Assessing natural ventilation strategies to improve thermal resilience to extreme temperatures of the residential buildings in Barcelona

Marcello Avanzini[1], Joana Ortiz[1], Thibault Péan[1], Elisenda Cleries[1], Luca Borghero[1], Jaume Salom[1]

1 IREC – Catalonia Energy Research Institute
Jardins de les Dones de Negre 1, 2ª pl.
08930 Sant Adrià del Besòs, Barcelona, Spain

ABSTRACT

In future years the frequency, duration and magnitude of extreme heat events, such as heat waves, is expected to increase due to climate change. The population is exposed to higher thermal discomfort and risk at home and, at the same time, high external temperatures make it more difficult to cool their household through natural ventilation. In order to propose adaptive measures, research should first assess the thermal resilience of the existing residential buildings when exposed to prolonged heat stress. Poorly insulated and non-equipped buildings typical of Southern European building stock are between the most affected typologies, suffering thermal discomfort both during mild winters and hot summers. The effect of torrid summers has been partly counterbalanced by vernacular control strategies adopted in the Mediterranean culture, such as natural cross-ventilation and solar shading devices. However, the effectiveness of those strategies is in doubt due a combination of the widespread of building design depending on mechanical ventilation at the expense of passive control and the increase of summer temperatures.
The objective of this study is to analyse the thermal resilience of a reference building in Barcelona against extreme temperature events and assess its ability to maintain a comfortable and safe indoor environment through passive strategies. A Building Energy Model of an apartment in a multi-family building has been designed to dynamically incorporate vernacular control strategies, such as natural ventilation and solar shading, based on internal (occupancy) and external inputs (temperature and irradiance) acting as triggers.
The building is first simulated during the period surrounding the record-high heat wave which hit Catalonia in summer 2018, and then repeated using different input weather data, which correspond to a heat wave period detected under two future climate change projections. All simulations discerned between two types of occupants' behaviours: aware and fixed.
Occupants' comfort is assessed according to the adaptive comfort model. Thermal risk is evaluated comparing the indicators of Heat Index and Humidex. The results have been assessed based on three main overheating and resilience metrics: the unmet hours, expressing the share of time spent in discomfort or risk conditions; the overheating intensity; and passive survivability indexes. The occupant control based on external temperature (Aware) provided around 2 and 5 ºC lower operative temperatures than a fixed schedule for natural ventilation (Night). Under future climate scenarios, the thermal risk values fall into the worst conditions using the fixed control, an occurrence avoided with aware ventilation. Considering the projected 2050 future scenario, the aware control reaches 18 nights above 28ºC and 9 nights above 30ºC while the fixed control counts with 38 and 91 nights, respectively.

KEYWORDS

Thermal Comfort; Heat Resilience; Heat Wave; Climate Change; Natural Ventilation

1 INTRODUCTION

The quantification of thermal resilience has so far been limited to shocks such as power outages, leaving aside thermal stresses caused by the combination of extreme climatic conditions and poor building design. Overheating (OH) in the urban environment is caused by several reasons, and consists in the increased temperature within the buildings as a consequence of extreme outdoor temperature, which is higher in urban environment in respect to the surrounding rural areas. Focusing on Dutch dwellings, (Hamdy et al., 2017) concluded that in summer, the free-running indoor temperature is almost always higher than the outdoor air temperature (6ºC on average). (Sakka et al., 2012) monitored the indoor thermal conditions in fifty low-income houses without air-conditioning during three heat waves which hit Athens in 2007. Indoor temperatures as high as 40ºC were recorded and the average minimum was always above 28ºC. Inhabitants were exposed to temperatures above 30ºC for almost 85% of the hot period, lasting up to 216 uninterrupted hours in the worst cases.

Exposure to high temperatures have serious consequences on human health, including fatigue, thermoregulation deficiencies, circulatory and respiratory diseases which could eventually lead to death (Ortiz et al., 2019), in particular for the more vulnerable population (elders, people with health conditions). More than 70,000 deaths in Europe were attributed to the 2003 heatwave alone (Robine et al., 2008), noting the close relationship between extreme temperatures and mortality. The use of passive strategies, such as natural ventilation and solar shading can already provide effective mitigation of OH. (Kuczyński et al., 2021) noted that optimal OH prevention in the UK can be provided by a combination of night ventilation, solar shading and high thermal mass, since each action ensures mitigation at different times of the day in a temperate climate. Optimal results in passive control strategies are achieved only with a direct involvement of occupants. Unfortunately, some resident might unintentionally perform adverse actions due to a lack of awareness, conflict with other priorities (e.g. noise, burglary), physical and health impediments (Schünemann et al., 2020). Additional obstacles were found by (Murtagh et al., 2019) in a survey directed to English householders, in which they demonstrated a generally low intention to take precautionary actions (e.g. install shading devices, increase albedo), despite recognizing overheating as a valid reason to do so. By simulating six natural ventilation profiles, (Schünemann et al., 2021) found that an optimal behaviour with cross ventilation reduces summer temperatures by 2-3ºC in moderate climate in Germany, compared to the minimum ventilation case. For one dwelling simulated, the OH intensity (measured in “over temperature degree hours” with the unit Kh, typically for a complete year) decreased by 79% (from 3,570 Kh/a to 770 Kh/a) for the living room and by 99% (from 2480 Kh/a to 20 Kh/a) for the bedroom. Its findings call for a more accurate representation of natural ventilation in building performance simulation, to draw meaningful conclusions from overheating assessments. This study contributes to ameliorate human-based control strategies for heat mitigation in typical Mediterranean climate (natural ventilation and solar shading). The strategies are tested with increasing levels of heat stress, corresponding to likely summer weather conditions under climate change. This is done aiming at reducing the demand for mechanical cooling at a minimum, still guaranteeing adequate comfort conditions. The structure of this paper is as follows: Chapter 2 first (2.1) explains the model defined as a case study, (2.2) describes the human-based control strategies and (2.3) the climate boundary conditions. Finally, (2.4) enlists the discomfort and risk indicators adopted to assess the thermal resilience. Chapters 3 and 4 are dedicated to results and conclusions.

2 METHODOLOGY

The present study analyses six dynamic energy simulations of the same reference building, combining two human-based control strategies and three different climatic conditions.

2.1 Case study

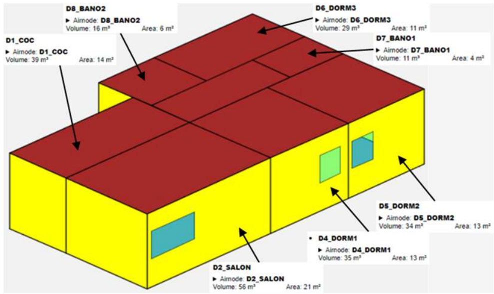

Figure 1: Geometry of the reference building used in the simulations, depicted from South-East

A model developed in TRNSYS for a three-occupants apartment was chosen as a reference building for the existing residential block in Barcelona metropolitan area. The 90m^2 apartment is located at an intermediate floor and its geometry is depicted in Figure 1. The model is composed by eight zones. The building is located close to the centre of Badalona. The location was chosen as that of the weather station "Badalona – Museu".

The envelope thermal properties represent those of a multi-storey residential building constructed in Catalunya within 1951 and 1980 (Agència de l'Habitatge de Catalunya, 2014), which represents around half of the residential stock in Barcelona, which main features are shown in Table 1. Probability profiles of occupancy and energy-consuming activities were obtained from a stochastic model based on the work of (Tejero et al., 2018). Internal gains are calculated in compliance with the stochastic profiles derived. Gains caused by occupation were distributed throughout the zones distinguishing between daily and nocturnal use. Moreover, a daylight control were implemented for the lighting. The air flow rate for natural ventilation is calculated under the hypotesis of cross-side ventilation, in line with the British Standard 5925:1991 (BS Standards, 1991). The opened area of the window used for the calculation is modulated dependending on the wind speed. Solar shading is implemented separately for windows facing East and West, according to the solar radiation on those surfaces. The infiltration is based on (European Committee for Standardization, 2007). It was decided not to implement any HVAC system. Table 2 sumarizes all the elements implemented:

Table 1: Building envelope thermal charactersitics; the values were retrieved from the Catalan building typology F, which represent an apartment block built within 1951 and 1980 (AHC, 2014)

Component	**U-value [W/m^2·K]**	**Thickness [m]**
External wall	1.223	0.23
External roof	1.170	0.34
External partition	2.254	0.18
Internal partition	2.465	0.09
Internal floor	1.863	0.28
Component	**U-value [W/m^2·K]**	**g-value [%]**
Window (1.1x0.8)	5.68	85

Table 2: Implementation of elements in the model

Element	**Implementation**
Occupancy	Stochastic (3 residents)
Lighting	Stochastic with daylight control
Internal gains	Stochastic, divided in day and night zones
Natural ventilation	Occupancy and temperature control
Solar shading	Occupancy, T and radiation control
Cross-side ventilation	BS 5925-1991
Infiltration	UNI-EN15242:2007

2.2 Human-based control strategies

Two types of occupancy-driven thermal mitigation strategies were defined to emulate the attitude of inhabitants of a free-floating building during hot summer days. The strategies were implemented in TRNSYS as follows:

- Aware
    - Natural ventilation is implemented based on occupancy and temperature; if the dwelling is occupied by at least one person, natural ventilation is activated when the average indoor operative temperature ranges between 24.5ºC and 28ºC or when the indoor temperature exceeds both 28ºC and the ambient temperature.

- Solar shading is implemented based only on temperature and solar radiation, but indipendently from the occupancy; blinds are closed when both temperature and total radiation on the external surface exceed the thresholds of 24.5ºC and 140 W/m^2 respectively, while blinds are opened if the temperature falls below 24.5ºC or radiation falls below 120 W/m^2.

- Fixed
  - Natural ventilation is implemented with the same occupancy and temperature control, but only as night ventilation between 0am and 7am.
  - Solar shading is implemented with the same temperature and radiation control, but only when the household is occupied (blinds are open during unoccupied hours); additionally, the maximum opaque fraction of blinds is reduced from 70% to 50%

2.3 Climate boundary conditions

The building response to the HW of 2018 was simulated with historic climate data from the weather station "Badalona Museu" (Meteo.cat |Servei Meteorològic de Catalunya, 2022). Two future weather input files were elaborated for the model using (Meteonorm, 2022), representing the climate conditions of an extremely hot summer in 2030 and 2050 under the most probable baseline scenario (RCP4.5) within those proposed by the IPCC (Kaito et al., 2000).As shown in Figure 2, the projected future heat waves are both more intense in temperature and extended in time than the HW of 2018. In particular, the maximum temperature during the HWs of 2030 (green) and 2050 (red) exceeds the threshold (31.4ºC) for eight and five consecutive days respectively, versus the three days of the 2018 HW. Similarly, the temperature reaches 36.1ºC in 2030 and 38.1ºC in 2050, while it peaked at 34.7ºC on the 8^{th} day of the monitored heatwave (4 August 2018.)

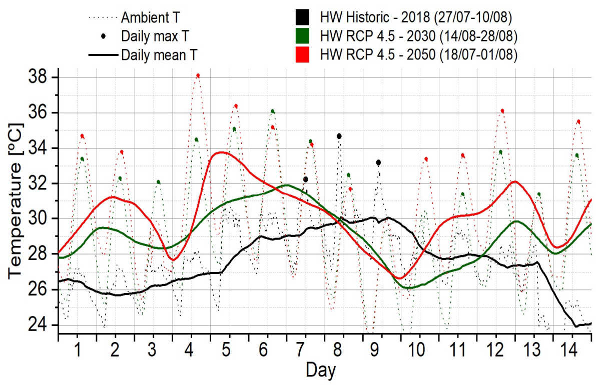

Figure 2: Ambient air (dotted line), daily mean (line) and maximum T (dots) during the two weeks surrounding the three heat waves under analysis: historic (black – from July 29 to August 11 of 2018) and forecasted (RCP 4.5) on the short-term (green) and the long-term (red); maximum daily T above the heat wave threshold for Badalona (31.4ºC) were marked (big dots).

2.4 Thermal Resilience indicators

Thermal resilience and overheating metrics retrieved in literature could be classified in three main categories: the unmet hours; the overheating intensity; and the passive survivability. The unmet hours express the share of time in which a certain condition is not fulfilled, notably the preservation of a comfortable or safe indoor environment. In this study, the metric was calculated for (2.4.1) the adaptive comfort model and for two risk parameters: (2.4.2) Heat Index and (2.4.3) Humidex. The OH intensity is generally expressed in degree-hours, as an integral in time of the excess temperature above a certain comfort threshold. This study employs (2.4.4) the set of coefficients proposed by (Hamdy et al., 2017) to evaluate buildings' response to heat stress. The passive survivability expresses how fast the temperature reaches an OH threshold, usually set to 30ºC for summer (O'Brien, 2016). This indicator is useful to assess the response to sudden shocks, such as power failures, but is less significant for progressive stresses like heat waves. In its place, simple indicators expressing the persistence of overheating in time has been used, namely: the number of consecutive days with maximum T above 32ºC and the number of consecutive hours above 30ºC and 28ºC, which also determine the number of consecutive nights experiencing those extreme temperatures for the whole summer season.

2.4.1 Adaptive comfort model

The adaptive comfort model defines three categories of comfort representing the perception of occupants of buildings without mechanical cooling during summer. The thresholds are:

$$T_{i,CAT} = 0.33 \cdot T_{rm} + 18.8 \pm \Delta T_{CAT} \tag{1}$$

where T_{rm} is the outdoor running mean temperature and $T_{i,CAT}$ is the operative temperature threshold for each comfort category, with ΔT_{CAT} equal to 2, 3 and 4 for categories I, II and III respectively (EN 16789-1:2019). $T_{i,CAT}$ is considered constant for T_{rm} above the validity limit of 30ºC, which is thereby used in the calculation.

2.4.2 Heat Index

The Heat Index (HI), also known as apparent temperature, represents the human-perceived equivalent temperature in shaded areas when relative humidity is combined with the air temperature. It can be calculated using the formula proposed for (Steadman, 1979):

$$\mathrm{HI} = 0.5 \cdot \left[\mathrm{T_{op}} + 61 + 1.2 \cdot \left(\mathrm{T_{op}} - 68\right) + 0.094 \cdot \mathrm{RH}\right] \tag{2}$$

where $\mathrm{T_{op}}$ is the operative temperature (in F) and RH is the relative humidity (in %) of the zone. In case the HI exceeds 80F (around 27ºC), the formula has to be replaced with the regression equation proposed by (Rothfusz, 1979), and A is an adjustment factor used under the conditions:

$$\begin{aligned}\mathrm{HI} = {} & -42.379 + 2.04901523 \cdot \mathrm{T_{op}} + 10.14333127 \cdot \mathrm{RH} - 0.22475541 \cdot \mathrm{T_{op}} \cdot \mathrm{RH} - 0.00683783 \cdot \mathrm{T_{op}^2} - \\ & 0.05481717 \cdot \mathrm{RH}^2 + 0.00122874 \cdot \mathrm{T_{op}^2} \cdot \mathrm{RH} + 0.00085282 \cdot \mathrm{T_{op}} \cdot \mathrm{RH}^2 - 0.00000199 \cdot \mathrm{T_{op}^2} \cdot \mathrm{RH}^2 - \mathrm{A}\end{aligned} \tag{3}$$

$$\mathrm{A} = \begin{cases} \left[\frac{(13-\mathrm{RH})}{4}\right] \cdot \sqrt{\left(\frac{17-\left|\mathrm{T_{op}}-9\ \right|}{17}\right)}, & \mathrm{RH} < 13\% \cap 80\mathrm{F} < \mathrm{T_{op}} < 112\mathrm{F} \\ \left[\frac{(\mathrm{RH}-85)}{10}\right] \cdot \left(\frac{87-\mathrm{T_{op}}}{5}\right), & \mathrm{RH} > 85\% \cap 80\mathrm{F} < \mathrm{T_{op}} < 87\mathrm{F} \end{cases} \tag{4}$$

Prolonged exposure to high values of HI can have serious consequences on health. Hence the United States National Weather Service (NWS) produces periodical forecasts and develops an alert system classifying the HI into four risk bands: Caution (27<HI<32), possibly leading to fatigue; Extreme Caution (32<HI<41), possibly leading to a heat stroke, cramps or exhaustion; Danger (41<HI<52), likely leading to heat cramps or exhaustion; Extreme danger (HI>52), highly likely leading to heat stroke (National Weather Service, 2022).

2.4.3 Humidex

The Humidex (H) describes how hot the weather feels to the average person, by combining the effect of temperature and humidity, derived from the dew point. The Humidex is the HI equivalent used by Canadian waring system, which defines five discomfort bands: Noticeable Discomfort (30<H<35); Evident Discomfort (35<H<40); Intense Discomfort (40<H<45); Dangerous Discomfort (45<H<55), or possible heat stroke; Heat Stroke Probable (H>55) (CSGNetwork.com, 2011). The formula used by (Environment Canada, 2013) is:

$$\mathrm{H} = \mathrm{T_{op}} + 0.5555 \cdot (\mathrm{E} - 10) \tag{5}$$

where $\mathrm{T_{air}}$ is the air temperature of the zone (in ºC) and E is the vapour pressure (in hPa), given by ($\mathrm{T_{dew}}$ is the dew point in K):

$$\mathrm{E} = 6.11 \cdot \mathrm{e}^{5417.7530 \cdot \left[\left(\frac{1}{273.16}\right) - \left(\frac{1}{\mathrm{T_{dew}}}\right)\right]} \tag{6}$$

2.4.4 Indoor Overheating Degree (IOD), Ambient Warmness Degree (AWD) and Overheating Escalation Factor

The Indoor Overheating Degree (IOD) was introduced by (Hamdy et al., 2017) to account for different comfort limits for separate dwelling zones, reflecting the particular occupant's behaviour and the adaptation capacity of each identified zone. For this study, the average temperature of all zones in the dwelling is considered. The formula is simplified as follows:

$$IOD = \frac{\sum_{i=1}^{N}\left[\left(\mathrm{T_{op,i}} - T_{comf}\right)^{+} \cdot \mathrm{t_i}\right]}{\sum_{i=1}^{N} \mathrm{t_i}} \quad (7)$$

where $T_{op,i}$ and T_{comf} are the operative temperature and the comfort threshold (in ºC) at time t_i and N is the total number of occupied hours. Results are presented for T_{comf} equal to 26ºC and to the upper adaptive comfort thresholds ($T_{i,CAT}$).

(Hamdy et al., 2017) also introduced the Ambient Warmness Degree (AWD) to quantify the warmness of a given climate scenario considering both the accumulation of amplitude and the duration of each occurrence. The indicator is calculated against a base temperature of 18ºC:

$$AWD_{18ºC} = \frac{\sum_{i=1}^{N}\left[\left(\mathrm{T_{amb,i}} - 18ºC\right)^{+} \cdot \mathrm{t_i}\right]}{\sum_{i=1}^{N} \mathrm{t_i}} \quad (8)$$

where $\mathrm{T_{amb,i}}$ is the ambient air temperature. Finally, the Overheating Escalation Factor (α_{IOD}) is a metric that represents the deviation of the intensity of indoor OH (IOD) from the severity of the outdoor warmness (AWD) which is causing it. α_{IOD} is then calculated as a coefficient:

$$\alpha_{IOD} = IOD/AWD_{18ºC} \quad (9)$$

α_{IOD} is used to estimate the sensitivity of dwellings to outdoor OH and quantify its ability to maintain comfortable indoor conditions despite the heat stress. Values of α_{IOD} above the unit mean that the internal T increase is steeper than the external, meaning that the building is not able to counter the heat stress and is escalating the OH effect. On the contrary, the closer α_{IOD} gets to zero the better the building is able to withstand external OH. A thermal resilient building should ideally present low values of α_{IOD} no matter the intensity of outdoor warmness.

3 RESULTS AND DISCUSSION

This chapter presents and discusses the main results obtained from the calculations of thermal resilience indicators (2.4) for the six scenarios under analysis, resumed in Table 3.

Table 3: Resume of thermal resilience indicators calculated for the six simulation scenarios during a period of two weeks surrounding the heat wave events

Indicator	Historic 2018 (27 Jul - 10 Aug) Aware	Historic 2018 (27 Jul - 10 Aug) *Fixed*	RCP4.5 Extreme 2030 (14 Aug – 28 Aug) Aware	RCP4.5 Extreme 2030 (14 Aug – 28 Aug) *Fixed*	RCP4.5 Extreme 2050 (18 Jul – 1 Aug) Aware	RCP4.5 Extreme 2050 (18 Jul – 1 Aug) *Fixed*
27<HI<32 – Caution	37%	*2%*	1%	/	/	/
32<HI<41 – Extreme caut.	62%	*83%*	88%	*64%*	64%	*24%*
41<HI<52 – Danger	/	*15%*	11%	*36%*	36%	*74%*
HI>52 – Extreme danger	/	/	/	/	/	*2%*
35<H<40 – Evident disc.	62%	*24%*	39%	*3%*	18%	*2%*
40<H<45 – Intense disc.	20%	*59%*	50%	*61%*	47%	*24%*
45<H<55 – Dangerous disc.	/	*15%*	11%	*32%*	35%	*59%*
H>55 – Heat stroke probable	/	/	/	*4%*	/	*15%*
Adaptive - CAT II	38%	*3%*	27%	*1%*	15%	/
Adaptive - CAT III	20%	*9%*	34%	*7%*	29%	*4%*

Adaptive - CAT IV	4%	*88%*	22%	*92%*	54%	*96%*
$AWD_{18ºC}$	9.5	*9.5*	10.7	*10.7*	11.6	*11.6*
IOD – T_{comf} = 26ºC	4.18	*7.26*	5.07	*8.34*	6.54	*9.32*
IOD – CAT I	0.54	*3.48*	0.89	*3.98*	2.06	*4.74*
IOD – CAT II	0.14	*2.50*	0.32	*2.98*	1.15	*3.74*
IOD – CAT III	0.01	*1.58*	0.09	*2.05*	0.46	*2.76*
α_{IOD} – T_{comf} = 26ºC	0.44	*0.76*	0.47	*0.78*	0.55	*0.80*
α_{IOD} – CAT I	0.06	*0.37*	0.08	*0.37*	0.17	*0.41*
α_{IOD} – CAT II	0.02	*0.26*	0.03	*0.28*	0.10	*0.32*
α_{IOD} – CAT III	/	*0.17*	0.01	*0.19*	0.04	*0.24*
Consecutive days above 32ºC (during all summer)	3 days	*18 days*	6 days	*69 days*	5 days	*87 days*
Consecutive hours above 30ºC (during all summer)	142 hours 5 nights	*332 hours* *13 nights*	136 hours 5 nights	*668 hours* *27 nights*	232 hours 9 nights	*930 hours* *38 nights*
Consecutive hours above 28ºC (during all summer)	330 hours 13 nights	*570 hours* *23 nights*	666 hours 27 nights	*2.177 hours* *90 nights*	454 hours 18 nights	*2.199 hours* *91 nights*

Figure 3 compares the indoor operative temperatures obtained with aware and fixed control during the two weeks around the 2018 HW (from 27 July to 10 August). The aware control is able to maintain indoor T within acceptable comfort values for most of the time (96% below CAT IV), albeit exceeding 32ºC for three consecutive days and reaching a maximum of 32.7ºC. The daily minimum T exceeds 30ºC for five consecutive nights and only gets below 28ºC once in the period analysed. With fixed control, the indoor T fluctuates considerably more, reaching a daily maximum T of 35.9ºC. The night ventilation is not able to adequately drop the temperature, leading to 88% of time in CAT IV and to seven consecutive nights above 32ºC.. Figure 4 repeats the comparison for the most severe HW found in the 2050 weather file (from 18 July to 1 August). Results reveal that, even with aware control, the maximum T exceeds 32ºC for twelve of the fourteen days analysed (five consecutive) and reaches a maximum of 35.5ºC, causing discomfort for more than half of the time (56% above CAT III). Just one night T is below 30ºC, while six nights experience T of above 32ºC (three consecutive). With fixed control, the indoor T reaches 36ºC twelve out of fourteen days (six consecutive) and peaks at 38.6ºC. Discomfort is experienced at all time (96% above CAT III), with minimum T never below 32ºC and above 34ºC for eight nights (four consecutives).

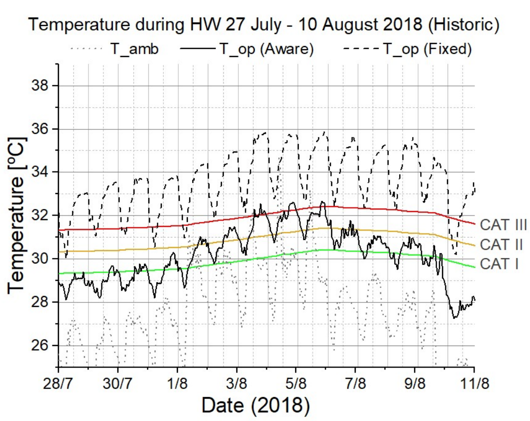

Figure 3: Indoor operative temperature (T_op - black) with aware (solid) and fixed ventilation (dashed), ambient temperature (T_amb – dotted line) and adaptive temperature thresholds profiles (CAT I, II and III) during the HW of 2018

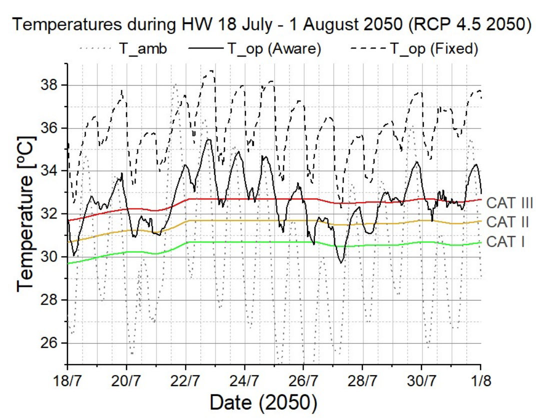

Figure 4: Indoor operative temperature (T_op - black) with aware (solid) and fixed ventilation (dashed), ambient temperature (T_amb – dotted line) and adaptive temperature thresholds profiles (CAT I, II and III) during the HW of 2050

When looking at the adaptive comfort model, the aware control can offer higher comfort in 2050 than fixed control in 2018. However, the ambient temperature in 2050 reaches levels for which T_{rm} often exceeds 30ºC, stepping out of the validity band of the adaptive comfort model. Figure 4 shows that the thresholds remain constant for four consecutive days (from 22 to 26 July) during the 2050 HW. Thermal comfort has a strong psychological bias, which means humans could adapt to a hotter climate with time. If that is the case, the adaptive comfort model might have to be revised by adjusting the comfort thresholds to higher temperatures.

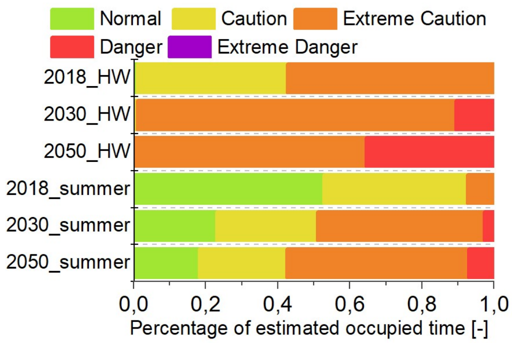

Figure 5: Share of time spent in each Heat Index caution band during the heat wave (HW – above) and the whole summer (below) of 2018, 2030 and 2050

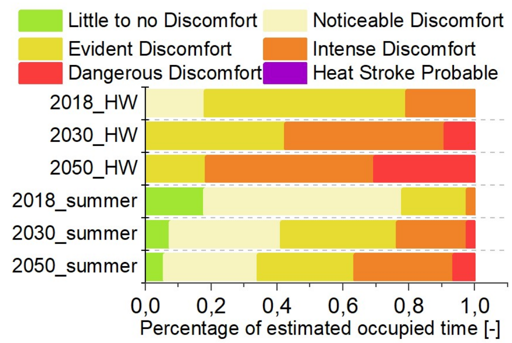

Figure 6: Share of time spent in each Humidex comfort band during the heat wave (HW – above) and the whole summer (below) of 2018, 2030 and 2050

Figure 5 and Figure 6 compare the unmet hours of Heat Index and Humidex calculated for the heat wave (HW) and the whole summer of 2018, 2030 and 2050.
Looking at HI shows that, while just 7% of time in summer 2018 is in *Extreme Caution* (57% for HW), around half of summer time in 2030 and 2050 is either in *Extreme Caution* or worse (always for HWs). *Danger* conditions are not experienced in 2018 HW, while they occur for 11% and 36% of time in 2030 and 2050. The considerations are similar looking at H, since the share of *Evident Discomfort* or worse grew from 22% in 2018 summer (82% for HW) to 66% in 2050 (always for HW) and that of *Intense Discomfort* or worse grew from 2% (21% for HW) to 36% (82% for HW). Again, *Dangerous Discomfort* only occurs in 2030 and 2050 HWs for 9% and 30% of time. The different definitions of the thresholds adopted by the two indicators make it impossible to line up exactly the HI risk bands with the H discomfort bands.

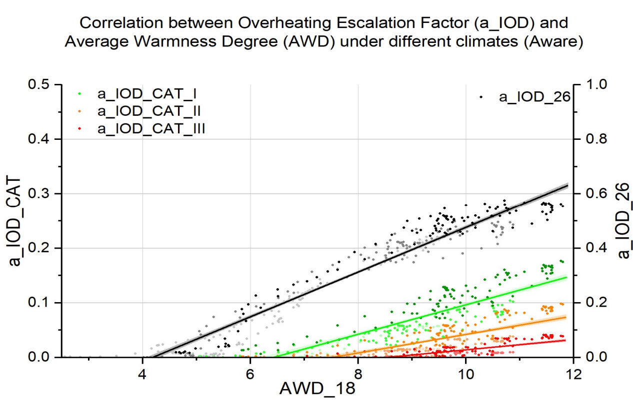

Figure 7: Correlation between Average Warmness Degree (AWD) and Overheating Escalation Factor (α_IOD), calculated using fixed (right – a_IOD_26) and adaptive comfort temperature thresholds (left – a_IOD_CAT), with aware ventilation control; dots are two weeks period around every summer day of 2019, 2030 and 2050

However, the share of time in dangerous conditions (*Danger* and *Extreme Danger* for HI, *Dangerous Discomfort* and *Heat Stroke Probable* for H) is almost equal under all circumstances, ranging from 11% and 35-36% with aware control in 2030 and 2050 up to 74-76% with fixed control in 2050. Figure 7 shows the correlation between the Average Warmness Degree (AWD) and the Overheating Escalation Factor (α_{IOD}), calculated with a constant comfort temperature (a_IOD_26) and with adaptive comfort thresholds (a_IOD_CAT), for the aware control scenario.
For harmonization purposes, all indicators were calculated for a two-weeks period around each day of the summers of 2018, 2030 and 2050 simulated in the study, corresponding to a single

dot in Figure 7. Regardless of the comfort threshold used, a linear proportion between AWD and α_{IOD} was found. These results mean that the thermal mitigation capacities of the building degrade with the severity of ambient conditions. α_{IOD} calculated with fixed control and T_{comf} = 26ºC reach values close to the unit (0.91 in 2030 and 0.92 in 2050), which would lead to an uncontrolled escalation in indoor OH. On the contrary, using aware control the IOD is far from exceeding the outdoor warmness (AWD).

4 CONCLUSIONS

This study compared two passive overheating mitigation strategies, which adopt natural ventilation and solar shading, under historic and future extreme climate conditions. The occupant control based on external temperature (Aware) provided much better results than a fixed schedule for natural ventilation (Night), as it is implemented in the Spanish Technical Code. In future climate, occupants will not be able to maintain indoor comfort by adopting standard cooling strategies typical of the Mediterranean region.

In order to minimize the use of air conditioning, occupants will have to embrace a proactive approach to thermal control strategies, acting on natural ventilation and solar shading according to temporary requirements. This task could be simplified with alert signals and automatic devices. Further research will aim to validate the results obtained, understand the impact of the hypothesis used in the implementation of the model (e.g. occupation, thermal inertia, infiltration, etc.) and isolate the effect of natural ventilation from that of solar shading.

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