0.08)	+0.03	(+0.00 to +0.05)	<0.001
Window area							
≤ 4m ²	0 (Ref.)		0 (Ref.)		0 (Ref.)		
>4m ²	+0.16	(+0.15 to +0.17)	+0.39	(+0.37 to +0.40)	+0.31	(+0.29 to +0.32)	<0.001
Nº orientations							
1 orientation	0 (Ref.)						
> 1 orientation	-0.40	(-0.41 to -0.37)	-0.33	(-0.35 to -0.30)	-0.83	(-0.04 to -0.12)	<0.001

*Results are adjusted for all the variables in the table using a multilevel mixed effects linear regression.

Among the five independent variables, all of them had a statistically significant relationship with indoor operative temperature in the three climate scenarios ($p < 0.05$). The temperature differences between the reference categories and the rest of the categories of each building parameter are, in general, strengthened in warm summers compared to those derived from the climate series.

Regarding the relationship between mean maximum indoor operative temperature and the built period (according to energy standards), the dwellings built in CT-79 period (1980-2006), presented higher average maximum indoor operative temperature than those built in no energy regulation period (before 1979) for the standard climatic series. However, in extreme warm summers, this difference was reversed and the newer dwellings (no energy regulation period) had lower mean maximum temperatures (-0.37°C less in 2022).

Considering the relation between mean maximum indoor operative temperature and floor level (studying differences between apartments located in the intermediate floor and in top floor), intermediate floors presented lower indoor operative temperature than those located on top floors in warm summers with heatwaves (-0.40°C less in 2022).

Regarding the orientation of main facades, the highest mean maximum indoor operative temperature was found in dwellings facing south, west and southwest, especially in the warmest summer (+0.44°C more in 2022 than those with main orientations in north, northeast and northwest).

The size of the window area showed that the bigger it was, the higher mean maximum indoor operative temperature was found in dwellings.

Having more than one orientation in the dwelling (so there is higher potential for cross-ventilation), reduces the mean maximum indoor operative temperature by 0.83°C compared to dwellings with only one orientation in the warmer summer.

Figure 4 shows the mean maximum indoor operative temperature in the warmest month of the simulation period (August) on the plan of studied neighbourhoods. The temperature ranges have been established every 2°C with the lowest limit in 26°C (fixed limit established by CIBSE for

bedrooms (CIBSE TM59, 2017)). Temperature differences between floors and orientations are particularly noticeable in the oldest neighbourhood (N1).

CLIMATE SERIES



Figure 4. GIS plan with maximum average indoor operative temperature in August for 2022 weather files considering microclimate (left: N1; right: N2)

4 DISCUSSION

Due to the urban scale of the study - neighbourhood level- two simplifications were considered: the dwellings were considered as a single thermal zone and the temperature results were monthly.

The analyses of indoor operative temperature in relation to building parameters were aligned with previous studies. Other articles found higher overheating in dwellings located on top floors: one showed that top floors were warmer than first floors during more than 50% of summer hours (Sharifi, Saman, & Alemu, 2019); another based on CIBSE assessment demonstrated that top floor apartments failed all the criteria while those located in intermediate floors passed (Gamero-Salinas, Monge-Barrio, & Sánchez-Ostiz, 2020); and a third one which analyses mean indoor temperatures found that apartments in top floors had a mean temperature 1.2°C higher than in other floors (Vellei et al., 2017). Other studies also found that the worst orientation in relation to overheating was South and/or West: one found a statistically significant difference between indoor overheating hours (IOH) in different orientations with the highest percentage in S and W orientations (Nebia & Aoul, 2017); another found 1.5%-2% higher IOH in south-facing rooms than in north-facing rooms (Tian, Zhang, Deng, & Hrynyszyn, 2020). Regarding number of orientations (related to the potential of ventilation), other studies verified the influence of cross-ventilation in meeting CIBSE TM-59 criteria (Botti, Leach, Lawson, & Hadjidimitriou, 2022); another research, conducted in the north of Spain, concluded that the residential typology with better temperatures was the one that had double-orientation that allow crossed ventilation (on average, 1°C less than the rest of the dwellings) (Figueroa-Lopez, Arias, Oregi, & Rodriguez, 2021). Window size is also a factor that has revealed a significant relation with indoor temperatures: other studies reinforce the idea that the larger the window area is, the more it contributes to the indoor overheating problem

(Vardoulakis & Heaviside, 2012); a monitoring study in the north of Spain, concluded that dwellings with a window area larger than 4m² were almost 3 times more likely to experience IOH than those with smaller window area (Arriazu-Ramos, Bes-Rastrollo, Sanchez-Ostiz Gutierrez, & Monge-Barrio, 2022).

Future research should consider these results to propose strategies from the design (at urban and building level) to the occupants' behaviour in order to improve indoor thermal conditions throughout the summer periods.

5 CONCLUSIONS

This study presents a comparative analysis of dwellings' indoor operative temperatures (IOT) for a typical summer (climate series 1980-2010, IWEC2) and two extreme warm summers with heat waves (2003 and 2022). This research quantifies the influence of microclimate and building parameters (floor level, orientation, window area and number of orientations) on dwellings' indoor operative temperatures. The analyses are based on simulation results for dwellings in two neighbourhoods with different urban morphologies and built periods related to different energy regulations in Spain.

The difference between considering the effect of microclimate on indoor operative temperature and not considering it was statistically significant ($p < 0.05$). The indoor operative temperature was higher when microclimate was considered: this difference was greater when the summer was warmer, reaching a difference between means of 1.3°C in 2022.

The results obtained for the extreme warm summers showed higher indoor operative temperature (difference of 4.1°C on average) than those obtained for the climate series. The indoor operative temperatures in summers with heatwaves exceeded the limit of 26°C, while the temperatures derived from the simulation with the climate series were below it.

Regarding the assessment of the influence that building parameters (built period, floor level, orientation, window area and number of orientations) have on indoor operative temperature, was statistically significant ($p < 0.05$). Dwellings in the older neighbourhood (built before any energy regulation), located on top floors, with one orientation and with windows area bigger than 4m² had the highest indoor operative temperature. The most favourable orientations for summer were N-NE and NW. These results were strengthened in extreme hot summers with heatwaves compared to those derived from the typical climate series. The differences in indoor operative temperature in relation to building parameters were more pronounced in the older neighbourhood.

The indoor overheating evaluation of dwellings in different climatic situations showed that, even in temperate climates with mild summers, it is important to assess temperatures through a summer with heatwaves and considering microclimate in order to analyse dwellings' real behaviour to high temperatures. Besides, the building parameters assessment allows to identify the key building parameters for the future objective of designing passive measures to adapt dwellings to warming conditions and to help policymakers to prevent the risk of overheating within cities, especially during heatwaves.

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