Resilient Design in The Tropics: An Overheating Assessment Method for Naturally Ventilated Buildings

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As a consequence of global warming, overheating has become the main source of discomfort when speaking about the thermal performance of buildings. On the one hand, energy consumption together with the risk of heatstroke rises during warm periods and in extreme situations such as heatwaves. On the other hand, there is no broadly accepted method to measure overheating. Most of the literature is limited to a simple count of hours above comfort limit, disregarding the intensity and temporal extent of the periods, whereas other methods have a limited application since they were developed for a certain type of building and location. This paper proposes a novel method for overheating assessment in existing and projected buildings based on 5-step criteria. The objective of the process is to assess the intensity and the total time extent of overheating following adaptive theory and established limits of human comfort. The method consists in hourly counts of overheating hours divided into five segments (i.e. hours above 0.1°K, 1°K, 2°K, 3°K, and 4°K) using the upper comfort limit as a threshold. The output of the method thus provides a quantitative answer regarding overheating in a building, assessing not only the intensity but the range of the problem, allowing to evaluate different strategies to regain comfortable conditions for the occupants.

Keywords: thermal comfort, overheating, tropics

1. Introduction

There is compelling evidence that the climate across the globe is changing. Yearly temperature averages, as well as absolute peaks, have been rising and they are expected to reach even higher marks in the near future. As a consequence, there will be longer and more intense heatwaves during warmer summer and spring seasons (de Wilde and Coley, 2012). The consequences of overheating in the human body are many, and they vary depending on different factors. Nevertheless, the starting point is always heat stress induced thermal discomfort, and sadly, for the most vulnerable occupants, the endpoint may be death or life-threatening diseases. Speaking about building performance, the main problem with this temperature increases is the fact that space cooling requires more energy than space heating.

While global warming is happening everywhere around the globe, recent studies have found that the developing world is suffering the worse part of it (Chen and Chen, 2013). Climate change has triggered a worldwide desertification phenomenon that is mostly occurring in the tropical and subtropical areas, encompassing the most populated countries in the world such as Brazil, Mexico, Indonesia, Nigeria, Pakistan India, and China (Figure 1). Temperature peaks are constantly escalating above 40°C and becoming a real threat to the wellbeing of the population in these regions in which, unlike other developed countries, the only available solution to overcome the overheating problem is restricted to passive means due to the socio-economic limitations (IPCC, 2013).

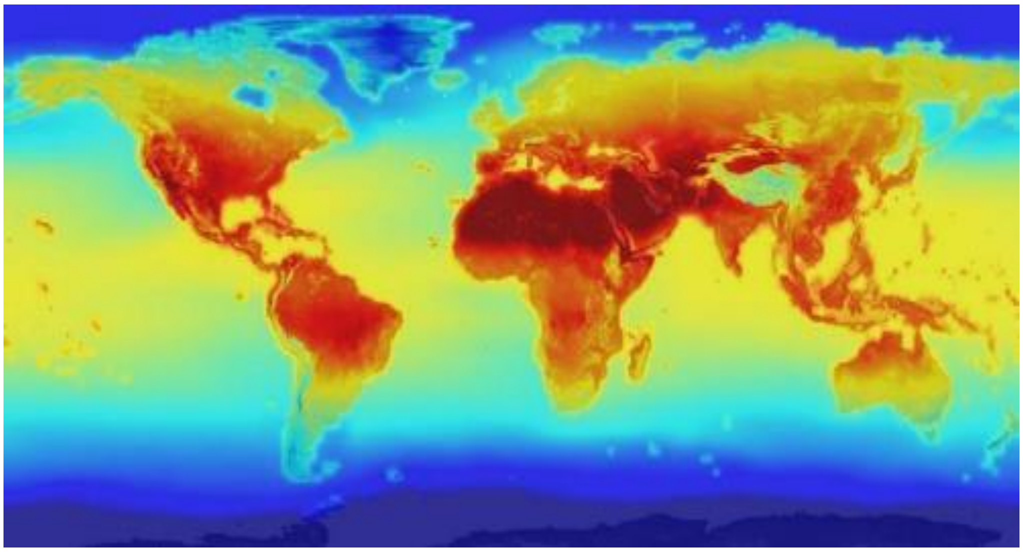

Figure 1. Map representation of future forecasted temperatures where is possible to appreciate how the highest temperatures are concentrated in the tropical and subtropical areas (Image source: NASA)

It is understood that the tropics are the immediate regions surrounding the equator. On the Northern Hemisphere, these are delimited by the tropic of Cancer at the coordinates 23°26′12.0″ and by the Tropic of Capricorn at the coordinates 23°26′12.0″ in the Southern Hemisphere. The subtropics are the areas between the tropics of Cancer and the tropic of Capricorn, and the latitude marks of 66.5° north and south. Nine of the ten most populated countries in the world fall within this area, which are also catalogued as developing regions (Figure 2).

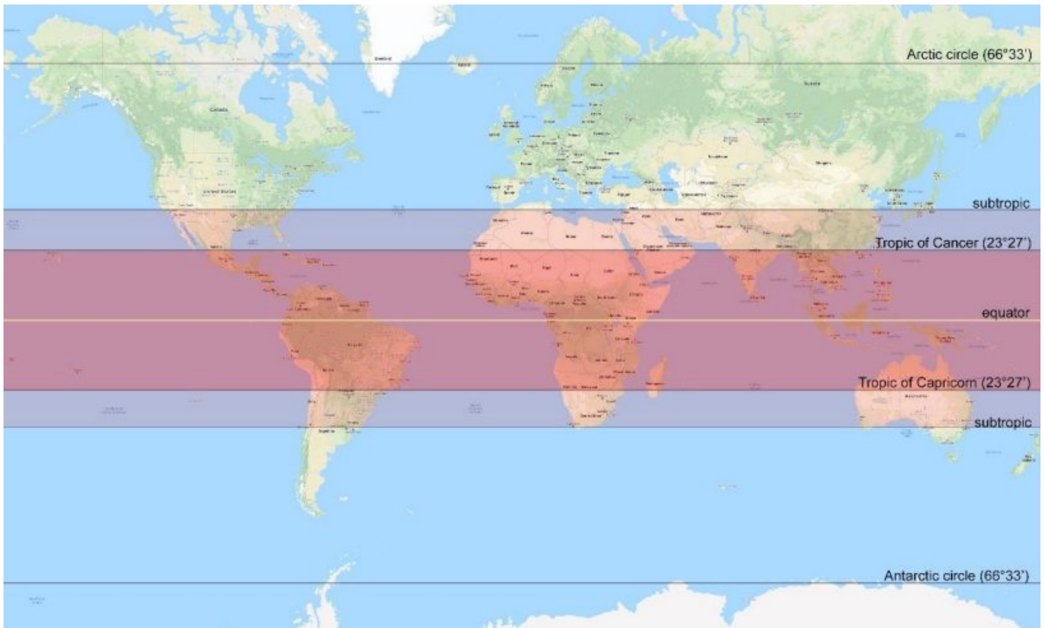

Figure 2. Global location of tropical and subtropical areas.

As part of a global effort to reduce energy consumption and therefore, CO^2 emissions, energy-saving policies for buildings have been implemented in many countries across the globe (Walsh, Cóstola and Labaki, 2017). In recent years, thermal comfort models have been used as the foundation to create healthy and comfortable spaces, while reducing their energy consumption. Meanwhile, comfort models for active or mechanically climatized buildings have been broadly developed and discussed for several decades. The current performance limits for passive or free-running buildings are relatively new, and for some specific cases, they remain unknown. Moreover, it is important to consider that two of the most relevant and most used comfort models, the ASHRAE standard 55 and the CEN Standard BS EN 15251 (renamed to EN 16798), were developed considering very specific survey and climatic data, which would have differ from that on a tropical or subtropical context (Nicol, Humphreys and Roaf, 2012). Thus, some modifications need to be addressed before assuming their effectiveness in a warmer context. Although some other comfort models seem to be more suited for this contexts, such as the ones developed by Humphreys and Szolokolays-Auliciems (Szokolay, 2008; Nicol, Humphreys and Roaf, 2012), the current implementation of energy standards such as BREEAM and LEED in developing countries, are somehow forcing the implementation of ASHRAE's and CEN Standard's comfort models, since this countries lack energy-saving regulations of their own.

There is not a broadly accepted method or formula to measure or quantify the possible overheating of a free-running building in a tropical or subtropical context. Most published literature is limited to a simple count of overheating hours above 0.1 or 1.0 °K, completely disregarding the intensity and length of the overheating phenomena. Other documents, such as the CIBSE's TM-52 (CIBSE, 2013), were written keeping in mind its implementation in a high latitude context (such as the UK), Nowadays, this document is being studied more as an early out-dated approximation to solve the problem rather than as a possible answer, partly because of the yearly progressive overheating due to climate change, but also due to their impractical application in other European settings where temperatures frequently rise above 30°C, such as the south of Portugal, Spain, and Italy.

This paper presents a new method to measure and assess overheating in free-running naturally ventilated buildings in tropical and subtropical climates. It was developed to measure the intensity and chronological length of overheating as means to determine the possible effectiveness of one or many adaptive opportunities and passive strategies to maintain or regain indoor comfort. Additionally, based on the theoretical principles of adaptive thermal comfort, this method intends to stablish the theoretical base to consider a possible limit of overheating to ensure comfort for the occupants and the effective applications of adaptive opportunities.

2. Method

Comfort models are limited by different factors according to their specific application. The width of a comfort band, thus its upper limit, is defined by the building class or acceptable limits (Carlucci *et al.*, 2018).Adaptive comfort theory suggests that a comfort band of ±4K, would ensure an 80% of acceptability limit on a predicted mean vote (PMV) scale, One of the reasons for this comfort width of ±4K, is that it can be possible when considering the previously experienced temperature of the user, therefore, the thermal history would be encompassed and taken into account (Nicol, Humphreys and Roaf, 2012).

There is not a common agreement between comfort models or literature regarding the highest possible temperature limit in which occupants of a free-running building would still be comfortable and fully operable. The ASHRAE standard 55 suggest an upper limit of 33.5°C for the U.S. while the original EN 15251 suggest 30.5°C for Europe. The reason for this is because both standards are based on user’s satisfaction questionnaires from which thermal expectations of the occupants were pre-established, as well as the common limit of what could be considered comfortable at those specific locations (CIBSE, 2013). The same applies to relative humidity levels Early work by (Lee and Givoni, 1971; Fanger, 1972) established that the optimum operative range of relative humidity is between 20 and 80% according to the findings in their experiments and fieldwork. Nevertheless, in tropical locations close to the equator such as Puerto Rico, Cuba or Barbados, occupants are constantly experiencing higher levels than the suggested 80% during daytime throughout the year. In a similar way, sub-tropical desert locations such as Egypt and Saudi Arabia, as well as most of the subtropical African countries, experience extreme dry conditions during great part of the daytime for most of the year. Despite of such conditions, building occupants in these areas are still functioning and most dwelling and workplaces are naturally ventilated, free running, relying on passive strategies to procure thermal comfort.

There is no further research that establishes the actual limits of thermal comfort for workspaces or living spaces in a tropical or subtropical setting. Research by (Gómez-Azpeitia *et al.*, 2012) and (Mishra and Ramgopal, 2015), reached different and apparently opposed conclusions, mainly because they followed different objectives and methodologies, obtaining incomparable results, but still, it is possible to say that they both agree when stating that there should be a different comfort limit corresponding to each location as a consequence of the thermal history, expectations and cultural background of the subjects. In most cases, those limits are different than the original suggested by the standards In a similar manner, research by (Vellei *et al.*, 2017) concluded that those limits are not only variable based on temperature but also on relative humidity. In line with this, they propose a method that significantly extends the relative humidity range for acceptable indoor conditions in naturally ventilated buildings, according to the thermal history and expectations of the users.

Adaptive opportunities are an efficient solution to achieve and maintain comfort. However, they are not necessarily faultless whenever they are applied. Adaptive 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 (Nicol, 2017) (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 (Oropeza-perez, 2019). Thus, it is important to anticipate its application in the early design stages and analysis.

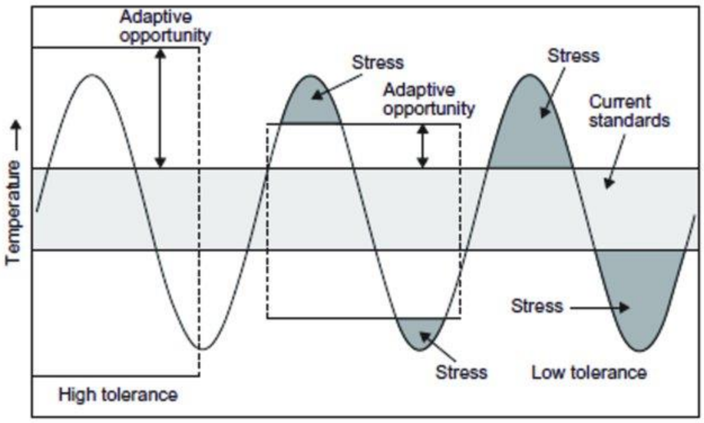

Figure 3. Effect range of passive strategies on a temperature curve with respect to the comfort zone and thermal stress (Taslim, Parapari and Shafaghat, 2015)

When speaking about tropical and subtropical locations, it is important to keep in mind that despite of what comfort models and adaptive thermal comfort theory suggest, most of the building stock of developing countries are solely depending on passive strategies as means to create and maintain comfortable conditions. Users maintain a closer relationship with outdoor spaces and therefore, they easily acclimatize and closely relate to exterior conditions, resulting in a more uniform thermal history (Humphreys and Nicol, 2002). This means that, according to some of the comfort models, people in these regions may have lived and will be living under what could be considered overheating conditions for most of their time. Nevertheless, regardless of the possible location of the comfort limit, in order to pursuit a better understanding and to evaluate the threat, it is necessary to quantify and fully appreciate the extent of this overheating phenomenon.

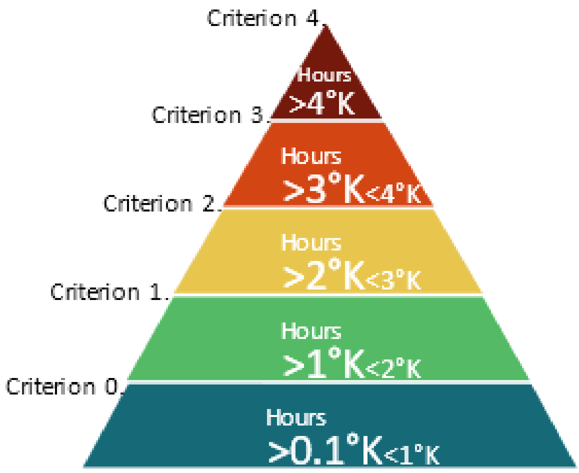

Figure 4. Graphical representation of overheating hours subdivision criteria

This paper proposes a method based on 5-step hourly subdivision criteria to assess the intensity and frequency of overheating in a sensitive manner. The method divides overheating temperatures depending on how far they are from the upper comfort limit. Each criterion could be described as follows:

- Number of hours above 0.1K. The total amount of hours where temperature is strictly above comfort 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 to the body. (Nicol, Humphreys and Roaf, 2012).
- Number of hours above 1°K. The total amount of hours where 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 a significant thermal stress.
- 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 regain comfort.
- 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 clearly present, but still it is possible to be solve and re-gain comfort.
- 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 where conditions may still be bearable for the less sensitive subjects.

Once the overheating hours corresponding to a reading or a simulation result are distributed across the five division method, it is possible to appreciate the frequency of overheating hours, as well as their distance from the upper comfort limit. Figure 3 provides a graphical representation of this.

3. Interpretation of results

With the interest of providing a better understanding of the method, six different examples were elaborated. The same building was simulated with six different weather files corresponding to three tropical locations and three subtropical locations.These locations are spread across 3 different continents, at different conditions and with variations on latitude, longitude, climate and altitude. Table 1 provides an overview of location specifics, climate generalities and simulation results.

	City	Country	Lat.	Long.	m.a.s.l.	Type of climate	Class.	Avrg. Yearly Temp.	Max. Temp.	% in comfort	% Above upper comfort limit	% Below lower comfort limit
1	Cancun	Mexico	20.03	-86.86	5	tropical	Aw	26	35.3	92.99	6.88	0.13
2	Sao Paulo	Brazil	-23.5	46.617	792	subtropical	Csc	20.2	33.5	91.55	0.65	7.80
3	Lagos	Nigeria	6.58	3.33	40	tropical	Aw	27.5	34.9	94.16	5.84	0.00
4	Cairo	Egypt	30.083	31.283	36	subtropical	BWh	22.5	41.8	83.49	7.59	8.92
5	Jakarta	Indonesia	-6.15	106.85	5	tropical	Af	26.3	34.5	96.55	3.45	0.00
6	New Delhi	India	28.583	77.2	212	subtropical	BSh	24.9	44.4	78.14	17.53	4.33

Table 1. Specifications and details of the locations and their simulation results.

The simulation file was setup assuming a completely passive, naturally ventilated building, excluding any possible neighbouring or contextual buildings. The average U-Value for the building envelope is 3.06 W/m²K and is composed by single glazing windows, plastered brick walls and a concrete slab cover. It considered a infiltration airflow of 0.75 air-changes per hour , as well as an automated window operation according to the interior and exterior temperature, imitating the potential user's behaviour.

The yearly hourly temperature of each of the locations is represented in Figure 5, where it is possible to appreciate the chronological occurrence of temperature peaks according to the weather files. In a similar way, the simulation hourly results are plotted in Figure 6, following the BS EN 15251 standard for naturally ventilated office buildings with a ±4K width comfort band. Following the established standard limits, everything that falls outside the upper comfort limits is considered as overheating despite the distance from the upper comfort limit. It is possible to appreciate in the results that the buildings located in tropical locations suffered only occasional overheating while the ones in subtropical climates experienced both overheating and underheating., In Table 1, it is possible to appreciate the percentages of comfort and overheating corresponding to the simulation results of Figure 6. With the purpose of focusing only in the overheating analysis, underheated periods will be excluded from examination.

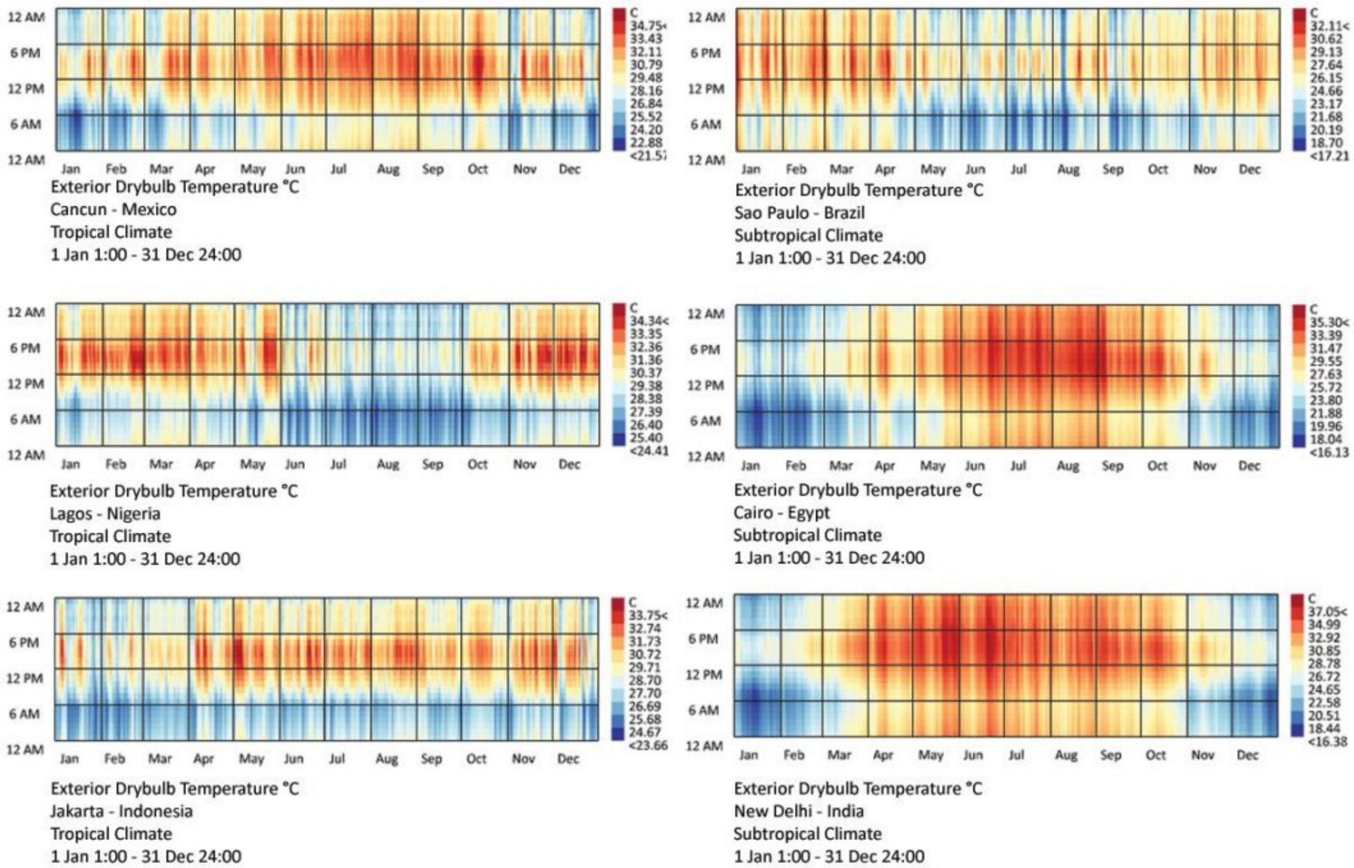

Figure 5. Hourly temperatures during the year of the 6 test locations

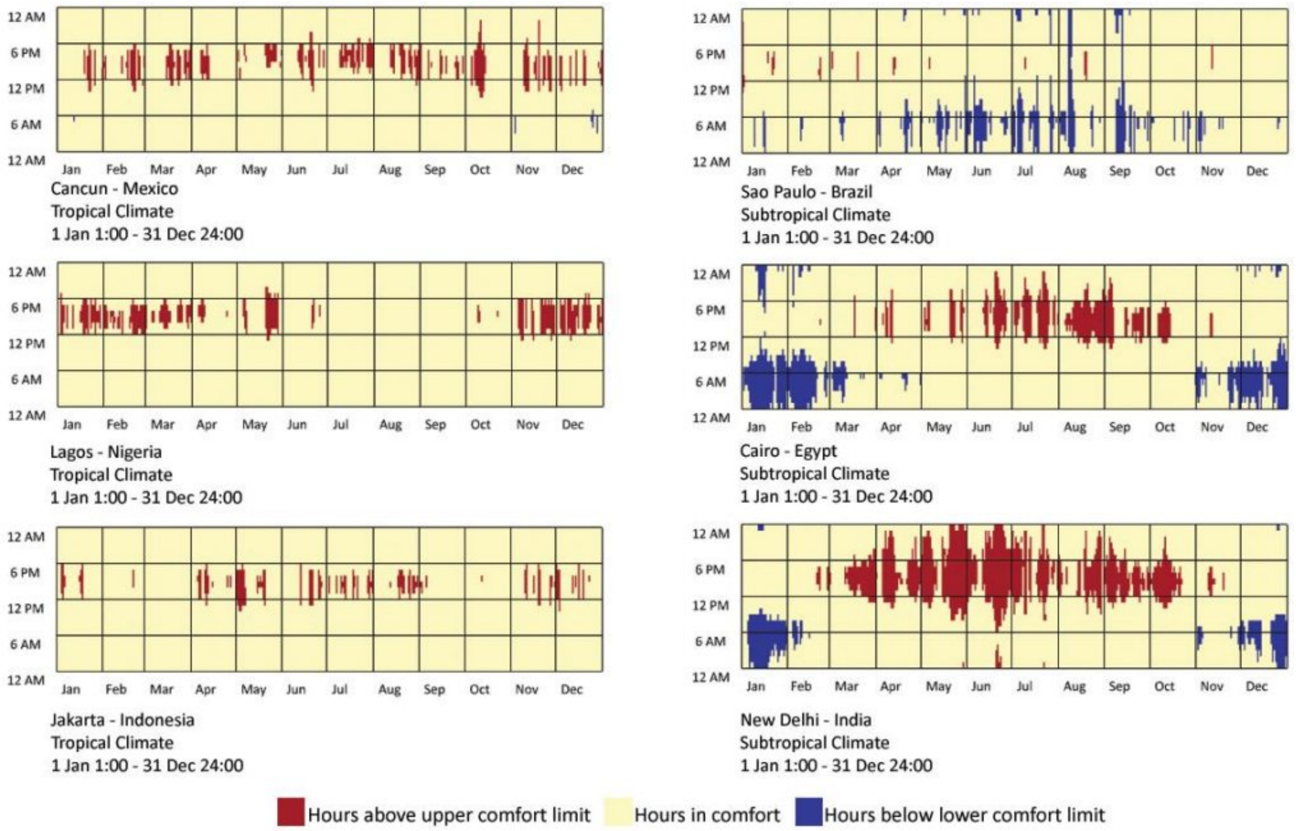

Figure 6. Simulations hourly results. Hours in yellow are in comfort, red are overheated, and blue are cold hours

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

- Criterion 0, hours >0.1°K but <1°K: the total amount of hours where overheating is occurring but 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 or require a solution, a high number means that in a particularly hot season, the building is in danger of displaying a constant overheating problem that will escalate further.
- Criterion 1, hours >1°K but <2°K: the total amount of hours where 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 one single adaptive opportunity can be highly effective against thermal stress. It can be summarized as the possibility of changing the surrounding environment by, for example, access to cold drinks, airflow improvement or clothing adjustments.
- Criterion 2, hours >2°K but <3°K: the total amount of hours where 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 in order 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: the total amount of hours where 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 endured for long periods without experiencing discomfort and performance reduction. 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: the total amount of hours where temperature is four degrees or more above comfort. This means that there are at least 8 °K or the same length of the comfort band between the current temperature and thermal neutrality. Overheating is occurring, and depending on the subjects and the context, it might not be possible to be endured, 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 decrease the thermal stress, although they may not increase the human performance of the users.

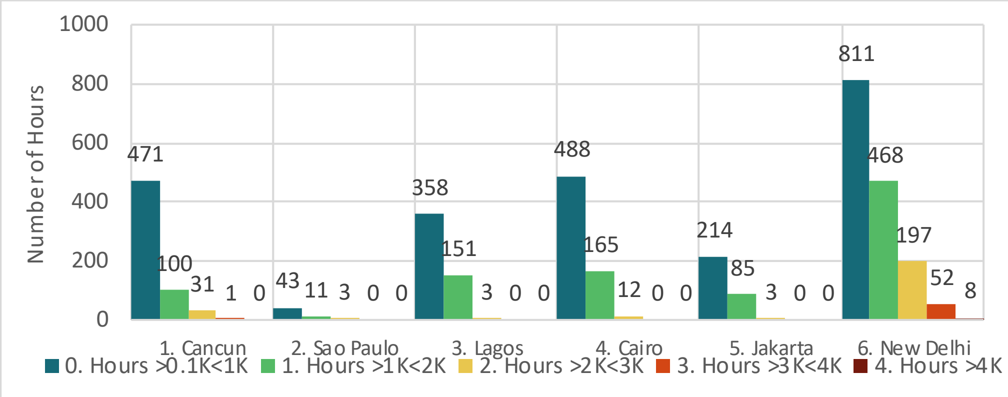

Figure 7. Yearly accumulative count of overheating hours according to each criterion in every location.

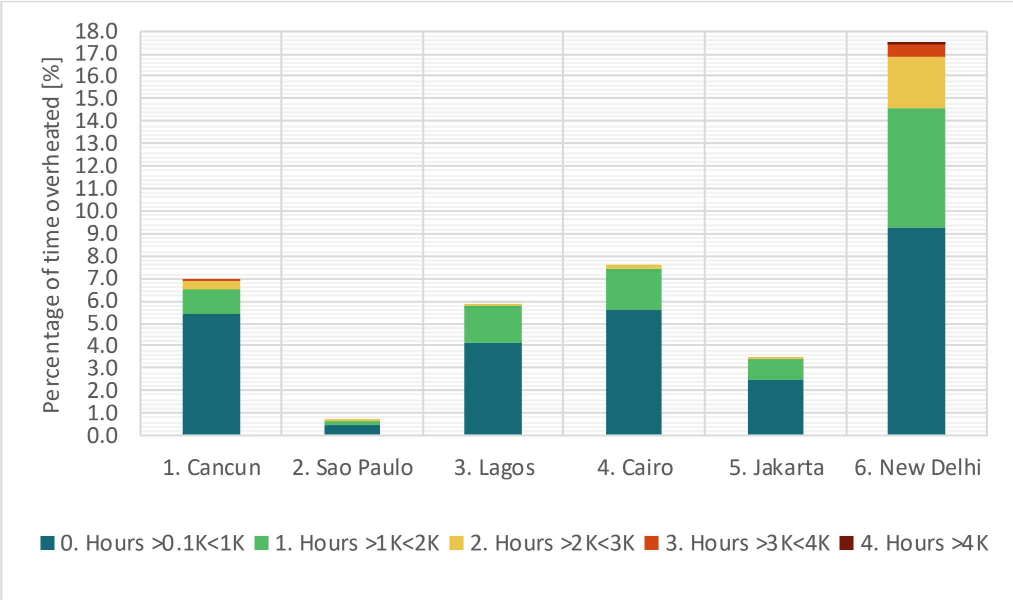

Figure 8. Yearly percentage of time overheated according to each criterion during the year

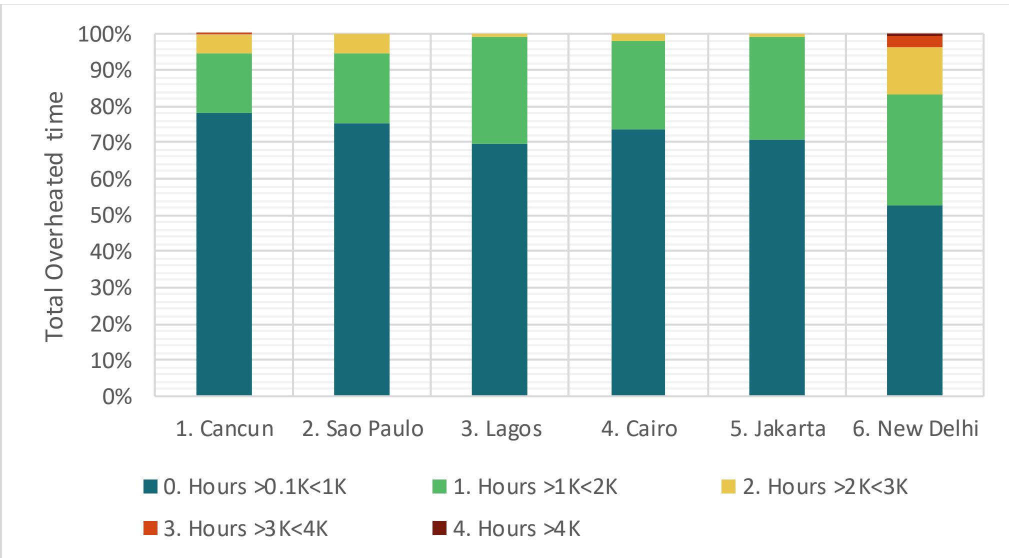

Figure 9. Distribution of the intensity of overheating according to each of the criteria within total overheating time

In figures 7 to 9 overheating hours in the simulation results of every location are plotted according to the criteria. The yearly accumulative count in Figure 7, the yearly percentage of time overheated in figure 8, and in Figure 9 the distribution of the intensity 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.

It is possible to appreciate that, while Jakarta performs best among tropical locations remaining 96.55% of the time in comfort, Cancun has the lowest percentage of time in comfort (92.99%). However, none of the three tropical locations (Cancun, Lagos or Jakarta) presents a persistent or threatening overheating problem since none them show hours above 3°K or 4°K. Jakarta and Lagos have only 3 hours of discomfort above 2°K during a year, which is perfectly manageable with adaptive opportunities, and even when Cancun has 31 hours of discomfort above 2°K, it only represent the 0.35% of time during a year, which is as well still manageable with adaptive opportunities. In figure 10 it is possible to see the concurrence and intensity throughout the year of these overheating events.

Speaking about sub-tropical locations, it is possible to appreciate that Sao Paulo is the best performing sub-tropical location, remaining 91.55% of the time in comfort with a 0.65% of time overheated, while New Delhi has the lowest percentage of time in comfort with a 78.14% of time and a 17.53% of time overheated, and Cairo in the middle of the two with a 83.49% of time in comfort and 7.59% of time overheated. It is possible to say that Sao Paulo does not have an overheating problem of any kind since all its numbers in every criteria are low and the very few it has, are mainly in criterion 0 and 1. In the case of Cairo, despite of the high number of overheating hours within criterion 0 and 1 , these are fully manageable through adaptive opportunities, and the 12 hours during the year corresponding to overheating hours >2°K, can be considered quite insignificant in a broader perspective since the overheating does not escalate any further, as it is shown in Figure 10. In the case of New Delhi, even when the graphs may apparently indicate the contrary, it does not necessary have a significative overheating problem, the numbers of the criterion 0 and criterion 1 does not necessarily represent a constant problem during the year since they can be manageable with adaptive opportunities. The numbers of the last 3 criterions do represent a recurrent problem, but given the amount of hours or percentage of time, it can be argued that they are manageable events spread during the year, in the number of hours above 2°K limit or criterion 2 is translated as 32.5°C, meaning that temperature has escalated that for 2.25% of the occupancy time. And .6% of the time 33.5°C or 52 hours, and 0.10% of the time 34.5°C or 8 hours, the original CIBSE TM-52 (CIBSE, 2013) suggest that a non-domestic building can be safely free-running or naturally ventilated if temperature never exceeds a maximum of 4°K and the 1°K limit is not exceed for more than 3% of occupancy time during the hottest 5 months of the year, even when these limits where drawn for buildings in the UK and the building in New Delhi would fail to pass these, and all the criteria in the CIBSE TM-52. People in New Delhi would still be occupying and using the building, and they would only consider having a recurrent overheating problem during the months of May and June when is frequent. (Mishra and Ramgopal, 2015).

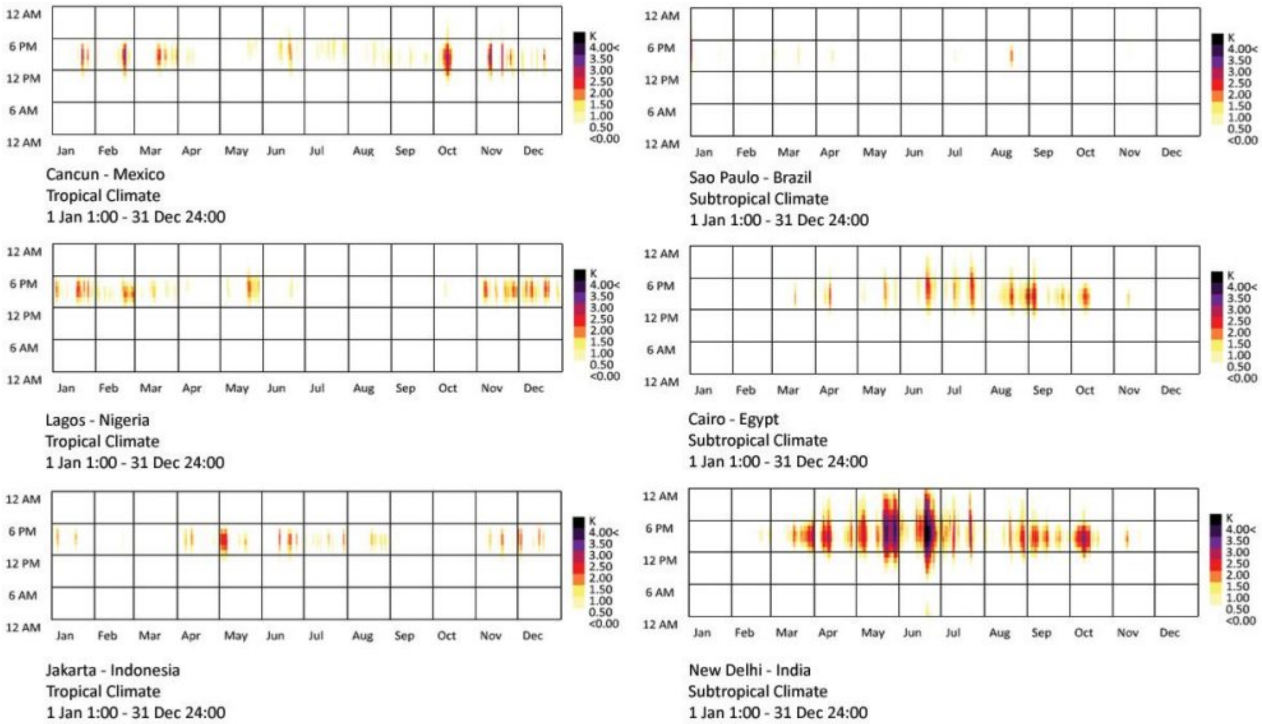

Figure 10. Yearly distribution of overheating hours and their distance to thermal neutrality

4. Conclusions

This method provides a novel approach to visualize and understand overheating hours. 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 temperatures. Nevertheless, further research needs to be conducted specifically focused in every location to establish the possible overheating limits in a clear and exact way according to the specifics of the users, since this methodology is case-sensitive.

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