Resilient Design in Extreme Climates: An Overheating Assessment Method for Naturally Ventilated Buildings

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Abstract

Owing to global warming, overheating has become a risk and the main source of discomfort when speaking about indoor thermal comfort. On one hand, energy consumption together with the risk of heatstroke rises during warm periods. While on the other hand, there is no broadly accepted method to measure overheating in naturally ventilated buildings. Most of the literature is limited to a simple count of hours above comfort limit, disregarding the intensity and temporal extent of the overheating periods. This paper proposes a novel five-step method for the assessment of overheating in existing and new buildings. The objective is to assess the suitability of a building interior for human occupation through the analysis of the overheating periods; the proposed method uses as a key framework, adaptive comfort theory and the established limits for thermal comfort and human health. It consists of the hourly counts of overheating hours according to their distance to the upper comfort limit (i.e., hours above 0.1°K, 1°K, 2°K, 3°K, and 4°K). The output of the method provides quantitative results useful to determine the effect of overheating in thermal comfort and the risk it represents.

1. Introduction

Nowadays, there is no doubt that anthropogenic heat due to the ever-increasing burning of fossil fuels to the atmosphere is the main cause of Climate Change (CC). Temperatures are progressively rising across the globe establishing new records on practically daily basis [1], and despite the global efforts, energy consumption for the purpose of space cooling keeps increasing at a frightening rate.

1.1 Overheating as an epidemic

The unceasing overheating in buildings provoked by Global Warming (GW) phenomena meets all the requirements to be considered an epidemic. Overheating during a heatwave simultaneously affects a disproportionately large number of individuals, and it represents a potential health risk if the proper measures are not considered [2], [3]. As a reflection of this, it has been found in recent studies [4], [5] that morbidity and mortality increase during heatwaves, as well as the appearance of heat stroke-related symptoms. The starting point of every health-related event on account of overheating, is always heat-induced thermal stress, whereas the endpoint of it, can differ, depending on the vulnerability of the exposed person exposed.

Overheating is affecting everyone around the world in different ways. As a consequence of the accumulation of Greenhouse Gases (GG), the temperature gradient between the equator and the poles is decreasing following the increase of temperature at the poles [6]. Ironically, heat-related health issues and fatalities are increasing at a higher rate in high-latitude temperate countries, rather than in tropical and sub-tropical locations where temperatures are considerably higher, and where they frequently reach conditions surpassing the tolerable limits of the human body, the reason being that people in tropical settings are more adapted and acclimatized to experience these events, rather than the inhabitants at prevailing temperate, continental and cold climates, where weather conditions can be considerable colder [7].

1.2 Overheating, Air Conditioning, and natural ventilation

The implementation of Air Conditioning (AC) systems is the modern solution for an old problem that was historically and traditionally solved with passive strategies. Vernacular architecture across the globe, and especially the one found in tropical regions is climate-responsive, the architectural design was conceived to create and maintain comfortable conditions bearing in mind the local climate's conditions, challenges and opportunities [8], [9]. Given the current environmental and energy-related situation, natural ventilation, selectively treated, should be considered as the main passive cooling alternative in all climates, as it has been recently confirmed, that even at high latitude locations, the climate potential along with the proper balance of building materials can be highly efficient [10], [11].

Not so long ago, it was believed that AC systems were beneficial for the indoor air quality and they were particularly recommended for buildings in metropolitan areas [12]. Nevertheless, further studies exposed this as a misconception, as they were found to be the main source of discomfort and other diseases such as the Sick Building Syndrome (SBS) [13], [14]. Additional research has demonstrated that the recent efforts to improve the air quality in the cities, such as the ones performed in Mexico City, are starting to yield results, and the quality of the air surrounding the building is safe to breathe, and in some cases safer than that provided by AC systems[15], [16]. Moreover, there is research [17] that concludes that the original notion of natural ventilation, as it was found on hospitals before the arrival of the AC, is better for the patients since it reduces the risk of cross-contamination from virus and bacteria among patients, implying natural ventilation as a healthier solution, as it was found in another research, where they concluded that the sleep quality in naturally ventilated spaces is better since the percentage of time of REM sleep decreases as the concentration of CO^2 raises [18].

Another aspect worth mentioning is the potential risk that a sealed building represents, considering that an AC equipment requires a sealed envelope as well as demanding and constant maintenance, and its omission may result in the spread of diseases as it was confirmed by CIBSE and ASHRAE after the emerge of the COVID-19 pandemic [19] [20]. Buildings are supposed to provide safety and shelter to its occupants, and a sealed building can become easily dangerous and uninhabitable whenever an interruption in the ventilation system occurs, as it happened in 2012 in New York, during the aftermath of Hurricane Sandy, when some of the buildings became dangerous to be occupied as they were too hot and the indoor air quality in them was too risky, due to the lack of mechanical ventilation and the lack of provision of natural ventilation. [21]. Natural ventilation does not mean tolerance to heat and adaptation to overheating, as when it is properly designed, it can be more comfortable, safer and as effective and relieving as an AC system [22].

The systematic use of mechanical ventilation systems seems to be justified by a misconception. Natural ventilation does not mean tolerance to heat and adaptation to overheating when it is properly designed, it can be more comfortable, safer and as effective and relieving as an AC system [22]. Another misconception is the idea that AC systems help to maintain productivity, presuming cognitive performance decreases with the appearance of thermal stress; new studies suggest this was an overestimation, as it was found out that the building occupants of naturally ventilated buildings possess a sufficient cognitive reserve as long as adaptive opportunities are within their reach [23].

Thermal comfort theory started as a machine-centred formula to determine the thermostat setting of AC systems and with numerous inaccurate statements, such as the establishment of a universal fixed comfort band, where it was assumed comfort conditions for most of the occupants regardless outdoor conditions and cultural and social backgrounds [24].

Fortunately, nowadays we are experiencing a transitional phase where the adaptive thermal theory is being extended, and comfort standards such as the North American (ASHRAE Standard 55) and the European (CEN standard BS EN 16798), are slowly turning into a user-centred approach, considering the people's adaptation opportunities and behaviour capabilities, rather than machine's [25], [26].

At the moment, there is not a broadly accepted method to measure overheating in free-running or naturally ventilated buildings. Comfort theory is currently limited to a single count of hours above comfort, disregarding the intensity and extent of the time overheated. Over the years, there have been different approaches such as the ones proposed by CIBSE's TM52 and TM59 [27], [28], although, they have been heavily criticized since their criteria have been found difficult to satisfy, and further research needs to be done to validate them; moreover, its application is only limited to high latitudes European context, while the overheating of interior spaces, is a widespread problem around the globe, considering this, a comparable metric or measuring system would be of great assistance for the exchange and comparison of results, analysis methods and the implementation of passive cooling strategies in buildings.

1.3 Objectives

This research introduces a new method to measure and assess overheating in naturally ventilated buildings. It starts with an explanation of the theory in which is based on, followed by a description of its criteria and methodology. Due to the nature of its calculations, it can be used for the overheating estimation of new projects via building simulations or existing buildings through field studies. It is applicable to all sorts of naturally ventilated buildings including full-time or seasonal buildings. Additionally, since the method is based on the theoretical principles of adaptive thermal comfort and the latest findings in the field, it can be used to measure the effect of overheating in the thermal comfort perception, as well as a tool to determine the safety and habitability of interior spaces under extreme climatic conditions.

2. The old methods

The original thermal comfort approach was designed as a tool to regulate the operation of HVAC equipment. It was formulated considering data from experiments elaborated in the US during the '70s, during which, it was established a fixed comfort band (Comfort Zone) ranging from 20° to 26°C, based on a Predicted Mean Vote – Predicted Percentage of Dissatisfied (PMV-PPD) scale, a method derived from experiments in closed chambers, developed to measure the satisfaction-dissatisfaction of a group of individuals [29]. Despite the research produced during the forthcoming decades, current adaptive standards such as the ASHRAE standard 55 and the European EN 15251 (nowadays EN 16798) [30], [31] are still somehow linked to the original PMV-PPD method and they still hold similar principles.

Nowadays, after the internationalization of these two standards, one of their main issues is not necessarily their composition, but the fact they are being applied in contexts with very different conditions than the ones they were designed for, considering that they were developed studying very specific data regarding the climate, thermal expectations and thermal background of the people participating in the field studies, all of these elaborated in various locations across Europe and the United States of America [25], [32], [33].

2.1 Issues with the old methods

As these standards continued to be applied and researched, it was a matter of time before their applicability and composition were questioned. Among the most relevant finding in the evolution of thermal standards, are the findings by Cheung et al [34], where the accuracy and reliability of the PMV-PPD method was tested and it was discovered that the method's prediction of thermal sensation is only accounted for 34% of the subjects with a range of overestimation of dissatisfaction of 15-25%, questioning the application of the current standards since they are both based on this method. Other researchers [35]–[39] reached similar conclusions when testing the established theoretical comfort limits; and among the common findings, it is highlighted the unaccounted adaptability of the subjects when speaking about naturally ventilated buildings.

Recent studies reported that occupants in a mix-mode building were more tolerant to temperatures above and below the comfort limits, whenever the building operated as naturally ventilated, the occupants demonstrated efficient use of adaptive opportunities higher than the ones predicted by the standard [40]. Under the same type of research, another work developed in Asia [41], suggested that Asians were more tolerant to warm temperatures since they report to be comfortable within a generalized offset of 1-2K above the upper comfort limit suggested by ASHRAE standard 55. Both works implied the possibility of extending the comfort band according to these findings, proving the possibility for the application of a wider and less strict comfort metric.

There is not a common agreement between comfort models or theoretical literature regarding the highest possible temperature limit in which the occupants of a free-running building would be comfortable. The ASHRAE standard 55 suggests an upper limit of 33.5°C for the U.S., whereas the EN 15251 suggests 30.5°C for Europe. The reason for this difference is because both standards are based on user's satisfaction questionnaires from which the thermal expectations were established, as well as the range of common limits of what could be considered comfortable at those specific locations [27].

The same omission has been found when speaking about relative humidity, early work by P.O. Fanger and B. Givoni, [29], [42] established that the optimum operative range of relative humidity is between 20 and 80%. Nevertheless, in tropical locations close to the equator such as Puerto Rico, Cuba, Malaysia or Vietnam, occupants are constantly experiencing higher levels than the ones suggested during most of the time. In the same way sub-tropical desert locations such as Egypt and Saudi Arabia, as well as most of the subtropical African countries, experience extremely dry conditions during a great part of the year. Despite these conditions, most building occupants in these areas are still comfortable, and most dwellings and workplaces are naturally ventilated, relying on passive strategies to achieve thermal comfort conditions.

There is no further research that establishes the actual limits for thermal comfort neither for workspaces nor dwellings located in tropical or subtropical settings. Research by [43] and [37], reached differently and opposed conclusions, mainly because they followed different objectives and methodologies, obtaining incomparable results, but still, it is possible to say that they agreed in stating that there should be a different comfort limit for each location, and it should consider the thermal history, expectations and cultural background of the subjects.

2.2 The typical method versus the new method

It is important to remark the applicability and utility of the proposed method in contrast with the current standards. Standards such as the EN 15251 provide a variable upper comfort limit that is meant to be considered the boundary in which most occupants are expected to remain mostly comfortable and operable, whereas, in the method presented in this research, it can be applied in two different ways.

In low latitudes, tropical and subtropical locations, where temperatures are frequently high, it can be used as a fixed comfort band to assess and evaluate indoor thermal quality and comfort conditions. Occupants in these locations are adapted and acclimatized to high temperature and they possess a better understanding of adaptive opportunities as well as a higher upper comfort limit.

In high latitudes, continental, temperate, and polar locations, where temperatures are rarely high, it can also be used as a fixed comfort band, although only to assess and evaluate the safety or the risk, of a certain building during an extreme weather situation, it may be the temporary effect of a heatwave, or to estimate the effect of a possible failure in the ventilation system. Additionally, the proposed method can also be used to evaluate indoor thermal comfort conditions during the warmest seasons of the year assuming the upper comfort limit as the one established in the local normative rather than the 39°C degrees boundary; with this, it is possible to estimate the effect of the thermal stress induced by overheating, as well as the effect of adaptive opportunities to regain thermal comfort conditions.

3. Thermal comfort and overheating

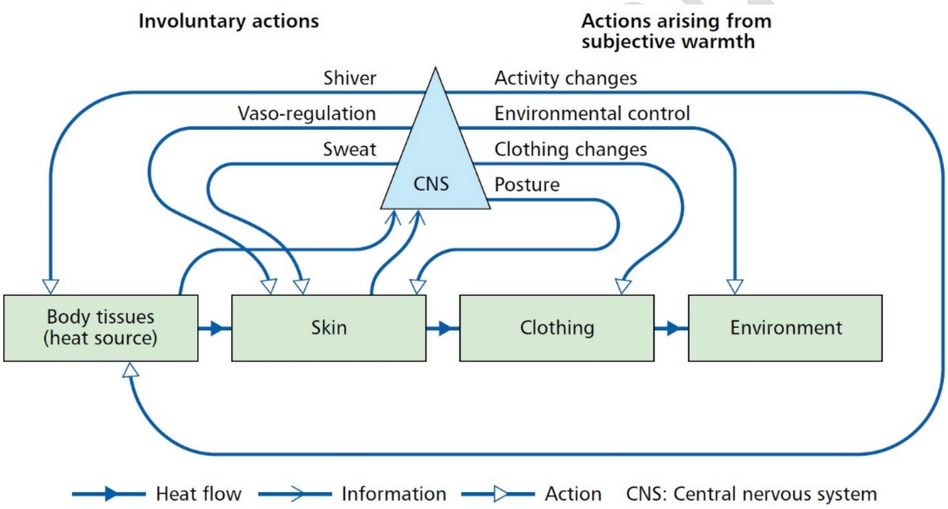


Figure 1. A diagram representing the control system for ensuring the internal body temperature is kept constant (Image source: [27], [44]).

Thermal comfort is directly related to the thermal necessity and capacity of the human body. The original literature in the subject [44] defines thermal comfort as a consequence of the self-regulatory system, where the nucleus of everything is the core of the body, followed by the subsequent layers such as the skin, clothing, and the surrounding environment (Figures 1 and 2). Considering this, it is possible to say that the human core temperature oscillates around 37°C [44], intending to be more specific about this range, B.R.M. Kingma et al, [45]–[47] coined the term Thermoneutral Zone (TNZ), defined as the temperature range from 26° to 30°C. Assumed as the temperature in which a person, laying at rest, naked and surrounded by still air and mean radiant temperatures within this range, would not have the physical need to either sweat or shiver to maintain homeostasis, therefore, there would be thermal stability of the body and no energy would be expended by the thermoregulatory system.

Whenever a person is exposed to overheated environments, the physical involuntary response of the body is sweating, meanwhile, the psychological response is thermal stress. As a result of this, most persons would look for ways to improve their comfort sensation by modifying their surroundings spaces through different actions, these specific actions are the ones defined as adaptive opportunities [25].

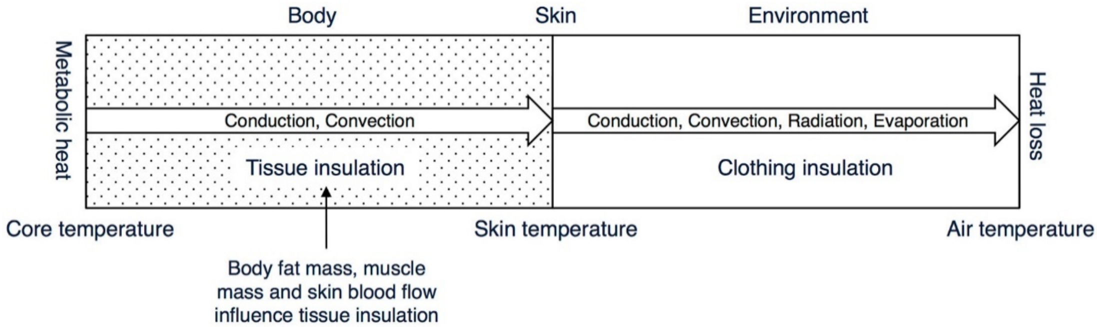


Figure 2. Schematic representation of a biophysical heat balance model. From left to right, heat balance is satisfied when metabolic heat production equals heat loss. The temperature gradient between the core and skin temperature is determined by metabolic rate and tissue insulation. (Source : [47], [48])

3.1 Adaptive opportunities

Adaptive opportunities are an efficient solution to achieve and maintain comfortable conditions. However, they are not necessarily faultless. Adaptive comfort theory suggests that the correct use of passive strategies together with adaptive opportunities may improve the thermal sensation and therefore push further the upper comfort limit [49] (Figure 3). Still, the effectiveness of these strategies and opportunities is variable depending on the conditions in which they are applied, they are more efficient when preventing overheating rather than when solving overheating [50]. Thus, it is important to anticipate its application when assessing the risk of overheating.

The overheating assessment method presented here, proposes a 35°C lower comfort limit. This temperature can be interpreted as the last point where occupants are mostly operational, and the conditions they are experiencing does not represent risks to their health. Although, depending on the subjects, they might be experiencing certain thermal stress which is not supposed to be a threat, given that it is assumed that the subjects are acclimatized [51].

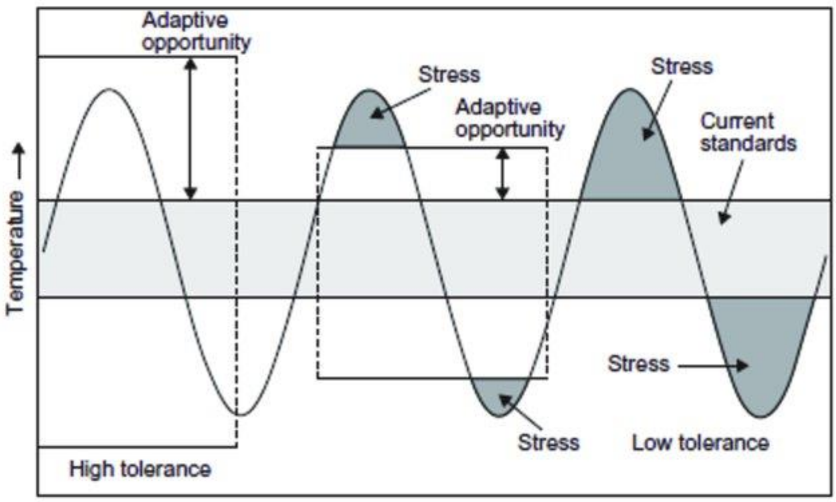


Figure 3. Effect range of passive strategies on a temperature curve concerning the comfort zone and thermal stress [52]

3.2 Adaptive thermal comfort in tropical and subtropical locations

When speaking about tropical and subtropical locations, it is important to keep in mind that despite what comfort models and adaptive thermal comfort theory suggest, most of the building stock in developing countries are solely depending on passive strategies as means to create and maintain comfortable conditions. Previous studies conducted in this settings [39], [53]–[55], concluded that most of the analysed subjects reported to be in comfort, as long as adaptive opportunities were possible, according to adaptive thermal theory, the reason for this is that most of the inhabitants of these locations acclimatize easily to warm conditions as they hold a closer relationship with the exterior environment, resulting in a more uniform thermal condition due to their thermal history [56]. If the conditions of these settings are evaluated according to North American and European the comfort models, the obtained results, as they come from the comfort equations, are most likely to indicate that people in these regions have lived and will be living under what could be considered overheating conditions, but since those limits were established in different contexts, they are not necessarily applicable for these locations. However, regardless of the possible location of the upper comfort limit, in order to gain a better understanding of the limits of overheating together with and evaluation of the possible risk it may represent, it is necessary to quantify and fully appreciate the extent of this overheating situation.

3.3 Thermal comfort in naturally ventilated buildings

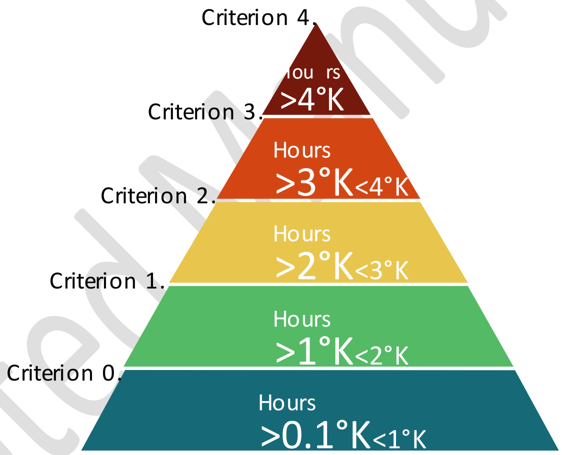
Recent work by F. Nicol [24], [49], [57], [58] suggests that adaptive thermal comfort in naturally ventilated buildings have different comfort ranges of operative temperatures. And for this reason, he proposes a general comfort band from 10°C to 35°C, this temperature range is derived from the findings of numerous fieldworks at several naturally ventilated buildings across the globe, the analysis tool to reach this range, was a method described as “comfort clouds”, with which, it was possible to visualize subjects as “clouds” in a graph, and each of them accounted as a specific group representative of a building or a group of buildings, by doing this, it is possible to better relate them to the outdoor conditions whenever the subjects concurred to report comfort. In general terms, this method was found to be more perceptive when defining a comfort range rather than the typical statistical analysis method where field data becomes flattened and simply interpreted as neutral temperature [24], [49], [57], [58].

The comfort range proposed by F. Nicol [24] is meant to be used to define the capacity of a building to maintain the interior conditions within this range. It also assumes the availability and use of adaptive opportunities. On a first glance, it might look like a broad range with an overestimation of comfort possibilities, nevertheless, it is important to remark that the criteria considered for this comfort band encompass a wide range of climates, cultures, and locations, that derived in the idea that there is not a universal “Comfort Temperature”, on the contrary, there many possible comfort ranges and conditions since there are many factors involved. For example, a group of inhabitants in the arctic circle may find an interior space at 10°C relieving and safe, while the outdoor temperature is below -20°C during the coldest months of the year, and those same subjects would probably find interior temperatures above 25°C quite uncomfortable during the warmest months, when outdoor temperatures are rarely above 29°C, in a similar way, a group of inhabitants in a sub-tropical temperate zone could find an interior space at 35°C relieving and refreshing whenever the outdoor temperatures are around 45°C, while they could find cold and uncomfortable an interior space at 18°C whenever the outdoor temperature is 15°C during the coldest months of the year. The specific comfort band to be applied in a specific case can be extrapolated from a field study using Nicol's comfort clouds, however, the delimitation of this specific comfort band is conditioned to the availability of adaptive opportunities and the user's possibilities of modifying their surrounding environment.

3.4 Adaptive thermal comfort in other regions

In other regions such as in temperate, Mediterranean, polar, and sub-polar regions, active means are needed at some point during the year to remain in comfort, therefore, the possibility of having free-running buildings is seasonal. Even when most buildings are equipped with heating systems, cooling systems were relatively uncommon until recent years. Unfortunately, due to Global Warming and Climate Change, the use of AC equipment is becoming more and more common in higher latitudes where they used to be uncommon. The comfort band of the proposed method may not be useful to assess adaptive thermal comfort in the same way it is used in lower latitude locations, since the thermal expectations of the users are going to be in a range below 30° [25] and the limit in the proposed method is 35°C, nevertheless, this method can still be used if the upper comfort limit is replaced with one derived from a locally accepted comfort model. Additionally, the proposed method in this paper can be used to assess the habitability and thermal autonomous capacity of a given building, in other words, how safe is to occupy the building without the aid of active means since the main function of a building is to provide shelter and protection from the natural environment, therefore, the new method can help to assess this in the unlikely but possible situation of a power failure during the hottest months of the year in a given location.

4. The new method



5.

6. Figure 4. Graphical representation of overheating hours subdivision criteria

This paper proposes a method based on 5-step hourly subdivision criteria to evaluate overheating. The method was designed as a tool to assess the intensity and frequency sensitively. The first part of the method divides overheating temperatures depending on how far they are from the adaptive upper comfort limit of 35°C, or the upper comfort limit of a locally established comfort equation. Each criterion could be described as follows:

- The number of hours above 0.1K. The total amount of hours where the temperature is strictly above the comfort limit but less than 1°K. The number of hours may represent in a rigorous way time outside of the comfort limit but not an overheating problem since a temperature change of less than 1°K is almost imperceptible for the body. [25].

- The number of hours above 1°K. The total amount of hours where the temperature is one whole degree or more above comfort but less than 2°K. This specific distance from the upper comfort limit is taken as a starting point since sensitive subjects would start feeling thermal stress, although it would still not represent a problem or significant thermal stress.

- The number of hours >2°K. The total amount of hours where the temperature is 2°K or more above comfort limit, but less than 3°K. This is where thermal stress is already manifested, and something should be done to recover comfort conditions.

- The number of hours >3°K. The total amount of hours where the temperature is three degrees or more above comfort but less than 4°K. This is where thermal stress is present, but still, it is possible to be solved and return to comfortable conditions.

- The number of hours >4°K. The total amount of hours where the temperature is four degrees or more above comfort. The last step before severe overheating can occur where conditions may still be bearable for the less sensitive subjects, but dangerous for sensitive subjects.

Once the overheating hours corresponding to a reading or a simulation result are distributed across the five-bands method, it is possible to appreciate the frequency of overheating hours, as well as their distance from the upper comfort limit. Figure 4 provides a graphical representation of this.

4.1 Yearly, seasonal, and monthly analyses

When analysing a building in a warm climate, different temporal scales can be useful to understand the occurrence of overheating. A yearly analysis provides a general overview to identify in a general way, the susceptibility for overheating and how this phenomenon may be spread across the year. A seasonal analysis can be useful to understand the thermal performance of a mixed-mode building during the temperature peaks of a given season. A monthly analysis provides more specific information regarding the intensity and chronological distribution of the overheating hours, where is possible to identify how dangerous the risk might be, as well as the effect of passive and adaptive strategies reflected on the percentage of time overheated.

To perform the analysis, the first step is to group the resultant temperatures within the five-step criteria, whenever they applied. The data can be obtained through a simulation model or physically collected thought fieldwork. When preparing the data, it is important to keep in mind the occupancy hours, otherwise, the results of the analyses can be misleading, since the non-occupancy hours would be affecting the final counts. This is directly dependent on the use of the building, for example, in an office building, the analysis may only include from 8:00 a.m. to 8:00 p.m. since it is the only time with people occupying the building, whereas, in the case of a dwelling, or an apartment building, the analysis should include the whole 24 hours as occupancy time, since it can be occupied at any time, especially if the analysis is for a risk assessment during an emergency.

The yearly and the seasonal analyses show the frequency of the phenomenon in an accumulative manner, where is possible to identify how predisposed to, and how severe the overheating may be. However, it fails to provide specific information about the overheating phenomena regarding its specific timing, and recurrence. When reading the results, it is important to make a distinction among the different criteria since the numbers represent different effects, for example, an elevated number in criterion 0 or 1, may not be interpreted as a troublesome overheating, as long as adaptive opportunities are available, whilst an elevated number in criterions 3 and 4 may end up putting into questions the habitability and safeness of the building that would need to be further evaluated through a monthly analysis. This type of analysis can also be helpful if they are elaborated during the design phase of a building, utilizing performance-based data to define certain elements during multiple iterations and computer simulations.

A monthly analysis provides the necessary data to evaluate the frequency of the overheating recurrence during all the months of the year, but especially for the warmest month of a location. The objective of the analysis is to present and organize the overheating hours, so it is possible to see how uncomfortable, or how dangerous a building can be. Overheating follows a cause-and-effect pattern; therefore, it is possible to be predicted and prevented when a place is predisposed to overheat, it happens when the combination of certain climate conditions converges, hence the hottest weeks or months of the year can be narrowed down and evaluated. When presenting the data arranged in a monthly way, it is possible to calculate the percentage of time overheated and it is easier to picture its effect, for example, a given building located in a subtropical zone has a yearly total of 157 hours above 38° and 61 above 39°, and during the hottest month of the year, that in this case is July, there are 53 hours above 38° and 14 hours above 39°, meaning that during this specific month 58 hours or 8.1% of the time, overheating can escalate dangerously. Looking at the same numbers, it is also possible to infer if overheating could have happened on a daily basis.

5 Examples of overheating assessment case studies.

5.1 Location data

With the interest in providing a better understanding of the method, eight different examples were elaborated as case studies. The same building was simulated using eight different EPW weather files, the calculation periods for all the files covered 15 years from 2004 to 2018 [59]. The locations are spread across the globe in prevailing tropical, subtropical, and Mediterranean locations, where overheating was identified as a problem. Other geographical regions were excluded since the assessment was aimed to explore the limits of extreme overheating and thermal comfort, the overheating limit of 35°C, may not be suited for testing in other regions, given that there are previous studies where the user's tolerance to overheating are less, as they are marked by the limits of the ASHRAE-55 standard and the CEN Standard BS EN 15251, settled as 33.5°C and 30.5°C, respectively [60]. In figure 5 it is possible to appreciate the hourly yearly temperatures of the locations selected as case studies.

Table 1 Specifications and details of the locations including Köppen's Climate classification, yearly average, yearly average maximum and yearly average minimum temperatures and absolutes minimum and maximum peaks.

	City	Country	Latitude	Longitude	Altitude	Type of Climate	Koppen´s Class.	Avrg. Yearly Temp. [°C]	Avg. Max. Temp [°C]	Max. Temp [°C]	Avg. Min. Temp [°C]	Min. Tem [°C]
1	Hermosillo	Mexico	29.10	-111.05	191	Subtropical	BWh	25.3	33.4	46.0	17.8	3.0
2	Teresina	Brazil	-5.06	-42.82	67	Tropical	Aw	29.1	34.7	40.0	24.5	20.0
3	Cordoba	Spain	37.85	-4.85	92	Mediterranean	Csa	18.1	25.1	41.3	11.8	-0.4
4	Naples	Italy	40.85	14.30	72	Mediterranean	Csa	17.3	21.3	39.0	13.1	-2.0
5	Cairo	Egypt	31.12	31.41	116	Subtropical	BWh	22.9	28.2	41.8	18.0	7.0
6	Abuja	Nigeria	9.25	7.00	344	Tropical	Aw	26.4	31.8	39.8	22.1	12.9
7	New Delhi	India	28.59	77.21	215	Subtropical	BSh	24.8	30.8	43.8	20.0	3.6
8	Karachi	Pakistan	24.91	67.16	31	Subtropical	BWh	26.9	32.2	42.0	22.3	7.0

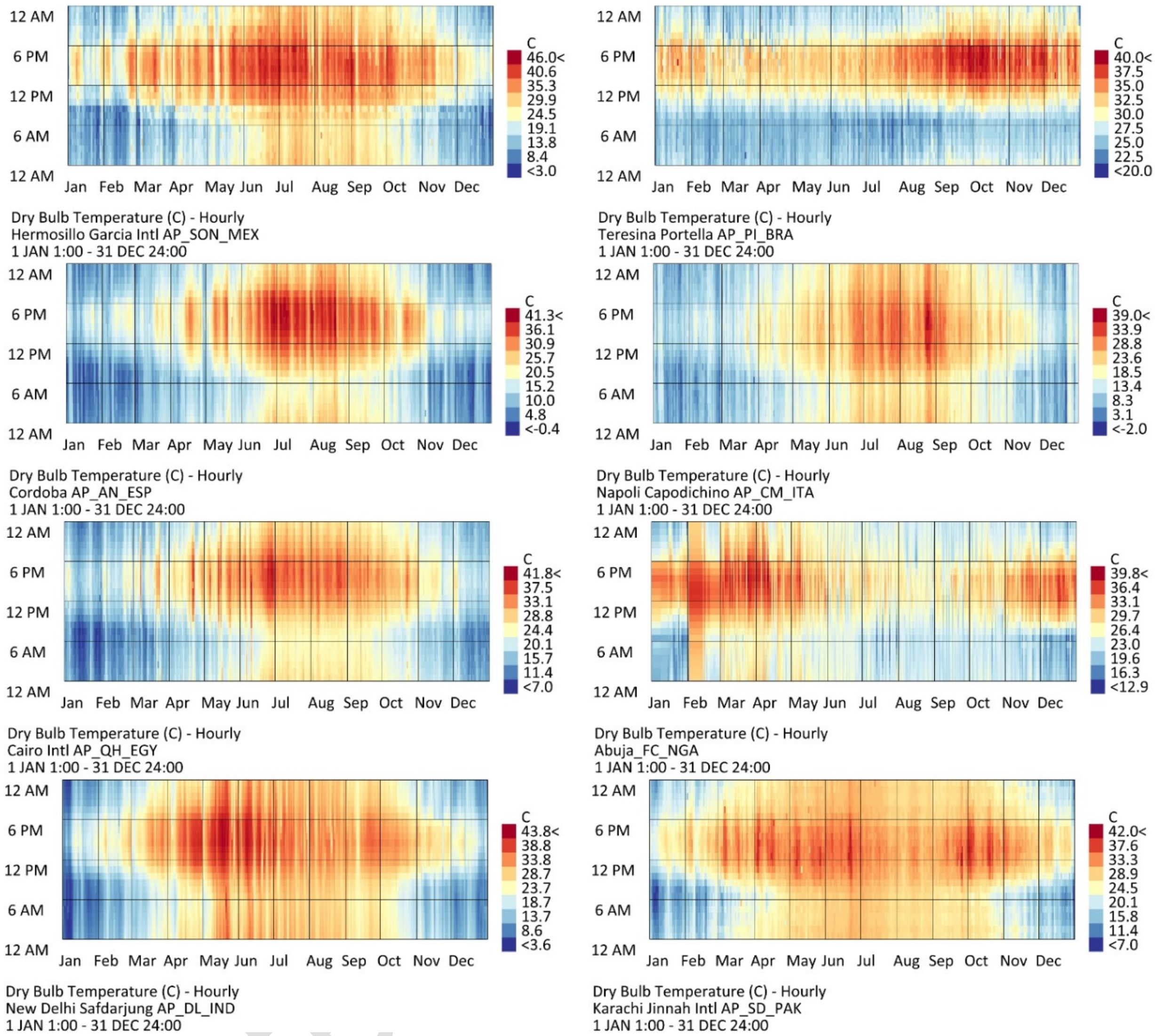


Figure 5. The yearly hourly temperature of each location according to the weather files (2004-2018).

5.2 Simulation Assumptions

A reference building was established, and a digital model was elaborated using the Ladybug tools under Rhino Grasshopper, with Energy plus as a simulation engine. The reference building was modelled as a dwelling space with a surface of 54m² with an interior height of 2.5m, based on a rectangular floor plan, window openings were in the north and south facades. The total area of the window fenestrations, accounted for a relatively low window to floor ratio of 0, equivalent to 0.15 in a window to wall ratio. A ratio within the characteristic range of dwellings located in subtropical regions [9]; table 2 provides a summary of these values. The building materials were selected according to the traditional methods found in common among the locations [61]. In table 3, there is a summary of the building materials and the U-Values considered. For the internal conditions, and occupancy of 3 m² per person or 0.33 people per m² was considered, with and equipment load of 10 W/m² and a lighting load of 3 W/m².

The simulation file was set up assuming a completely passive, naturally ventilated building, excluding any possible neighbouring or contextual buildings. A permanent infiltration value of 0.75 ACH was included, as well as an automated window operation algorithm, according to the interior and exterior temperatures, imitating the possible user's behaviour. For the window openings, a 50% of fraction operable window glazing area was configured.

Table 2. Building model details

Interior Surface	53.87 m²
Interior Volume	134.66 m³
WFR	0.21
WWR	0.15
Infiltration	0.75 ACH
Interior Height	2.50 m

Table 3. Building materials and U-Values in the building model

Elements	Materials	U-Value	Width
Exterior Walls	brick and cement	2.22 W/m²K	200 mm
Roof	Concrete Slab	1.48 W/m²K	300 mm
Exterior Windows	Single Glazing	5.2 W/m²K	12 mm
Floor	Concrete & Flooring	3.13 W/m²K	4500 mm

5.3 The European standard vs the new method

In figure 6, it is possible to appreciate the yearly hourly distribution of the operative temperatures, with the interest in comparing the methodology proposed in this paper, with a valid and currently prescribed standard. The comfort, overheating and underheating hours are plotted in Figure 7, according to the resultant comfort limits established by the CEN standard BS EN 15251 standard for naturally ventilated office buildings, the comfort was calculated assuming a ±4K width comfort band. In Figure 8, are the hourly upper comfort limits according to the comfort algorithm. Following the same criteria, In Figure 9 are the yearly distributions of overheating hours and their distance from the 35°C, following F. Nicol upper limit for naturally ventilated buildings. Table 4 shows the comfort assessment results, according to the CEN standard BS EN 15251, with the total percentage of time in comfort, percentage of time underheated and percentage of time overheated, as well as the total percentage of time above 35°C. In the last column of Table 4 the difference between methods when prediction overheating hours are presented, the calculation was made subtracting the total overheating time predicted by the proposed method to the overheating time predicted by the CEN standard BS EN 15251.

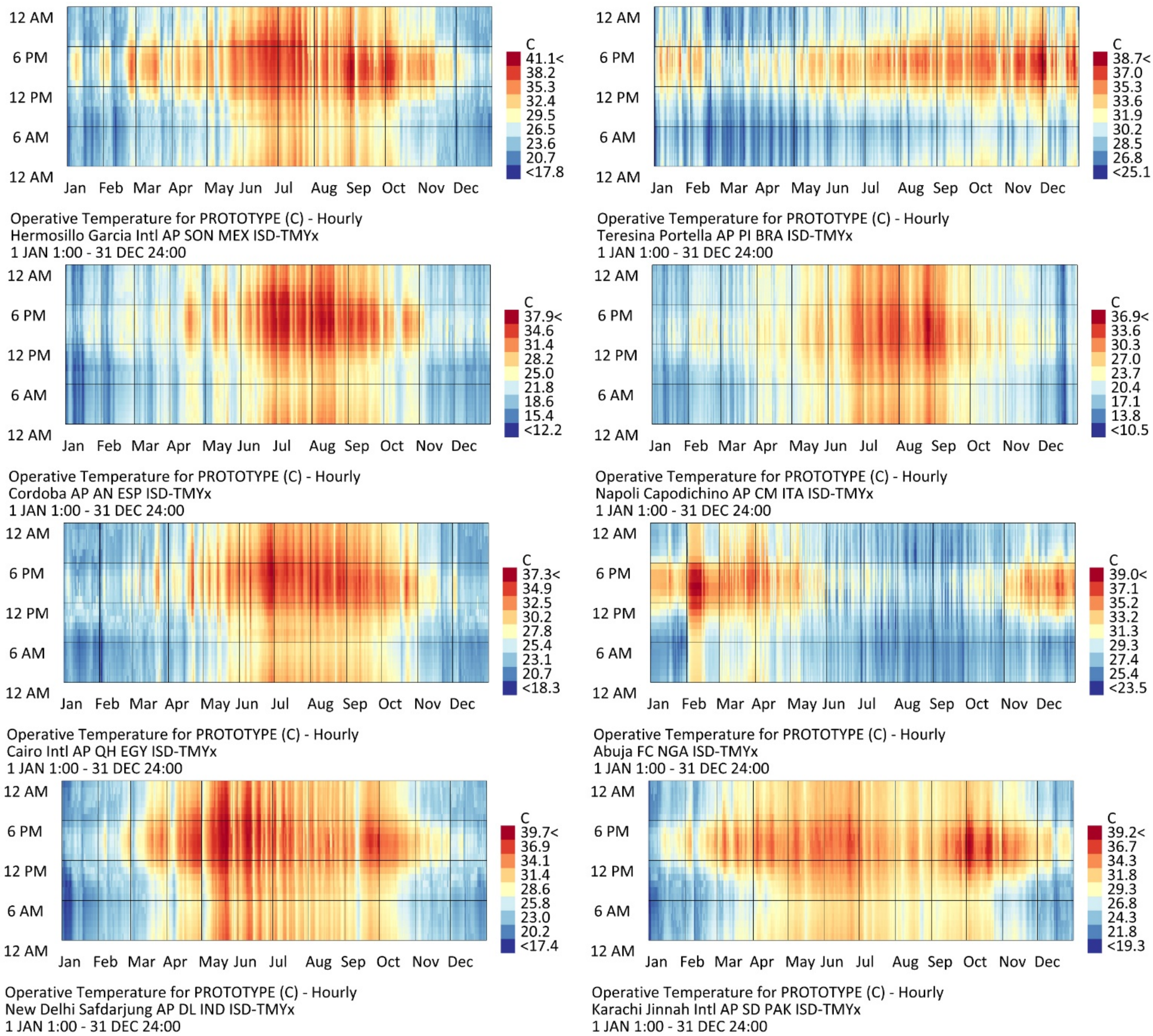


Figure 6. Yearly hourly distribution of the resultant operative temperatures of each location.

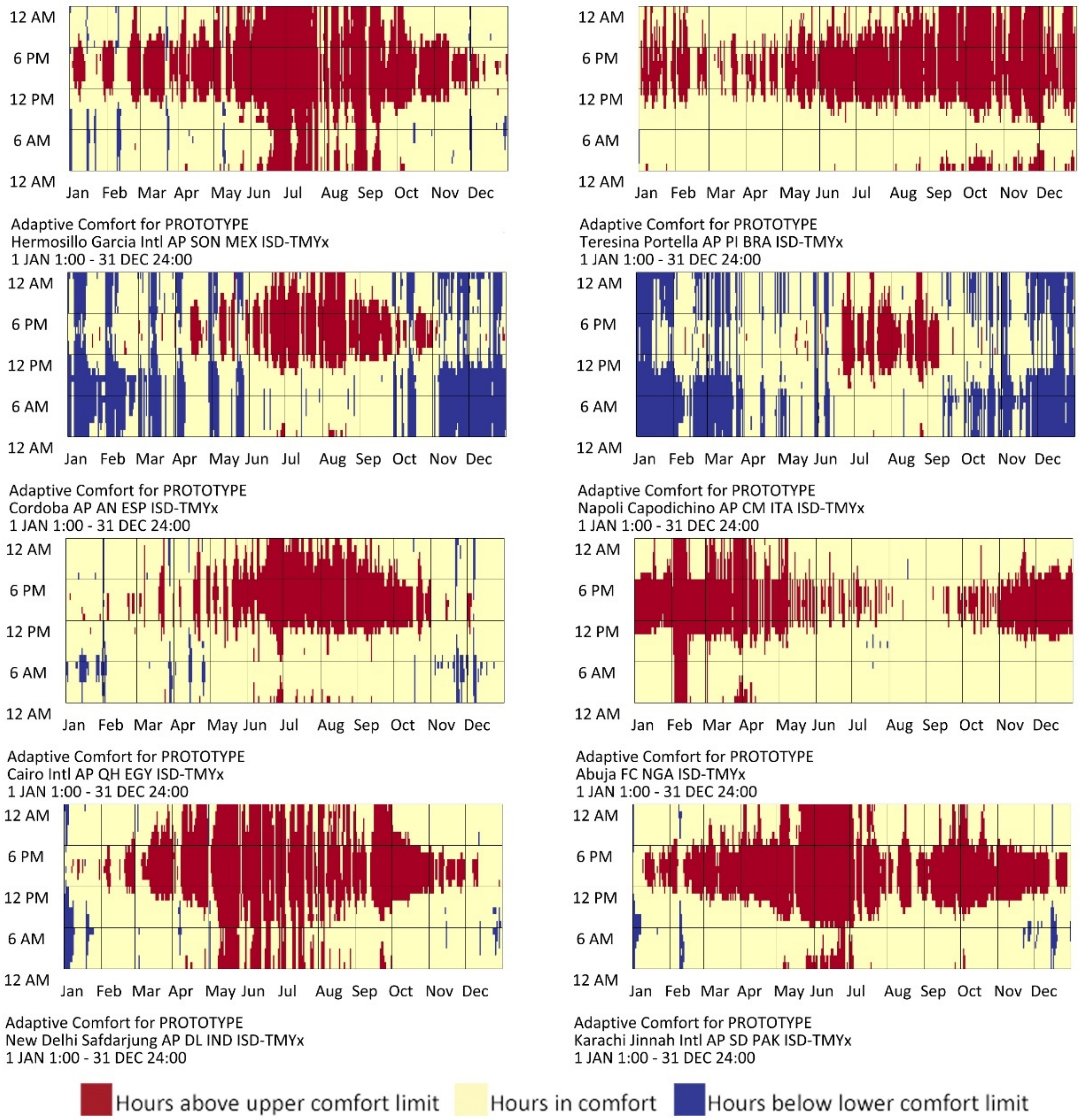


Figure 7. Comfort assessment according to the CEN standard BS EN 15251

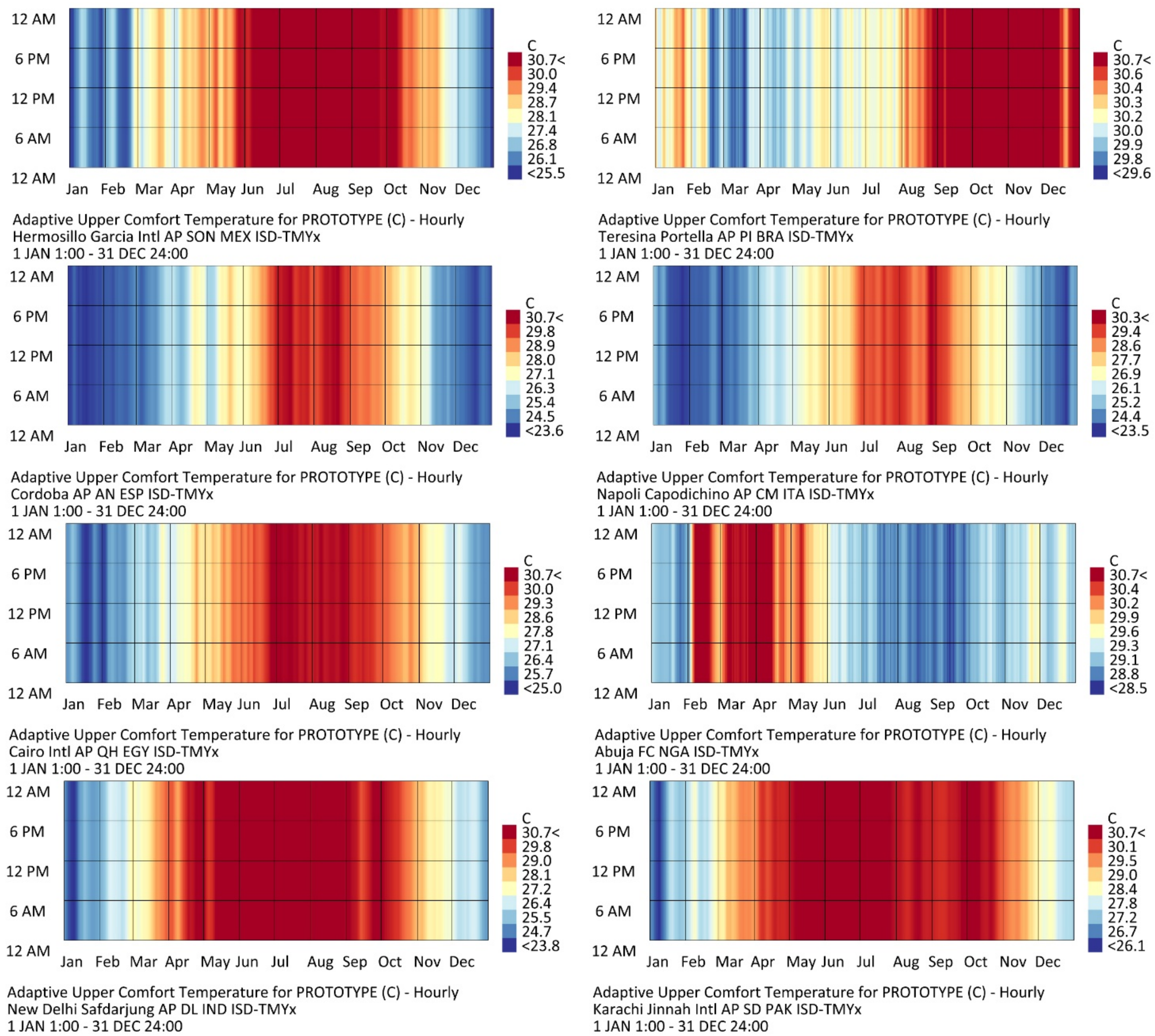


Figure 8. Comfort upper limit according to the CEN standard BS EN 15251

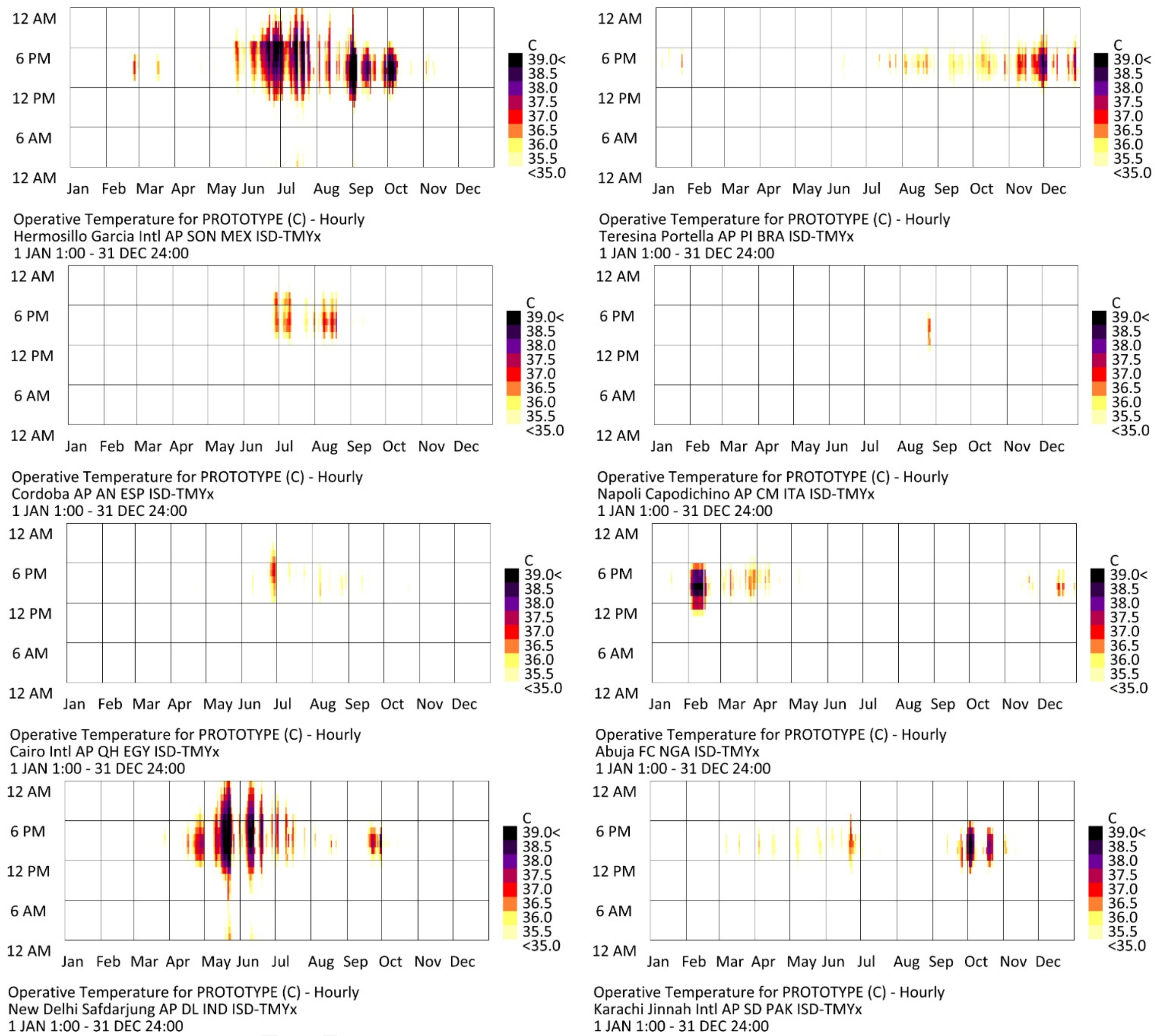


Figure 9. Yearly distribution of overheating hours and their distance to the 35°C boundary according to the proposed method.

Table 4. Comparison of overheating analysis between the CEN Standard BS EN 15251 and the proposed method, considering the total percentage of time above threshold temperatures.

CEN Standard BS EN 15251

City	Country	Comfort [%]	Hot [%]	Cold [%]	Total Overheating >35°C [%]	Difference between methods [%]
Hermosillo	Mexico	42.6	49.7	7.7	12.1	37.6
Teresina	Brazil	42.5	56.9	0.5	6.0	50.9
Cordoba	Spain	41.1	21.0	37.9	2.5	18.5
Naples	Italy	40.4	13.5	46.1	0.2	13.3
Cairo	Egypt	53.5	33.1	13.4	1.4	31.7
Abuja	Nigeria	60.0	39.0	1.0	3.3	35.7
New Delhi	India	44.0	48.9	7.1	9.2	39.8
Karachi	Pakistan	40.4	54.2	5.5	3.4	50.7

The difference between methods for the overheating prediction can be noticed at first sight when comparing Figure 7 and Figure 9. When speaking about the CEN standard BS EN 15251, everything that falls outside the upper comfort limits is considered as overheating despite the distance from the upper comfort limit, whereas in the proposed method, there is a sensible count considering the strength of the overheating, the application of this approach incorporates the possibility of an important energy-saving attribute mean to mitigate Climate Change.

The locations with the fewer overheating differences are Cordoba (13.4%) and Naples (7.6%), both Mediterranean locations with the lowest yearly average temperatures and minimum temperature peaks, in the predictions of both methods, there is no overheating during winter, according to the European standard, the overheating season is spread during the summer months, in contrast with the proposed method where overheating is only occasionally during the summer temperature peaks, being reduced from months to days. The similar trend continues in the locations with values above 20% but below 30%, Cairo (21.5%), Abuja (24.8%), New Delhi (28.4) and Hermosillo (29%), where according to the European standard, the peak of overheating season is during the summer months, but the phenomenon is also present during the beginning and the end of the winter, and spreads over the mid-seasons (autumn and spring), whereas in the proposed method, for the cases of Cairo and Abuja, overheating is almost only occurring during the temperature peaks of the year, in the cases of Hermosillo and New Delhi, the overheating is constantly present during the warmest summer months of the year, with occasional peaks during the mid-season. The locations with the higher prediction difference are Teresina (34.1%) and Karachi (34.2%), both with the highest average yearly temperatures, and considerable visible difference, meanwhile, the European standard predicts overheating during the whole year, the prediction of the proposed method is limited for the highest peak temperatures of the year. The contrast between the two methods, is in accordance with the findings of previous studies [39], [62], [63], where is stated that the people in warm locations are more tolerant to high temperatures, and a higher upper-temperature limit is suggested, these studies are mostly based on the responses of the subjects, and overheating is recognized as a problem during the warmest months of the year, especially during the temperature peaks.

5.4 Measuring overheating with the new method.

Following the steps in the proposed methodology, the simulation results were distributed across different criteria. The data of each criterion was interpreted as follows:

- Criterion 0, hours >0.1°K but <1°K (>35°C but <36°C): the total amount of hours where overheating is occurring, but it is still imperceptible to the human body. This step provides a sensible representation of how prone to overheating a building might be, even when it does not necessarily represent a problem, a high number means that in a particularly hot season, the building is in danger of displaying a constant overheating problem that will eventually escalate further.

- Criterion 1, hours >1°K but <2°K (>36°C but <37°C): the total amount of hours where the temperature is one whole degree above comfort but less than two. This number of hours represent the total time outside the comfort limit, where overheating can be perceived by sensitive users, but not necessarily indicate an overheating problem since the temperature rise is only 1°K. Yet, not all that time can be accounted for as effective time overheated since it depends on the sensitivity of the occupants. This is where thermal stress begins to be present and a single adaptive opportunity can be highly effective against thermal stress. This opportunity can be summarized as the possibility of changing the surrounding environment by, for example, access to cold drinks, the operability of window openings for airflow improvement or clothing adjustments, among others.

- Criterion 2, hours >2°K but <3°K (>37°C but <38°C): the total amount of hours where the temperature is two degrees or more above comfort but less than three. This is where thermal stress is already present, and something should be done to regain comfort. These are the number of hours where access to more than one passive opportunity would be psychologically relieving since the effect of multiple passive opportunities can be accumulative.

- Criterion 3, hours >3°K but <4°K (>38°C but <39°C): the total amount of hours where the temperature is three degrees or more above comfort but less than four. At this distance from the upper comfort limit, thermal stress is a problem for occupants and depending on the context and the subjects, it may not be possible to be tolerated for long periods without experiencing thermal discomfort and a reduction of performance. During short periods of exposure, multiple adaptive opportunities can be relieving and efficient against thermal stress, but they can be rendered useless if overheating persist for longer periods.

- Criterion 4. hours >4°K (>39°C): the total amount of hours where the temperature is four degrees or more above comfort. Overheating is occurring, and depending on the subjects and the context, it might not be possible to be tolerated, human performance is decreased, and physiological manifestations of thermal stress will be present. This condition should be avoided in all possible cases, the access of passive strategies can be helpful to provide psychological relief and it may decrease thermal stress, nevertheless, exposure to these conditions during long periods could be harmful to the health of the occupants.

5.5 The yearly analysis

In figures 10 to 12, the overheating hours from the simulation results are plotted according to the criteria. The yearly accumulative count in Figure 10, the yearly percentage of time overheated in Figure 11, and Figure 12, the distribution of overheating according to each of the criteria within total overheating time or in other words, out of the total overheated time, what percentage of it corresponds to each of the criteria.

With the information contained in Figures 10 to 12, it is possible to elaborate a yearly overheating analysis. The information contained in this graph is useful to provide a general idea about the overheating in a given building, it communicates, for how long it happens and how intense it can be, but it fails to communicate, whenever is happening, since it is impossible to know if its seasonal, monthly, or scattered throughout the year.

Different types of graphics can be useful to visualize diverse aspects of the data. Figure 10 can be merely representative, as a tool to compare the overheating intensities of a certain location, it is a basic count of the hours where it is possible to compare and visualize the general frequency of the overheating. Figure 11, is a graph where the percentage of overheating hours are stacked and colour coded, in a graph like this it is possible to appreciate the percentage of occupancy time during the year when overheating is happening. Figure 12 is a graph where it is possible to visualize the intensity of the overheating hours within the overheating periods (rather than during the whole year).

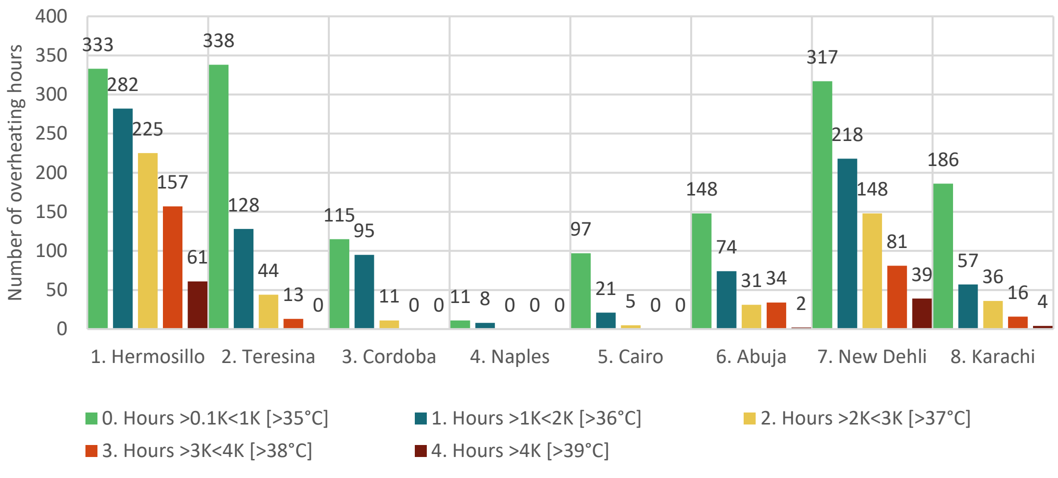


Figure 10. Yearly accumulative count of overheating hours according to each criterion in every location.

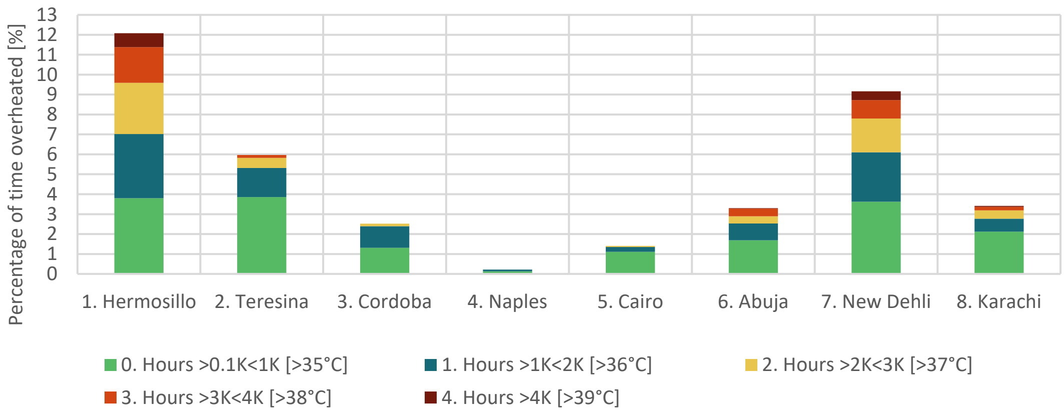


Figure 11. Yearly percentage of time overheated during the year according to each criterion.

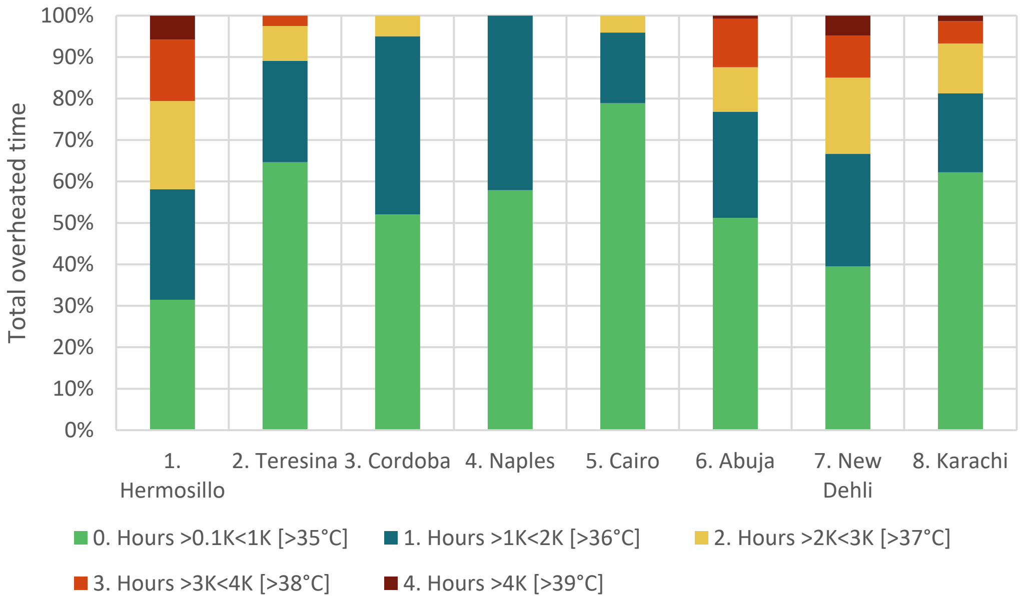


Figure 12. Distribution of the overheating intensity according to each of the criterion within the total overheating time.

5.6 The monthly analysis of Hermosillo, Mexico

With the interest of analysing a building with an overheating problem, a monthly analysis was performed using an example in the city of Hermosillo, Mexico. In the previous figures (9 to 12), it was possible to appreciate that the overheating was constantly happening, although it was impossible to realise when. In figure 13, it is possible to see the yearly hourly distribution of overheating hours, where it is possible to appreciate the presence of overheating during almost half of the year, additionally, in figure 14, in the accumulative count of overheating hours for each month, it is possible to see that in the period from June to October, overheating reached temperatures of above 39°C, in Figure 14, the percentage of the time, brings in to context the amount of time with overheating, with June and July with over 37% of the time overheated and August and September with above 20% of the time, and lastly, October with slightly more than 10%. These months also stand out in Figure 16 where it is possible to appreciate clearly that they are the warmest months of the year.

With the previous information is possible to see how overheating is spread. The overheating season is from June to October, where June and July are the warmest months of the year. Given the number of overheating hours above 37°C, it is possible to infer that the occupants of this construction configuration would be exposed to high overheated conditions during long periods, bringing into question the habitability of the building. Given that the examples were calculated as dwellings considering an occupation of 24 hours a day, the percentage of time overheated may not look as alarming as it could be, in contrast as it could be if the analysis only included a schedule from 9 to 5, that would include the warmest hours of the day and the percentage of time overheated would be considerably more. In a different temporal scale, it is important to consider in the occupancy hours the seasonal use a building may have, as it is the case of schools that are not occupied during the warmest seasons of the year. The overheating problem can be narrowed down to the warmest months and additional measures, such as the implementation of passive strategies and adaptive opportunities can be considered to fix this.

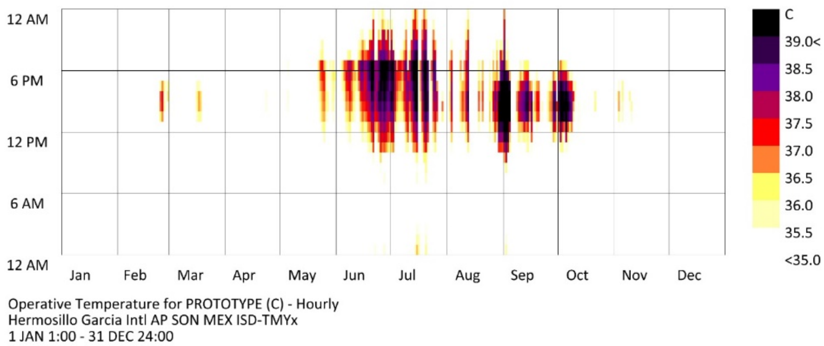


Figure 13. Yearly distribution of overheating hours and their distance to the 35°C boundary according to the proposed method for the location of Hermosillo, Mexico.

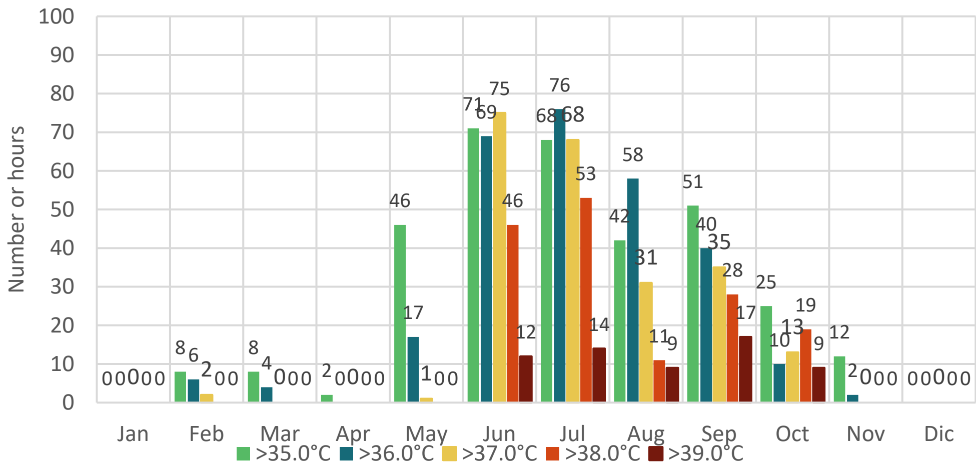


Figure 14. Accumulative count of overheating hours for each month according to each criterion for the location of Hermosillo, Mexico

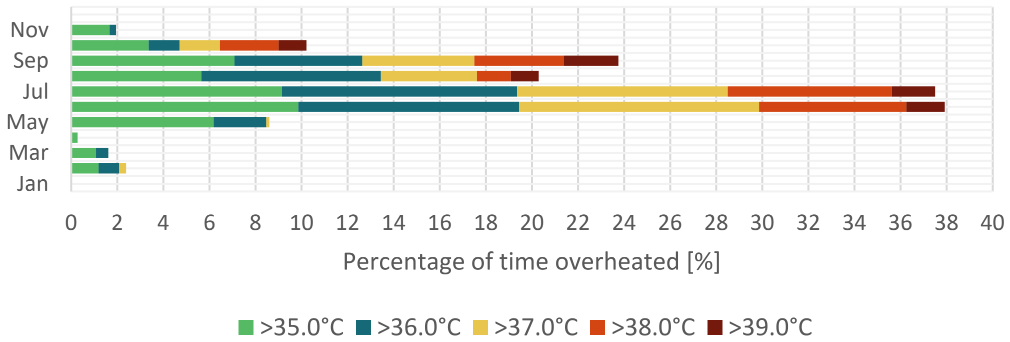


Figure 15. Percentage of time overheated during the year according to each criterion for the location of Hermosillo, Mexico.

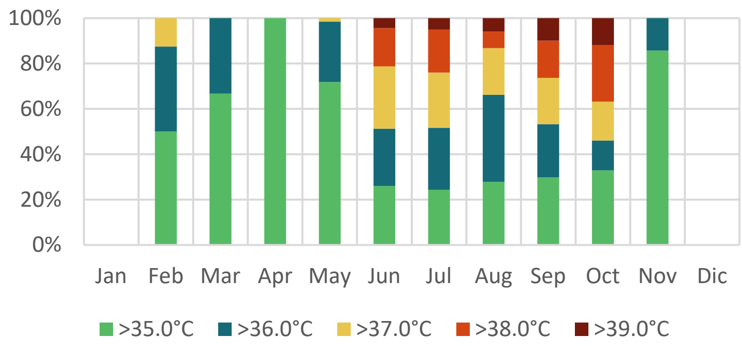


Figure 16. Distribution of the overheating intensity according to each of the criterion within the total overheating time for the location of Hermosillo, Mexico.

5.7 The monthly analysis of Teresina, Brazil

With the interest of elaborating an overheating assessment in a mild warm climate, a monthly analysis was performed using an example in the city of Teresina, recognized as the warmest city in Brazil. In figure 17, it is possible to see the presence of overheating during almost half of the year, with only 2 months with darker colours; in Figure 18, in the accumulative count of overheating hours for each month, it is possible to see that only in November and December, overheating reached temperatures above 38°C for very few hours, but never above 39°C. in Figure 19, the overheating as a percentage of the time brings in to context the actual amount of time that may represent the presence of thermal stress and it is only during December and November, since from January to September temperatures never escalate above 37°C, and during October, there is only one hour above 37°C.

Given the results obtained, it is possible to establish that the building in Teresina does not have an overheating problem. More than 85% of the overheating time are temperatures within the first two criteria, representing only around 5 out the 6% of the total percentage of the time overheated during the year. Given that temperatures are at no point above 39°C, only 7 hours during November and 6 during December are above 38°C, and only 25 and 18 hours are above 37°C, it is possible to affirm that overheating can be manageable with passive opportunities without any major interventions to the building.

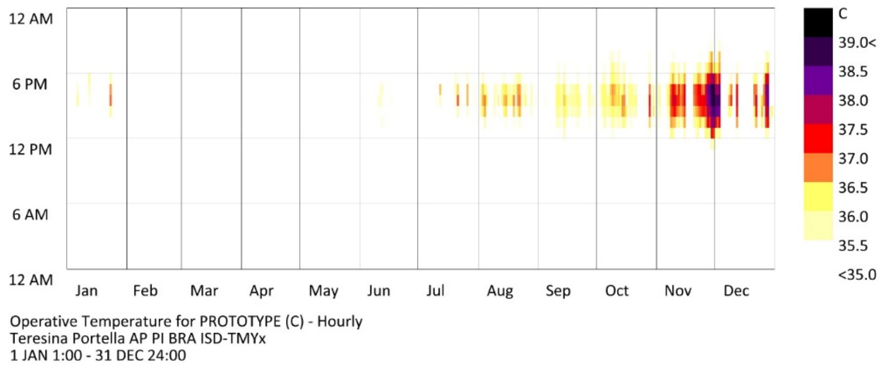


Figure 17. Yearly distribution of overheating hours and their distance to the 35°C boundaries according to the proposed method for the location of Teresina, Brazil.

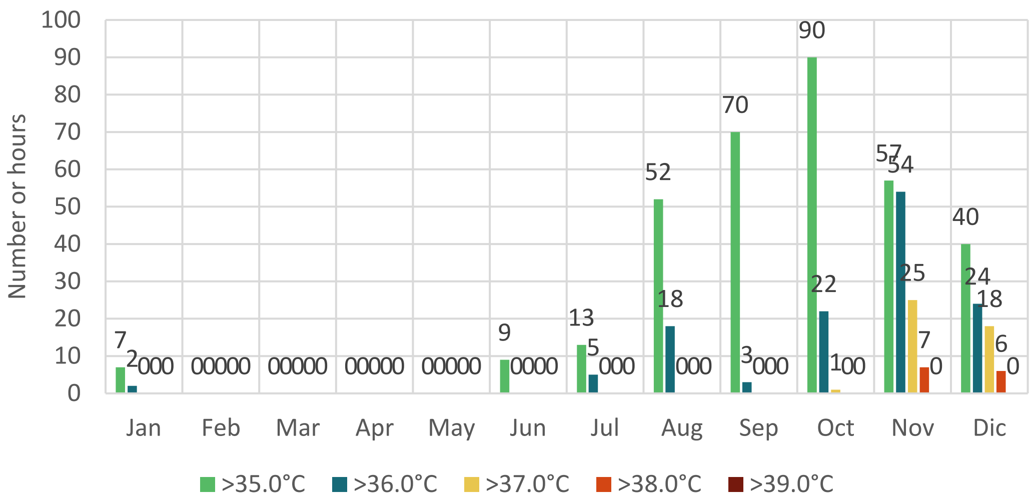


Figure 18. Accumulative count of overheating hours for each month according to each criterion for the location of Teresina, Brazil.

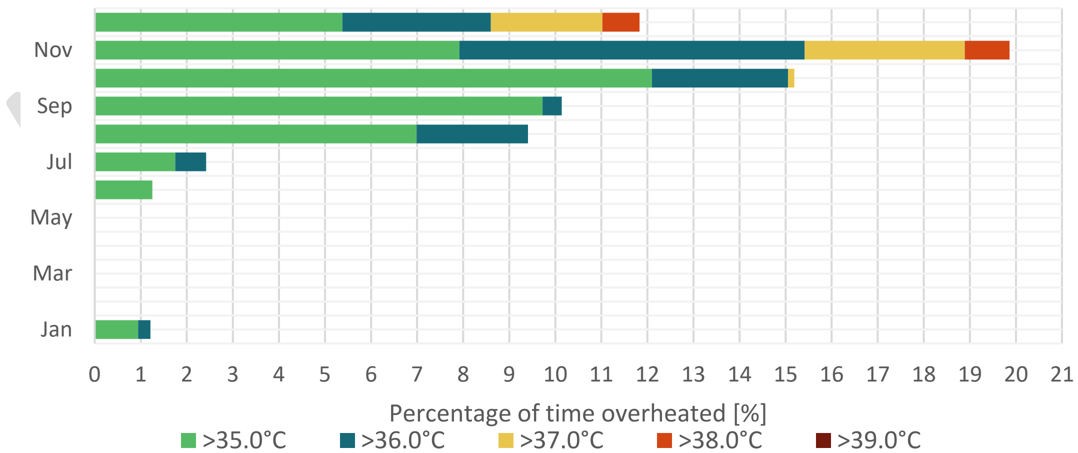


Figure 19. Percentage of time overheated during the year according to each criterion for the location of Teresina, Brazil.

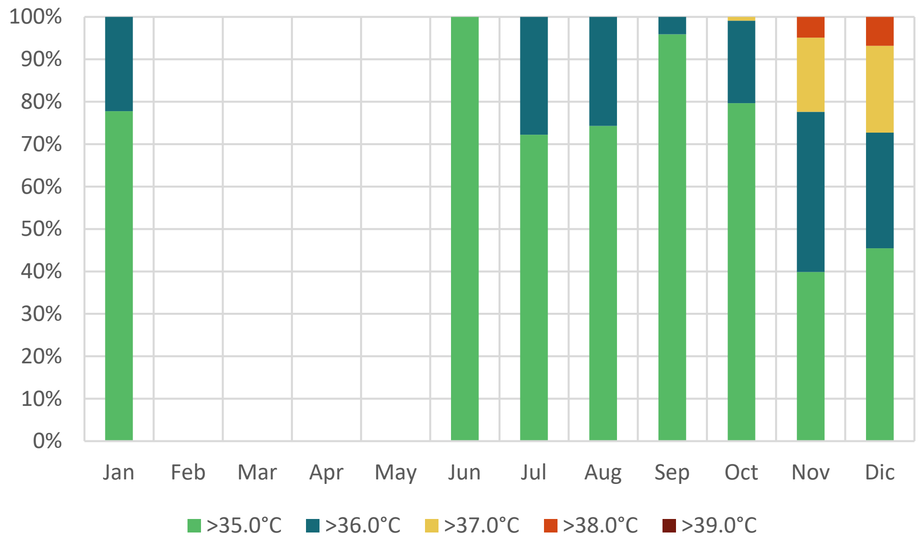


Figure 20. Distribution of the overheating intensity according to each of the criterion within the total overheating time for the location of Teresina, Brazil.

6. Conclusions

Climate Change is affecting the environment everywhere, provoking dangerous conditions on the planet. The proposed method in this research is a promising approach, to ensure the possibility of better healthy and protective buildings with a better capacity to provide a benign environment for their occupants, not only during a hot season, but also during a natural disaster where the energy supply may be interrupted. This method is also a useful tool for reducing the use of AC in buildings and suitable for the assessment of natural ventilation, as one of the main cooling strategies, from which the greatest gain would be the reduction of energy consumption, in addition to a possible decline of the heat island effect in urban settings, which are significative steps towards the improvement of the environment, the quality of living and people's health.

This method also provides a novel approach to visualize and understand overheating hours in naturally ventilated buildings. The application of this method can be as it stands when measuring the potential risk to human health for the occupants of a building in any climate, as well as to measure the comfort potential for buildings located under extreme climates. When applying the method, the first three criteria prove useful sensible information regarding what could be interpreted as "the beginning of overheating", where adaptive opportunities are highly effective as means to remain in comfort and address thermal stress. The fourth criterion represents the theoretical limit of overheating for sensible subjects, while the fifth criterion could be interpreted as the beginning of unbearable and dangerous temperatures. Nevertheless, further research needs to be conducted specifically focused in every location to establish the possible overheating limits clearly and exactly according to the specifics of the users, since this methodology is case-sensitive. It is expected that this method can be applied in other climate regions to establish a parametric approach for expanding its applicability.

7. References

[1] J. Sillmann *et al.*, "Understanding, modeling and predicting weather and climate extremes: Challenges and opportunities," *Weather Clim. Extrem.*, vol. 18, no. November, pp. 65–74, 2017, doi: 10.1016/j.wace.2017.10.003.

[2] F. C. Curriero, K. S. Heiner, J. M. Samet, S. L. Zeger, L. Strug, and J. A. Patz, "Temperature and mortality in 11 cities of the eastern United States," *Am. J. Epidemiol.*, vol. 155, no. 1, pp. 80–87, 2002, doi: 10.1093/aje/155.1.80.

[3] A. L. Ferreira Braga, A. Zanobetti, and J. Schwartz, “The time course of weather-related deaths,” *Epidemiology*, vol. 12, no. 6, pp. 662–667, Nov. 2001, doi: 10.1097/00001648-200111000-00014.

[4] M. Nitschke, G. R. Tucker, A. L. Hansen, S. Williams, Y. Zhang, and P. Bi, “Impact of two recent extreme heat episodes on morbidity and mortality in Adelaide, South Australia: A case-series analysis,” *Environ. Heal. A Glob. Access Sci. Source*, vol. 10, no. 1, p. 42, Dec. 2011, doi: 10.1186/1476-069X-10-42.

[5] L. R. Turner, D. Connell, and S. Tong, “Exposure to hot and cold temperatures and ambulance attendances in Brisbane, Australia: A time-series study,” *BMJ Open*, vol. 2, no. 4, p. e001074, Jul. 2012, doi: 10.1136/bmjopen-2012-001074.

[6] WMO, *“WMO Statement on the Status of the Global Climate in 2017.” World Meteorological Organization, 2017. WMO_1108_EN_web_000.pdf.WMO statement on the status of the global climate in 2017*, no. WMO-No. 1212. 2018.

[7] A. Gasparrini, Y. Guo, and M. Hashizume, “Mortalité attribuable au froid et à la chaleur : Analyse multi-pays,” *Environnement, Risques et Sante*, vol. 14, no. 6, pp. 464–465, 2015, doi: 10.1016/S0140-6736(14)62114-0.

[8] I. Meier, S. Roaf, and I. Gileard, “The vernacular and the Environment towards a comprehensive Research methodology,” *Proc. 21st Int. Conf. …*, no. September, pp. 19–22, 2004, [Online]. Available: http://plea-arch.net/PLEA/ConferenceResources/PLEA2004/Proceedings/p0841final.pdf.

[9] W. Weber, *Lessons from Vernacular Architecture*. New York: Routledge, 2013.

[10] S. Yannas and J. Rodríguez-Álvarez, “Domestic overheating in a temperate climate: Feedback from London Residential Schemes,” *Sustain. Cities Soc.*, vol. 59, no. April, p. 102189, 2020, doi: 10.1016/j.scs.2020.102189.

[11] E. E. Alders, “Adaptive heating, ventilation and solar shading for dwellings,” *Archit. Sci. Rev.*, vol. 60, no. 3, pp. 150–166, 2017, doi: 10.1080/00038628.2017.1300132.

[12] M. Ackermann, *Cool Comfort: America’s Romance with Air-Conditioning*. Smithsonian Books, 2002.

[13] M. J. Mendell, Q. Lei-Gomez, A. G. Mirer, O. Seppänen, and G. Brunner, “Risk factors in heating, ventilating, and air-conditioning systems for occupant symptoms in US office buildings: The US EPA BASE study,” *Indoor Air*, vol. 18, no. 4, pp. 301–316, Aug. 2008, doi: 10.1111/j.1600-0668.2008.00531.x.

[14] L. Fang, D. P. Wyon, G. Clausen, and P. O. Fanger, “Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance,” *Indoor Air, Suppl.*, vol. 14, no. SUPPL. 7, pp. 74–81, 2004, doi: 10.1111/j.1600-0668.2004.00276.x.

[15] L. T. Molina, B. De Foy, O. Vázquez Martínez, V. Hugo, and P. Figueroa, “Title Air quality, weather and climate in Mexico City,” *WMO Bulletin*, 2009. https://public.wmo.int/en/bulletin/air-quality-weather-and-climate-mexico-city (accessed Jun. 26, 2020).

[16] J. J. West, P. Osnaya, I. Laguna, J. Martínez, and A. Fernández, “Co-control of urban air pollutants and greenhouse gases in Mexico City,” *Environ. Sci. Technol.*, vol. 38, no. 13, pp. 3474–3481, Jul. 2004, doi: 10.1021/es034716g.

[17] R. A. Hobday and S. J. Dancer, “Roles of sunlight and natural ventilation for controlling infection: Historical and current perspectives,” *J. Hosp. Infect.*, vol. 84, no. 4, pp. 271–282, Aug. 2013, doi: 10.1016/j.jhin.2013.04.011.

[18] J. Xiong, L. Lan, Z. Lian, and R. De dear, “Associations of bedroom temperature and ventilation with sleep quality,” *Sci. Technol. Built Environ.*, vol. 26, no. 9, pp. 1274–1284, 2020, doi: 10.1080/23744731.2020.1756664.

[19] T. Circle *et al.*, “ASHRAE Position Document on,” *Ashrae*, no. 14 April, pp. 1–24, 2020.

[20] CIBSE, “CIBSE COVID-19 Ventilation Guidance version 4,” 2020. [Online]. Available: https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q3Y00000HsaFtQAJ#.

[21] U. G. Council, “Ensure Operable Windows in Residential Buildings.” NYC Bulding Resiliency Task Force, New York City, pp. 1–4, 2013.

[22] B. Ford, *Passive downdraught evaporative cooling: Principles and practice*, vol. 5, no. 3. 2001.

[23] F. Zhang, R. de Dear, and P. Hancock, “Effects of moderate thermal environments on cognitive performance: A multidisciplinary review,” *Appl. Energy*, vol. 236, no. December 2018, pp. 760–777, 2019, doi: 10.1016/j.apenergy.2018.12.005.

[24] J. F. Nicol and S. Roaf, “Rethinking thermal comfort,” *Build. Res. Inf.*, vol. 45, no. 7, pp. 711–716, 2017, doi: 10.1080/09613218.2017.1301698.

[25] F. Nicol, M. Humphreys, and S. Roaf, *Adaptive thermal comfort: Principles and practice*. London: Routledge, 2012.

[26] S. Carlucci, L. Bai, R. de Dear, and L. Yang, “Review of adaptive thermal comfort models in built environmental regulatory documents,” *Build. Environ.*, vol. 137, no. February, pp. 73–89, 2018, doi: 10.1016/j.buildenv.2018.03.053.

[27] CIBSE, “The limits of thermal comfort : avoiding overheating in European buildings,” *CIBSE Tm52*, pp. 1–25, 2013, doi: 10.1017/CBO9781107415324.004.

[28] CIBSE, “Design methodology for the assessment of overheating risk in homes,” *Tech. Memo. 59*, 2017.

[29] P. O. Fanger, *Thermal comfort : analysis and applications in environmental engineering*. New York: McGraw-Hill, 1972.

[30] ANSI/ASHRAE, “Thermal environmental conditions for human occupancy,” *ANSI/ASHRAE Stand. - 55*, 2017, doi: ISSN 1041-2336.

[31] Finnish standards association, “Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, SFS-EN 15251.” British Standards Institution, London, 7AD.

[32] M. A. Humphreys, J. F. Nicol, and I. A. Raja, “Field studies of indoor thermal comfort and the progress of the adaptive approach,” *Adv. Build. Energy Res.*, vol. 1, no. 1, pp. 55–88, Jan. 2007, doi: 10.1080/17512549.2007.9687269.

[33] F. Nicol and M. Humphreys, “Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251,” *Build. Environ.*, vol. 45, no. 1, pp. 11–17, 2010, doi: 10.1016/j.buildenv.2008.12.013.

[34] T. Cheung, S. Schiavon, T. Parkinson, P. Li, and G. Brager, “Analysis of the accuracy on PMV – PPD model using the ASHRAE Global Thermal Comfort Database II,” *Build. Environ.*, vol. 153, no. December 2018, pp. 205–217, 2019, doi: 10.1016/j.buildenv.2019.01.055.

[35] I. Oropeza-Perez and P. A. Østergaard, “Potential of natural ventilation in temperate countries - A case study of Denmark,” *Appl. Energy*, vol. 114, pp. 520–530, 2014, doi: 10.1016/j.apenergy.2013.10.008.

[36] G. Gómez-Azpeitia, “Outdoor and Indoor Thermal Comfort Temperatures Comparison in Warm Dry Climates,” *Lema.Arq.Uson.Mx*, no. July, pp. 1–6, 2011, [Online]. Available: http://www.lema.arq.uson.mx/rab/wp-content/uploads/2012/08/Outdoor_and_Indoor_Thermal_Comfort.pdf.

[37] A. K. Mishra and M. Ramgopal, “An adaptive thermal comfort model for the tropical climatic regions of India (Köppen climate type A),” *Build. Environ.*, vol. 85, pp. 134–143, 2015, doi: 10.1016/j.buildenv.2014.12.006.

[38] S. Q. da S. Hirashima, A. Katzschner, D. G. Ferreira, E. S. de Assis, and L. Katzschner, “Thermal comfort comparison and evaluation in different climates,” *Urban Clim.*, vol. 23, pp. 219–230, 2018, doi: 10.1016/j.uclim.2016.08.007.

[39] F. Nicol, “Adaptive thermal comfort standards in the hot-humid tropics,” *Energy Build.*, vol. 36, no. 7, pp. 628–637, 2004, doi: 10.1016/j.enbuild.2004.01.016.

[40] J. Kim, R. De Dear, F. Tartarini, T. Parkinson, and P. Cooper, “Ventilation mode effect on thermal comfort in a mixed mode building,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 609, no. 4, 2019, doi: 10.1088/1757-899X/609/4/042029.

[41] T. Parkinson, R. de Dear, and G. Brager, “Nudging the adaptive thermal comfort model,” *Energy Build.*, vol. 206, p. 109559, 2020, doi: 10.1016/j.enbuild.2019.109559.

[42] D. H. K. Lee and B. Givoni, *Man, Climate, and Architecture*, vol. 61, no. 2. 1971.

[43] G. Gómez-Azpeitia, G. Bojórquez-Morales, P. Ruiz, I. Marincic, E. González, and A. Tejeda, “Extreme adaptation to extreme environments: case study of hot dry, hot sub-humid, and hot humid climates in Mexico,” *Proc. 7th Wind. Conf. Chang. Context Comf. an Unpredictable World.*, vol. 8, no. 8, pp. 12–15, 2012, doi: 10.17265/1934-7359/2014.08.001.

[44] J. F. Nicol and M. A. Humphreys, “Thermal Comfort As Part of a Self-Regulating System.,” *Build Res Pr.*, vol. 1, no. 3, pp. 174–179, 1973, doi: 10.1080/09613217308550237.

[45] W. van Marken Lichtenbelt, M. Hanssen, H. Pallubinsky, B. Kingma, and L. Schellen, “Healthy excursions outside the thermal comfort zone,” *Build. Res. Inf.*, vol. 45, no. 7, pp. 819–827, 2017, doi: 10.1080/09613218.2017.1307647.

[46] H. Pallubinsky, B. R. M. Kingma, L. Schellen, B. Dautzenberg, M. A. van Baak, and W. D. van Marken Lichtenbelt, "The effect of warmth acclimation on behaviour, thermophysiology and perception," *Build. Res. Inf.*, vol. 45, no. 7, pp. 800–807, 2017, doi: 10.1080/09613218.2017.1278652.

[47] B. R. M. Kingma, M. Schweiker, A. Wagner, and W. D. van Marken Lichtenbelt, "Exploring internal body heat balance to understand thermal sensation," *Build. Res. Inf.*, vol. 45, no. 7, pp. 808–818, 2017, doi: 10.1080/09613218.2017.1299996.

[48] B. Kingma and W. Van Marken Lichtenbelt, "Energy consumption in buildings and female thermal demand," *Nat. Clim. Chang.*, vol. 5, no. 12, pp. 1054–1056, Dec. 2015, doi: 10.1038/nclimate2741.

[49] F. Nicol, "Temperature and adaptive comfort in heated, cooled and free-running dwellings," *Build. Res. Inf.*, vol. 45, no. 7, pp. 730–744, 2017, doi: 10.1080/09613218.2017.1283922.

[50] I. Oropeza-Perez, "The influence of an integrated driving on the performance of different passive heating and cooling methods for buildings," *Buildings*, vol. 9, no. 11, 2019, doi: 10.3390/buildings9110224.

[51] S. Roaf and F. Nicol, "Acceptable Temperatures in Naturally Ventilated Buildings Introduction : The Natural Ventilation Imperative," 2018.

[52] S. Taslim, D. M. Parapari, and A. Shafaghat, "Urban design guidelines to mitigate urban heat island (UHI) effects in hot-dry cities," *J. Teknol.*, vol. 74, no. 4, pp. 119–124, 2015, doi: 10.11113/jt.v74.4619.

[53] M. K. Nematchoua and J. A. Orosa, "Building construction materials effect in tropical wet and cold climates: A case study of office buildings in Cameroon," *Case Stud. Therm. Eng.*, vol. 7, pp. 55–65, 2016, doi: 10.1016/j.csite.2016.01.007.

[54] H. Feriadi and N. H. Wong, "Thermal comfort for naturally ventilated houses in Indonesia," *Energy Build.*, vol. 36, no. 7, pp. 614–626, 2004, doi: 10.1016/j.enbuild.2004.01.011.

[55] A. Basso and R. M. Caram, "Evaluation of natural illumination and thermal comfort conditions in the Ribeirao Preto's Technological Village," *Energy Build.*, vol. 36, no. 7, pp. 638–642, 2004, doi: 10.1016/j.enbuild.2004.01.001.

[56] M. A. Humphreys and J. F. Nicol, "Adaptive thermal comfort and sustainable thermal standards for buildings," *Energy Build.*, vol. 34, no. 6, pp. 563–572, 2002, doi: 10.1016/S0378-7788(02)00006-3.

[57] F. Nicol, "Limits to acceptable indoor temperatures," in *Proceedings of the Comfort at the Extremes Conference*, 2019, pp. 22–30, [Online]. Available: https://comfortattheextremes.com/.

[58] F. Nicol, "The Shapes of Comfort," 2020.

[59] Climate.OneBuilding.Org, "Repository of free climate data for building performance simulation," 2019. http://climate.onebuilding.org/WMO_Region_3_South_America/CHL_Chile/BI_Bio-Bio/CHL_BI_Concepcion-Carriel.Sur.Intl.AP.856820_TMYx.2003-2017.zip (accessed Jul. 01, 2020).

[60] J. F. Nicol and M. A. Humphreys, "Adaptive thermal comfort and sustainable thermal standards for buildings," *Energy Build.*, vol. 34, no. 6, pp. 563–572, 2002, doi: 10.1016/S0378-7788(02)00006-3.

[61] K. Okazaki, D. Kusumastuti, K. Probadi, and T. Saito, "Comparison of Current Construction Practices of Non-Engineered Buildings in Developing Countries," *15th World Conf. Earthq. Eng.*, 2012.

[62] G. Desogus, L. G. Felice Cannas, and A. Sanna, "Bioclimatic lessons from Mediterranean vernacular architecture: The Sardinian case study," *Energy Build.*, vol. 129, pp. 574–588, 2016, doi: 10.1016/j.enbuild.2016.07.051.

[63] M. A. Humphreys, H. B. Rijal, and J. F. Nicol, "Updating the adaptive relation between climate and comfort indoors; new insights and an extended database," *Build. Environ.*, vol. 63, pp. 40–55, 2013, doi: 10.1016/j.buildenv.2013.01.024.