Viabilidad del modelo de confort térmico adaptativo bajo condiciones de clima cálido subhúmedo: ahorro energético en refrigeración en campeche, México
Oscar May-Tzuc, Mario Antonio Jiménez-Torres, Andrea del Rosario Cruz y Cruz, Román Canul-Turriza, Juan Edgar Andrade-Durán, Felipe Noh-Pat
Revista Hábitat Sustentable Vol. 13, N°. 1. ISSN 0719 - 0700 / Págs. 120 - 131
https://doi.org/10.22320/07190700.2023.13.01.10

Recibido 08/05/2023
Aceptado 14/06/2023

FEASIBILITY OF THE ADAPTIVE THERMAL COMFORT MODEL UNDER WARM SUB-HUMID CLIMATE CONDITIONS: COOLING ENERGY SAVINGS IN CAMPECHE, MEXICO

VIABILIDAD DEL MODELO DE CONFORT TÉRMICO ADAPTATIVO BAJO CONDICIONES DE CLIMA CÁLIDO SUBHÚMEDO: AHORRO ENERGÉTICO EN REFRIGERACIÓN EN CAMPECHE, MÉXICO

VIABILIDADE DO MODELO DE CONFORTO TÉRMICO ADAPTATIVO EM CONDIÇÕES DE CLIMA QUENTE SUBÚMIDO: ECONOMIA DE ENERGIA NA REFRIGERAÇÃO EM CAMPECHE, MÉXICO

Oscar May-Tzuc
Facultad de Ingeniería, Universidad Autónoma de Campeche, San Francisco de Campeche, México
https://orcid.org/0000-0001-7681-8210
oscajmay@uacam.mx

Mario Antonio Jiménez-Torres
Departamento de Ingeniería y proyectos, Universidad Internacional Iberoamericana, San Francisco de Campeche, México
https://orcid.org/0000-0002-8331-1888
mario.jimenez@unini.edu.mx

Andrea del Rosario Cruz y Cruz
Facultad de Ingeniería, Universidad Autónoma de Campeche, San Francisco de Campeche, México
https://orcid.org/0000-0001-8861-1276
andrcruz@uacam.mx

Román Canul-Turriza
Facultad de Ingeniería, Universidad Autónoma de Campeche, San Francisco de Campeche, México
https://orcid.org/0000-0003-2081-9913
roacanul@uacam.mx

Juan Edgar Andrade-Durán
Facultad de Ingeniería, Universidad Autónoma de Campeche, San Francisco de Campeche, México
https://orcid.org/0000-0002-7370-1209
jeandrad@uacam.mx

Felipe Noh-Pat
Facultad de Ingeniería, Universidad Autónoma de Campeche, San Francisco de Campeche, México
https://orcid.org/0000-0003-1981-8323
felipnoh@uacam.mx

RESUMEN

El enfoque convencional para alcanzar el confort térmico generalmente se centra en modificar la temperatura de consigna en edificios totalmente climatizados. Sin embargo, el enfoque del confort térmico adaptativo es una alternativa que considera la interacción entre los edificios, el clima local y los usuarios para permitir mejoras significativas en el ahorro de energía. El trabajo analiza la viabilidad de implementar estrategias de confort térmico adaptativo, comparando modelos adaptativos basados en la norma ASHRAE 55-2020 y un modelo regional para la tipología climática tropical de México, contrastando los resultados respecto del enfoque estático. Se analizó térmicamente 13 locaciones del Estado de Campeche obteniendo que las estrategias de ventilación son aplicables en todo el Estado y que ambos modelos aseguran mejoras en el consumo de energía. Además, los resultaron siguieren que es necesario desarrollar más modelos adaptativos locales para proponer estrategias con mejor potencial de impacto en la región.

Palabras clave
confort térmico adaptativo, clima cálido subhúmedo, ahorro energético

ABSTRACT

The conventional approach to achieve thermal comfort generally focuses on modifying the setpoint temperature in fully air-conditioned buildings. However, the adaptive thermal comfort approach is an alternative that considers the interaction between buildings, the local climate, and the users to allow significant improvements in energy savings. This paper analyzes the feasibility of implementing adaptive thermal comfort strategies, comparing adaptive models based on the ASHRAE 55-2020 Standard and a regional model for the tropical climate typology of Mexico, and contrasting the results with the static approach. Thirteen locations in the State of Campeche were thermally analyzed, seeing that the ventilation strategies are applicable throughout the State and that both models ensure improvements in energy consumption. In addition, the results suggest that it is necessary to develop more local adaptive models to propose strategies with better potential impact in the region.

Keywords
adaptive thermal comfort, hot sub-humid climate, energy savings.

RESUMO

A abordagem convencional para alcançar o conforto térmico geralmente se concentra em modificar a temperatura de referência em edifícios totalmente climatizados. No entanto, a abordagem do conforto térmico adaptativo é uma alternativa que considera a interação entre os edifícios, o clima local e os usuários, a fim de permitir melhorias significativas na economia de energia. Este trabalho analisa a viabilidade de implementar estratégias de conforto térmico adaptativo, comparando modelos adaptativos baseados na norma ASHRAE 55-2020 e um modelo regional para a tipologia climática tropical do México, contrastando os resultados com a abordagem estática. Foram analisados termicamente 13 locais no estado de Campeche, concluindo-se que as estratégias de ventilação são aplicáveis em todo o estado e que ambos os modelos garantem melhorias no consumo de energia. Além disso, os resultados sugerem a necessidade de desenvolver mais modelos adaptativos locais para propor estratégias com maior potencial de impacto na região.

Palavras-chave
conforto térmico adaptativo, clima quente subúmido, economia de energia.

INTRODUCTION

Currently, the building sector is the second largest energy consumer in the world, covering about 40% of energy consumption and generating just over 30% of global emissions (Pérez-Fargallo et al., 2020). One of the main reasons behind this is the high rates of indoor thermal discomfort, meaning that 50% of the energy in buildings is destined to satisfy air conditioning needs (Jimenez-Torres et al., 2023). These patterns increase in cities with hot or tropical climates, which, in the last decade, have seen a constant increase in their population, leading, consequently, to a greater demand for air conditioning.

Under this scenario, the setpoint temperature in air conditioning equipment plays an important role in thermal comfort and high energy consumption. On one hand, this temperature is usually set at a fixed value (sometimes restricted), which means there is not adequate thermal satisfaction for all the occupants of the enclosures. In addition, the greater the difference between the setpoint temperature and the ambient temperature, the more electric power consumption increases. Based on this situation, several studies have shown that by increasing the setpoint or target temperature it is possible to reduce energy consumption by up to 30%. Even in tropical climate regions by setting a temperature above 25.5°C, significant reductions in energy use have been observed (Hoyt et al., 2015). However, it is important to emphasize that these studies have been made under what is currently known as the traditional approach, based on the Predicted Mean Vote (PMV) index, which is also known as the thermal balance model or static model (Sala et al., 1999), which has among its main drawbacks, limiting the interaction of users with the environment.

In the last decade, a new approach to the search for occupant comfort called adaptive thermal comfort (ATC), has become increasingly relevant. Its main idea is to replicate the natural behavior of humans, which is capable of adapting physiologically and psychologically to the increase in temperature to a given point. The adaptive model is based on diverse research regarding the relationships between acceptable indoor air temperature and outdoor air temperature, establishing that the comfort temperature depends on environmental conditions (Tsolkas et al., 2023). Several studies have been carried out under this approach to analyze the potential energy savings, even considering climate change scenarios. Salcido et al. (2016) demonstrated a savings potential of between 50 – 60% when using adaptive strategies. Other researchers (Sánchez-García et al., 2019; Sánchez-García et al., 2023) have established in different studies that, by implementing the adaptive comfort strategy, energy savings of more than 30% are achieved even under climate change scenarios.

However, the adaptive approach has also been the subject of debate in recent years since, although it presents important advances by incorporating adaptation variables, the model's formulation has bias. Among them is its inaccuracy when implemented in different constructions on having been designed based on data from office buildings (Yau & Chew, 2012). In addition, the ATC models promoted most internationally lack analysis in tropical climate regions, leaving doubts about their viability in Latin American locations (Rodriguez & D'Alessandro, 2019). This has led to questioning whether these models can promote a more intensive use of energy instead of reducing it, with one of the most recommended alternatives being the development of local adaptive models that fit the needs of the population where an impact is desired.

Therefore, this work addresses the possibility of reducing the demand for air conditioning equipment in communities with a hot-humid climate, located in the south of Mexico, using the adaptive comfort approach. The case of Mexico is interesting because the residential sector is one of the main energy consumers, allocating more than 20% to air conditioning processes (SENER, 2021). In addition, the locations where the hot-humid climate predominates represent 30% of the country's homes and the records indicate that energy requirements double there, so the analysis and search for energy efficiency techniques are imperative.

The research takes the State of Campeche, Mexico as a case study, analyzing the implementation of the ATC model promoted by the ASHRAE 55-2020 regulations (ASHRAE, 2020) and an adjusted regional model for the tropical climate of Mexico (Oropeza-Perez et al., 2017).

CHARACTERISTICS OF THE REGION OF CAMPECHE

The State of Campeche, Mexico, is one of three states of the country located in the southeast peninsular region. It is bordered to the north by the Gulf of Mexico, to the east by Quintana Roo, Yucatan, and Belize, to the west by Tabasco, and to the south by Guatemala. Its territorial extension is 57,484.9 km^2 with a population of just under 1 million inhabitants spread across 13 municipalities (Figure 1). 99.95% of the territory has a hot humid climate with rains in summer. On the energy issue, it is listed among the states with an electricity tariff for temperatures between 30°C and 31°C during the summer.

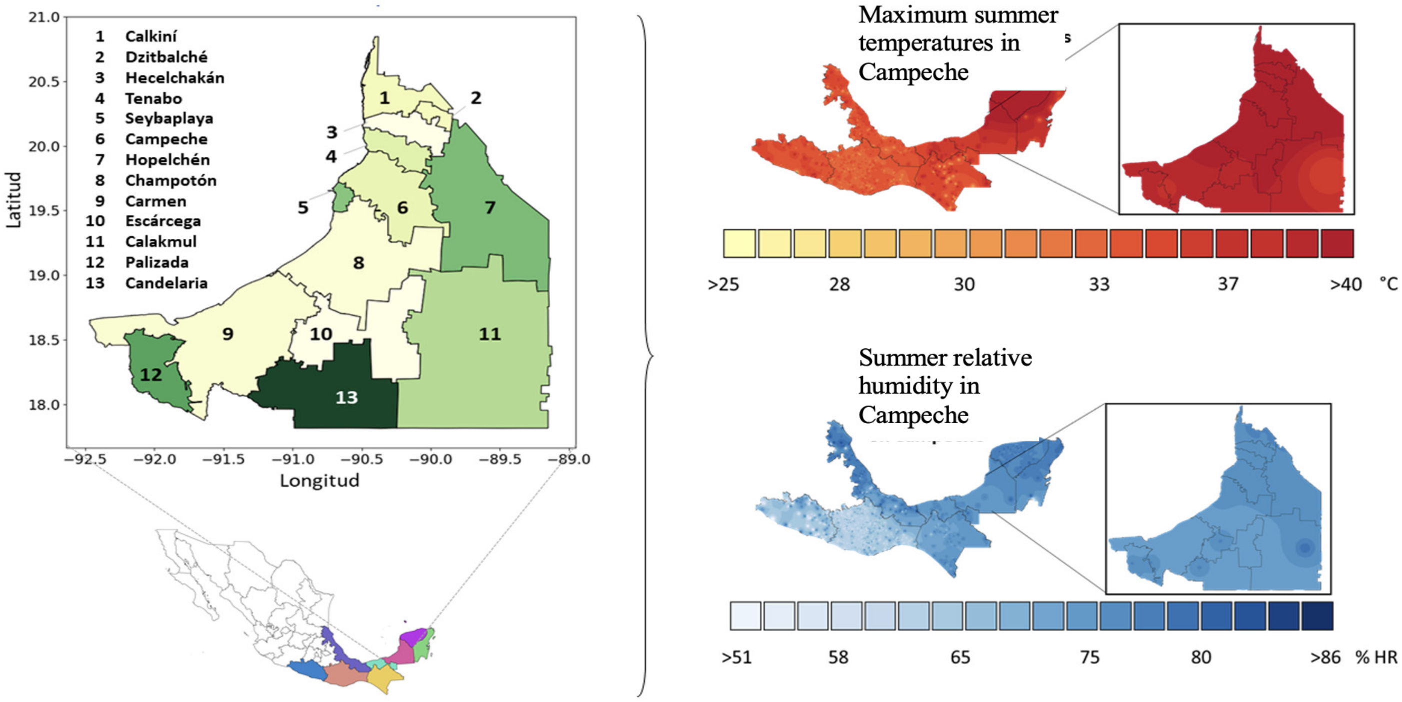

Figure 1. Geographical distribution and climatic characteristics of the State of Campeche, Mexico. Source: Preparation by the authors.

However, the latest weather station records indicate that temperatures inland exceed 37°C (INEGI, 2022), leading to high electricity consumption to satisfy the need for thermal comfort in homes. This is indicative that this region can potentially be benefited both from energy savings and thermal comfort by applying an adaptive approach.

METHODOLOGY

The study was divided into three stages: (i) obtaining the climatic and geostatistical information of the State of Campeche; (ii) applying the ATC models in the State's municipalities to obtain their comfort temperatures; (iii) calculating the potential cooling and heating hours for each municipality, as well as the feasibility of the ATC approach compared to the static model.

CLIMATIC AND GEOSTATISTICAL DATA

The meteorological information was obtained using the Meteonorm V7 software, downloading 13 climatic files of the State of Campeche for 2022, with one-hour intervals. The geostatistical data of population and territorial extension, as well as the entity's maps, come from the last population census made in 2020, whose information is freely accessible on the portal of the National Statistics and Geography System.

ADAPTIVE THERMAL COMFORT APPROACH

The ATC is based on the idea that the temperature inside a building (T_c) can be estimated from the outside ambient temperature (T_{out}).

This relationship is expressed by a linear regression using data collected in field studies both in the official updates of diverse international regulations and in regional adaptations of the approach (Carlucci et al., 2018):

$$T_c=mT_{out}+b \qquad \text{(Equation 1)}$$

where the slope *m* is a value proportional to the degree of adaptation of the region's climatic conditions and the abscissa *b* is the theoretical comfort value (based on measurements) at an outdoor temperature of 0°C (Equation 1).

---

1 inegi.org.mx

The paper aims to analyze two ATC models for Campeche. The first is the model promoted by the ASHRAE 55-2020 regulations (ASHRAE, 2020), which, although it does not follow an international standard, is one adopted most around the world. This ATC model was generated from data measured on 160 buildings located in countries on four continents, which has promoted its use as a standard in much of the world. The regulations indicate that a comfort temperature threshold at 80% reliability is obtained from the following linear equations (Equation 2 and Equation 3) (Carlucci et al., 2018):

Upper limit (acceptability 80%) =
$0.31\,\overline{T_{pma(out)}} + 21.3\,°C\ (10 \leq \overline{T_{pma(out)}} \leq 33.5)$ (Equation 2)

Limit to infer (acceptability 80%) =
$0.31\,\overline{T_{pma(out)}} + 14.3\,°C\ (10 \leq \overline{T_{pma(out)}} \leq 33.5)$ (Equation 3)

Where $\overline{T_{pma(out)}}$ represents the prevailing average outdoor temperature. When $\overline{T_{pma(out)}}$ is above or below this threshold, it is necessary to implement cooling or heating strategies inside the building to achieve occupant comfort.

The second ATC model evaluated is the one developed by Oropeza-Perez et al. (2017). This is distinguished by being the first regional ATC model designed for Mexico, which divides the country into four types of climate (arid, temperate, hot dry, and hot humid). The model was developed from 74 surveys distributed proportionally in the four climatic zones. The entire territory of the State of Campeche is classified as a hot humid climate. According to this, the ATC is given by equation 4:

$T_c = 0.38\,\overline{T_{pma(out)}} + 15.7\,°C$ (Equation 4)

To homogenize the description of this model with what is expressed by the ASHRAE 55-2020 standard, the upper (Equation 5) and lower (Equation 6) limits were defined by adding ± 3.5°C:

Upper limit (acceptability 80%) =
$0.38\,\overline{T_{pma(out)}} + 18.2\,°C\ (10 \leq \overline{T_{pma(out)}} \leq 33.5)$ (Equation 5)

Limit to infer (acceptability 80%) =
$0.38\,\overline{T_{pma(out)}} + 13.2\,°C\ (10 \leq \overline{T_{pma(out)}} \leq 33.5)$ (Equation 6)

For both approaches, it highlights the concept of $\overline{T_{pma(out)}}$. Its importance lies in the fact that the ATC is based on the premise that the temperature inside buildings does not depend exclusively on the current day, but is influenced by the ambient temperature of the previous days; where $\overline{T_{pma(out)}}$ represents these effects. In previous versions of ASHRAE regulation 55-2017, $\overline{T_{pma(out)}}$ was considered as a value obtained through monthly averages. From the last two modifications, this is linked to the days before the day of interest, whose equation is given by equation 7:

$\overline{T_{pma(out)}} = (1-\alpha)[T_{e(d-1)} + \alpha T_{e(d-2)} + \alpha^2 T_{e(d-3)} + \alpha^3 T_{e(d-4)} + \cdots]$ (Equation7)

Where α is a weighted value that varies between 0 and 1, while $T_{e(d-1)}$ represents the number of previous days to consider that may impact the internal temperature of the building. For this work, seven previous days were used, as well as an α of 0.8 which is for regions with a tropical climate as is the case of the State of Campeche considering the ASHRAE 55-2020 regulations.

COOLING AND HEATING HOURS POTENTIAL

The Cooling Degree Hours (CDH) (Equation 8) and Heating Degree Hours (HDH) (Equation 9) methods were used to identify the cooling and heating potential during the ATC's implementation. Both measure the influence of temperature changes on the energy performance of the building. The CDH is defined as the cumulative sum of subtracting a setpoint temperature (T_T) from the average ambient temperature of each hour (T_a). Where *h* indicates the total number of hours analyzed and the apostrophe (+) indicates that only positive results are effective during the summation. Similarly, the HDH indicates the cumulative sum of subtracting the average ambient temperature of each hour (T_a) from the setpoint temperature (T_T), (Jimenez-Torres et al., 2023):

$$CDH = \begin{cases} \sum_{h}^{8760} (T_a - T_{T,EC})^+ & \text{enfoque estático} \\ \sum_{h}^{8760} (T_a - T_{T,DC})^+ & \text{enfoque dinámico} \end{cases} \qquad \text{(Equation 8)}$$

$$HDH = \begin{cases} \sum_{h}^{8760} (T_{T,EH} + T_a)^+ & \text{enfoque estático} \\ \sum_{h}^{8760} (T_{T,DH} + T_a)^+ & \text{enfoque dinámico} \end{cases} \qquad \text{(Equation 9)}$$

Conventionally, the setpoint temperature is assigned to a static value. For CDH, it is given by the static cooling temperature (=25°C), and for HDH is given by

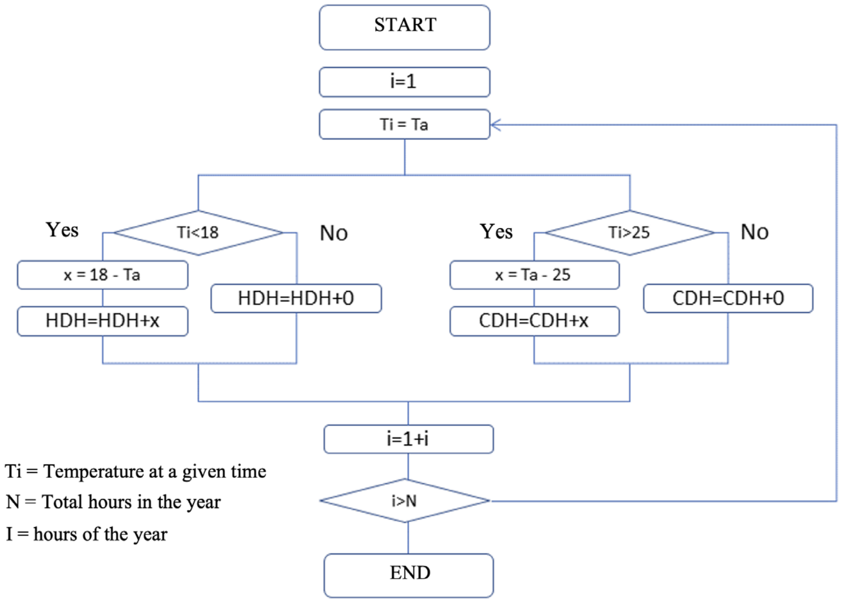

Figure 2. Flow diagram to obtain the static CDH and HDH. Source: Preparation by the authors.

the static heating temperature (= 18°C). Both values are within the range historically described in several regulations, such as the case of ANSI/ASHRAE 169-2020 (ANSI/ASHRAE, 2021). Figure 2 illustrates the algorithm used to calculate the static CDH and HDH.

For the adaptive approach, the setpoint temperature is considered dynamic and is given by the value of the comfort temperature at the 80% upper limit of acceptability (and the 80% lower limit of acceptability for the CDH and HDH, respectively. In this work, it is intended to compare both the adaptive model of the ASHRAE 55-2020 regulation and the regional model developed by Oropeza-Perez et al. (2017) compared to the static model to determine the viability of the adaptive approach.

VIABILITY INDICATORS OF THE ADAPTIVE APPROACH

The viability of the ATC for the region is measured by comparing the annual hours (h_i) when each of the municipalities is within the comfort threshold at an acceptability of 80%. This is known as the annual percentage of the potential application of natural ventilation (PNV) and is given by Bienvenido-Huertas et al. (2021):

$$PNV = \frac{100\sum_h^{8760} h_i}{8760} \quad \text{(Equation 10)}$$

RESULTS AND DISCUSSIO

ANALYSIS OF COOLING DEGREE HOURS

Figure 3 illustrates the spatial representation throughout Campeche on the demand for annual cooling hours considering the static approach (Figure 3a), the dynamic approach developed by Oropeza-Perez et al. (2017) (Figure 3b), and the dynamic approach based on the ASHRAE 55-2020 standard (Figure 3c). For all three cases, it is clear that the municipalities located in the north of the state are the ones that require the highest demand for cooling, even though the entire entity has the same type of climate. This can be explained because the State's northern municipalities have the lowest rainfall levels throughout the year, between 700 and 800 mm, while the southern municipalities see rainfall levels of 1500 to 2000 mm (INEGI, 2022). In addition, although INEGI data report that more than 77% of the state is covered by forest and grassland, the soil type is variable in the region. The areas where higher levels of CDH are reported are located in karstic soils with an abundance of rocky surfaces. As one heads south, the dominant physiography is hills, which coincides with the reduction in the demand for cooling. Finally, the lowest latitudes, with the lowest demand for CDH, are the State's swampy area.

From Figure 3, it is inferred that the static approach is the one that homogeneously demonstrates the highest demand for CDH in the year, in most of

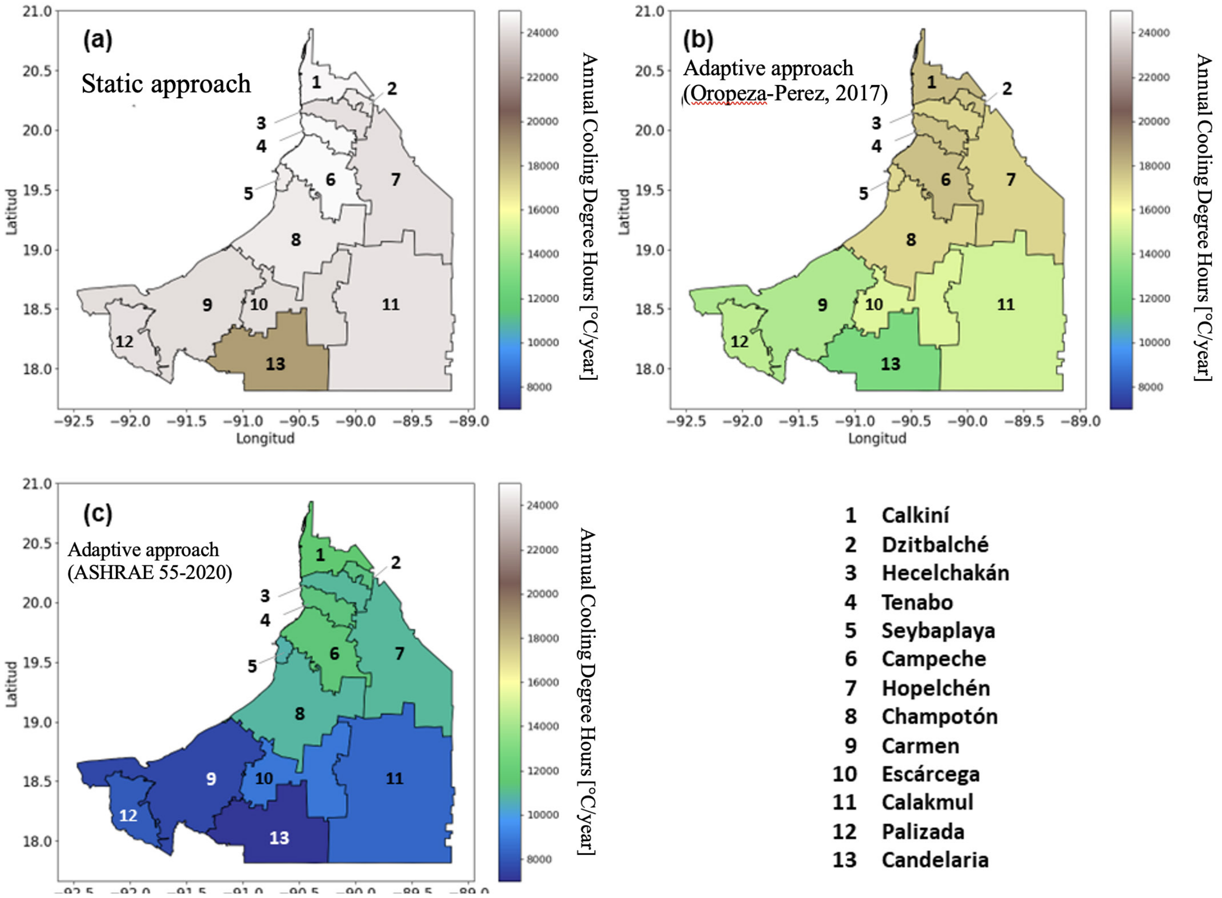

Figure 3. Cooling degree hours for the municipalities of Campeche: (a) static model; (b) regional adaptive model; (c) ASHRAE 55-2020 adaptive model. Source: Preparation by the authors.

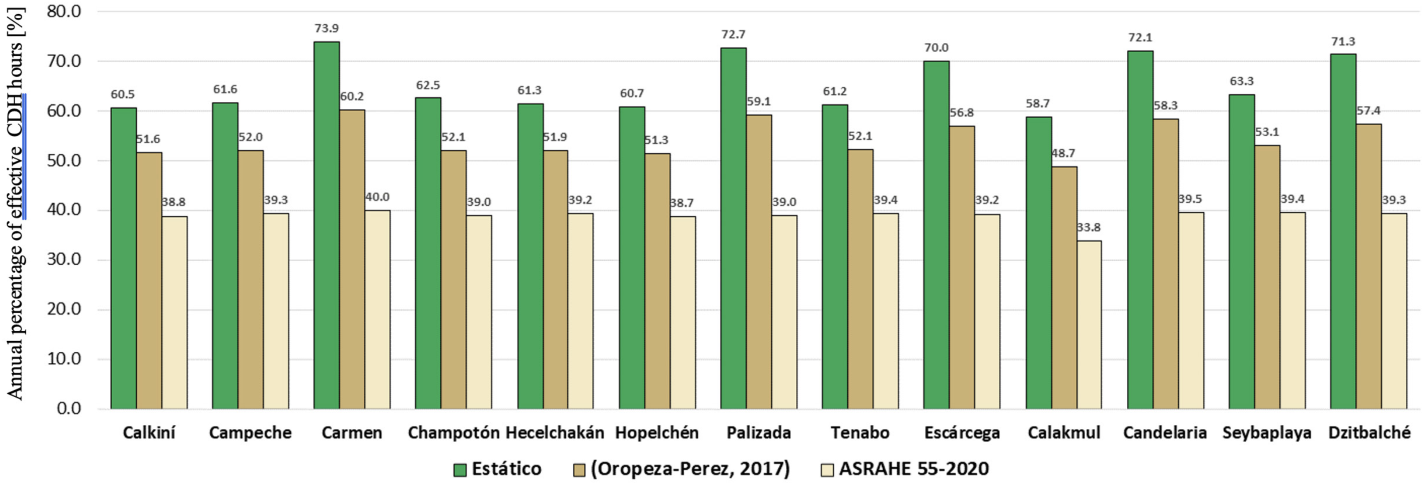

Figure 4. Annual comparison for the municipalities of Campeche on the percentage of cooling hours-year required using the static approach and the adaptive comfort approach. Source: Preparation by the authors.

the territory. Except for the municipality of Candelaria, the entire State has an almost constant CDH ranging from 24,000 to 24,800°C/hour-year. Comparing these values with those of Figure 3b and Figure 3c, it is seen that the adaptive approach leads to less energy use for cooling in all the entity's municipalities. However, there are notable differences between the two ATC models. The ASHRAE model indicates that it is possible to reduce the CDH index by between 53 and 62%, while the regional model, although exhibiting benefits, reduces these by half, decreasing between 28 and 31%, compared to the static approach. This may be because the ASHRAE 55-2020 model is designed under analysis in less hot climates, implying a less drastic reason to change for the occupants (m=0.31). This may lead to a critical limit in tropical climate regions, such as Campeche, to comply in theory with the model, but in practice, it increases occupant discomfort. On the other hand, the regional model indicates that populations in hot climates do not have a broad tolerance to heat (b=18.3), as well as a lower climatic adaptation to sudden temperature changes that occur in the region.

Another important point to analyze is how the integration of the adaptive approach impacts the operation hours of air conditioning equipment. Figure 4 presents the annual percentage of hours air conditioning equipment is used to cool rooms. The static approach shows a 60% use of air conditioning during the year, with the southern municipalities (Carmen, Palizada, Escárcega, and Candelaria) being the ones that use air conditioning the most. This implies that, despite their annual consumption being lower than the northern municipalities, they are the ones with the longest time outside their comfort zone. On the other hand, by using the regional adaptive model, it is possible to reduce effective CDH hours by between 10% and 8%; reducing operating hours in most municipalities to below 55%, while the ASHRAE model suggests that it is possible to reduce annual CDH hours to below 40%. However, it is important to consider what was discussed above, since, according to Humphreys et al. (2007) a poor implementation of the adaptive approach can be counterproductive as it would encourage occupants to use more energy to relieve heat stress. This demonstrates the value of the regional model by more clearly representing the characteristics of the State, while at the same time indicating that the adaptive approach is an appropriate option for reducing the energy consumption of air conditioning.

ANALYSIS OF HEATING DEGREE HOURS

For HDH, its analysis does not imply the need for heating actions in the State (temperatures in the

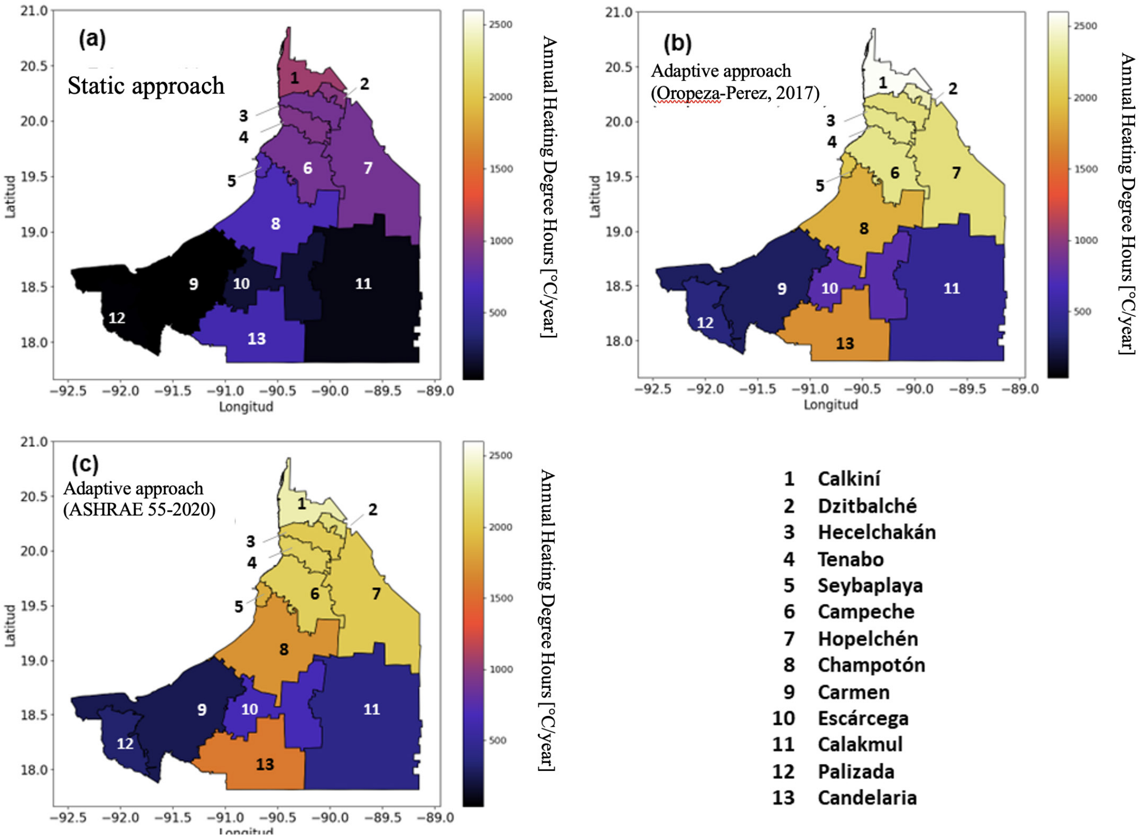

Figure 5. Heating degree hours for the municipalities of Campeche: (a) static model; (b) regional adaptive model; (c) ASHRAE 55-2020 adaptive model. Source: Preparation by the authors.

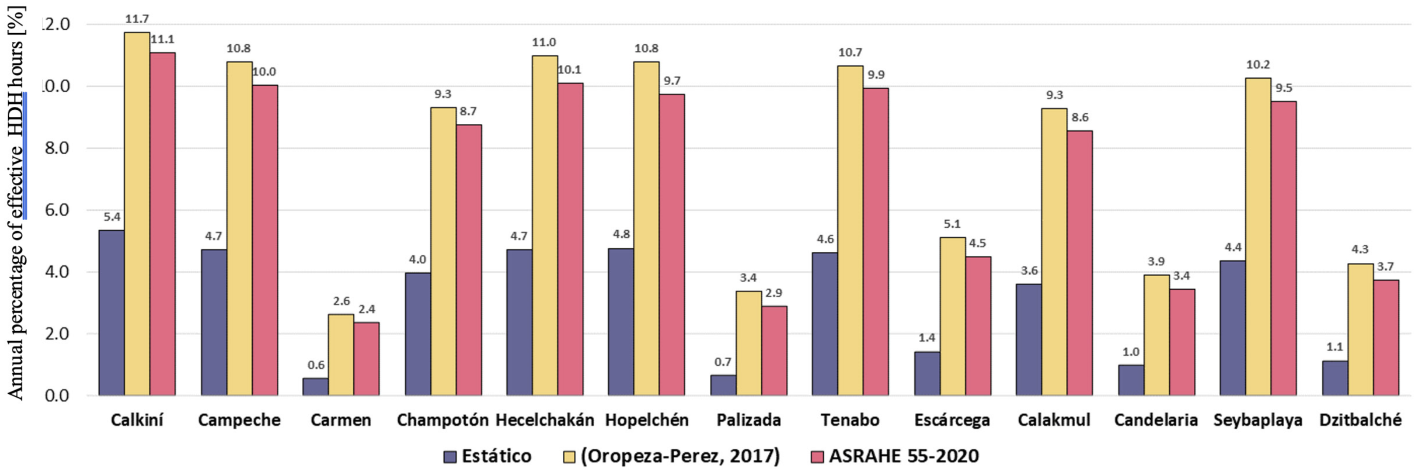

Figure 6. Annual comparison for the municipalities of Campeche of the percentage of heating hours-year required using the static approach and adaptive comfort approach. Source: Preparation by the authors.

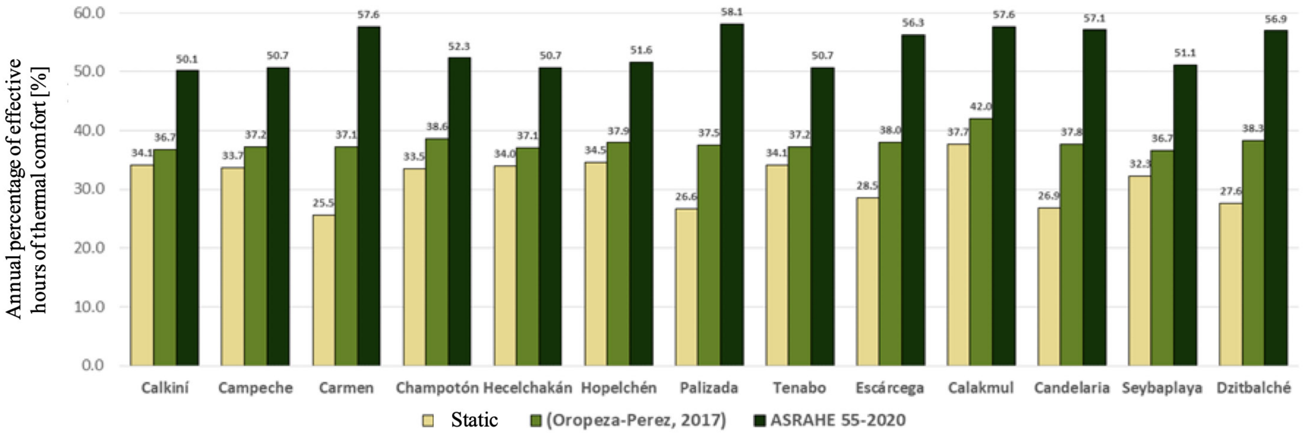

Figure 7. Annual comparison for the municipalities of Campeche of the percentage of heating hours-year required using the static approach and the adaptive comfort approach. Source: Preparation by the authors.

region are hardly ever lower than 18°C), but it is an indication of the time when the population may be in temperatures below the comfort zone.

According to Figure 5, there is a phenomenon similar to the case of the CDH where the municipalities of Carmen, Palizada, Candelaria, and Escárcega (located to the south) have the lowest discomfort rates during the year. The results of the static approach show that the HDH requirements for the State are minimal, coinciding with the tropical climate conditions of Campeche. However, remembering that here the HDH indicates the level of occupant discomfort, it is necessary to compare these with the adaptive results. Based on Figures 5b and 5c, the adaptive approach infers that HDH needs are higher. It is important to note that in comparison to the CDH case where the ASHRAE model varies by up to 20% from the regional model, the HDH difference between the two is minimal, which can be corroborated in the color scale of Figure 5. On average, the models differ by 9.8%, so in this case, they do agree on the heating estimate. It should be noted that this difference may be due to the perception of cold in tropical climate regions, where the population begins to feel discomfort at higher temperatures than in temperate regions.

On the other hand, the analysis was made regarding the annual hours that the population is below the comfort zone (Figure 6). The difference between the effective hours for both adaptive models only varies between 0.2% and 0.9%, with the municipalities with the lowest percentage of HDH being the ones where the smallest differences were found. In all cases, the adaptive model barely exceeded 10% of annual hours,

Table 1. Differences in the percentage of hours of CDH, HDH, and annual thermal comfort of each adaptive model compared to the static approach for the State of Campeche. Source: Preparation by the authors.

Municipality	Model (Oropeza-Perez et al., 2017)			ASHRAE 55-2020 Model		
	CDH	HDH	Comfort	CDH	HDH	Comfort
Calkiní	9.0	6.4	2.6	21.7	5.7	16.0
Campeche	9.6	6.1	3.5	22.2	5.3	16.9
Carmen	13.7	2.1	11.6	33.9	1.8	32.1
Champotón	10.4	5.3	5.1	23.6	4.8	18.8
Hecelchakán	9.4	6.3	3.1	22.1	5.4	16.7
Hopelchén	9.4	6.0	3.4	22.0	5.0	17.0
Palizada	13.6	2.7	10.9	33.7	2.2	31.5
Tenabo	9.1	6.0	3.1	21.8	5.3	16.5
Escárcega	13.2	3.7	9.5	30.8	3.1	27.8
Calakmul	10.0	5.7	4.3	24.8	5.0	19.9
Candelaria	13.8	2.9	10.8	32.6	2.5	30.2
Seybaplaya	10.2	5.9	4.3	23.9	5.1	18.8
Dzitbalché	13.9	3.1	10.8	32.0	2.6	29.4
Average	11.2	4.8	6.4	26.5	4.1	22.4
Standard Deviation	2.1	1.6	3.6	5.1	1.4	6.5

which translates into just under 40 days of the year, with most of that time being at night.

POTENTIAL NATURAL VENTILATION APPLICATION

The ultimate purpose of the analysis is to identify the level of positive impact that the implementation of adaptive strategies has in the 13 municipalities of Campeche. According to what was presented in Figure 7, the implementation of both adaptive models demonstrates advantages over the static approach. In the case of the ASHRAE 55-2020 model, it was identified that its use would be associated with the possibility of applying natural ventilation for at least 50% of the year in all municipalities of the State, with the possibility of being used in up to more than 57% in municipalities such as Palizada, Carmen, and Calakmul. In the case of the regional model, there are moderate benefits with an average percentage of natural ventilation use of 38% throughout the territory.

Table 1 shows that the adaptive regulatory approach and the regional approach improve the perspective of natural ventilation application by 16% and 6.4%, respectively. It is interesting to analyze the effects of the regional model. On one hand, the municipalities in the north of the state (Campeche, Calkiní, Hecelchakán, and Tenabo) have improvements of barely 2.4 and 3.5% compared to the traditional model. On the other hand, the best results occur in the southern municipalities.

In the case of the ASHRAE model, similar results can be found as indicated in the previous paragraph, which makes it clear that natural ventilation strategies based on the adaptive approach do not benefit the entire federal entity in the same way. In the case of the ASHRAE model, its effectiveness remains in doubt, specifically in the case of CDH, considering that it may be overestimating the population's tolerance to the region's extreme heat conditions. On the other hand, the regional model showed that, although it can be adjusted to climate conditions, it also makes clear the need to develop local comfort models that take into account the regional subdivision of the country's entities to propose strategies considering the reality of the Mexican southeast.

The results can be used to make other analyses such as identifying the percentage and degree of impact on the population when implementing natural ventilation strategies using the adaptive approach (Figure 8). In the case of the ASHRAE model, it is appreciated that the impact range is between 50% and 60%. In this case, the data can be divided into four strata, where the case of 54-56% was omitted due to the lack of values. According to the population data of each municipality, 48% of the inhabitants of Campeche have the possibility of applying natural ventilation strategies, just under 52% of the year. These results coincide with the fact that the most densely populated area is the municipalities of Campeche and Seybaplaya. On the other hand, 43% of the population has the possibility

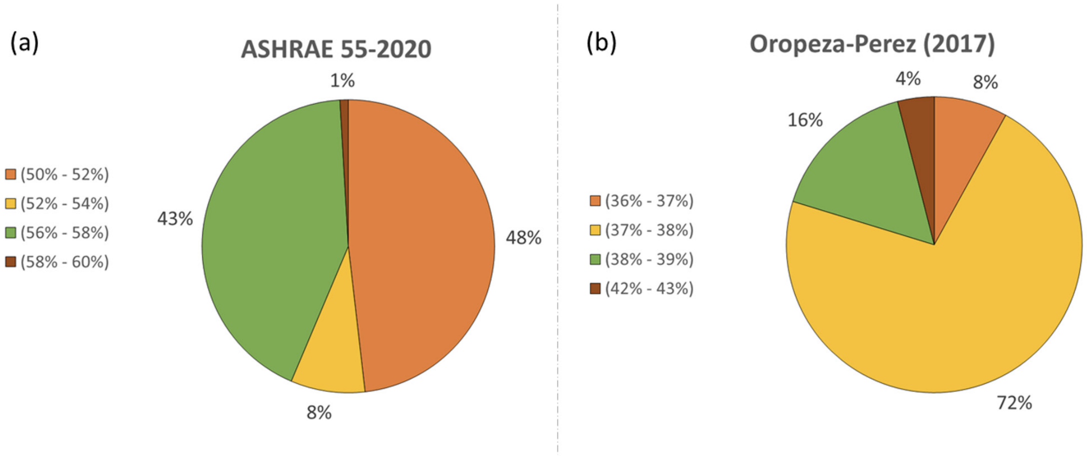

Figure 8. Population in the State of Campeche that the percentage of effective hours of ATC impacts (a) analysis based on ASHRAE 55-2020 model; (b) analysis based on regional model. Source: Preparation by the authors.

of implementing the adaptive approach to achieve thermal comfort levels between 56% and 58% per year. This is due to the greater demographic distribution in the southern municipalities where thermal stability is greater. In the case of the local model, the results are more concentrated. In this case, to provide a better appreciation, it was divided into four strata with 1% intervals. According to the results of this model, 88% of the population is in a range between 37 and 39% possibility of natural ventilation. This indicates that the model impacts a large percentage of the inhabitants. In addition, these values are above what can be achieved with the static approach. In this way, the regional model shows that, although to a lesser extent, the adaptive approach does favor the reduction of energy consumption for the State's inhabitants and questions the viability of implementing the conventional ASHRAE model in the region.

Finally, the adaptive approach has advantages both from the perspective of comfort and energy savings. In the case of Campeche, which is a young federal entity with a small and growing population, this type of approach offers the possibility of urban growth with better design and approach strategies. However, it is imperative to run more focused studies in the different municipalities to be able to make more specific estimates that fit the reality of the region.

CONCLUSION

This study focused on analyzing the implementation of the adaptive thermal comfort approach as a strategy to improve thermal sensation and energy savings in buildings in the state of Campeche. By reviewing the 13 climate files of each of the State's municipalities, the potential cooling and heating hours, and feasibility of the adaptive approach for the region were determined. For this purpose, the model of the ASHRAE 55-2020 regulation and a regional model developed for tropical climates in Mexico were analyzed. These models were compared with the conventional static thermal comfort approach to determine the advantages and differences between the two.

The results showed that both adaptive models can contribute to reducing the use of air conditioning equipment in the State's 13 municipalities. However, significant differences were found in the potential of both models, which were attributed to the fact that the model based on the ASHRAE 55-2020 standard, although widely used, may have biases as it is not designed with variables typical of a tropical climate. According to the results, the regional model averaged an 11.2% reduction in annual air conditioning hours while the regulatory-based approach obtained 15.4% and 16.0% respectively.

Regarding the feasibility of implementation, the regional adaptive approach demonstrated the ability to improve thermal comfort inside buildings by 2.6% to 11.6%, while the ASHRAE approach indicated improvements between 16% and 32%. On the other hand, the results of the regional model show that, although to a lesser extent, the adaptive approach does favor the reduction of energy consumption among the State's inhabitants, and opens the question about the feasibility of implementing the conventional ASHRAE model in the region.

Finally, the work gives rise to developing further studies focused on: (i) generating specific models for the different municipalities or subregions of the state to make estimates that fit the context of the country's southeast, (ii) studying adaptive behavior in the different building types n the region.

ACKNOWLEDGEMENTS

This work is part of the 014/UAC/2023 project and was carried out with the support of the Thematic Network 722RT0135 "Ibero-American Network of Energy Poverty and Environmental Welfare (RIPEBA), financed by the Call for Thematic Networks of the CYTED Program"

BIBLIOGRAPHIC REFERENCES

ANSI/ASHRAE. (2021). ANSI/ASHRAE Standard 169-2020 - *Climatic Design Building Standards*. Recuperado de: https://www.ashrae.org/file%20library/technical%20resources/standards%20and%20guidelines/standards%20addenda/169_2020_a_20211029.pdf

ASHRAE. (2020). *ASHRAE Standard 55-2020* - Thermal Environmental Conditions for Human Occupancy. Recuperado de: https://www.ashrae.org/file%20library/technical%20resources/standards%20and%20guidelines/standards%20addenda/55_2020_a_20210430.pdf

Bienvenido-Huertas, D., Pulido-Arcas, J. A., Rubio-Bellido, C. & Pérez-Fargallo, A. (2021). Feasibility of adaptive thermal comfort for energy savings in cooling and heating: A study on Europe and the Mediterranean basin. *Urban Climate*, *36*, 100807. DOI: https://doi.org/10.1016/j.uclim.2021.100807

Carlucci, S., Bai, L., De Dear, R. & Yang, L. (2018). Review of adaptive thermal comfort models in built environmental regulatory documents. *Building and Environment*, *137*, 73-89. DOI: https://doi.org/10.1016/j.buildenv.2018.03.053

Hoyt, T., Arens, E. & Zhang, H. (2015). Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. *Building and Environment*, *88*, 89-96. DOI: https://doi.org/10.1016/j.buildenv.2014.09.010

Humphreys, M. S., Nicol, J. M. & Raja, I. A. (2007). Field Studies of Indoor Thermal Comfort and the Progress of the Adaptive Approach. *Advances in Building Energy Research*, *1*(1), 55-88. DOI: https://doi.org/10.1080/17512549.2007.9687269

INEGI. 2022. *Aspectos Geográficos: Campeche 2021*. Aguascalientes.

Jimenez-Torres, M., Bienvenido-Huertas, D., May Tzuc, O., Bassam, A., Ricalde Castellanos, L. J. & Flota-Bañuelos, M. (2023). Assessment of climate change's impact on energy demand in Mexican buildings: Projection in single-family houses based on Representative Concentration Pathways. *Energy for Sustainable Development*, *72*, 185-201. DOI: https://doi.org/10.1016/j.esd.2022.12.012

Oropeza-Perez, I., Petzold-Rodriguez, A. H. & Bonilla-Lopez, C. (2017). Adaptive thermal comfort in the main Mexican climate conditions with and without passive cooling. *Energy and Buildings*, *145*, 251-258. DOI: https://doi.org/10.1016/j.enbuild.2017.04.031

Pérez-Fargallo, A., Bienvenido-Huertas, D., Rubio-Bellido, C. & Trebilcock, M. (2020). Energy poverty risk mapping methodology considering the user's thermal adaptability: The case of Chile. *Energy for Sustainable Development*, *58*, 63-77. DOI: https://doi.org/10.1016/j.esd.2020.07.009

Rodríguez, C. M. & D'Alessandro, M. (2019). Indoor thermal comfort review: The tropics as the next frontier. *Urban Climate*, *29*, 100488. DOI: https://doi.org/10.1016/j.uclim.2019.100488

Sala, M., Gallo, C. & Sayigh, A. A. M. (1999). *Architecture - Comfort and Energy*. Elsevier.

Salcido, J. C., Raheem, A. A. & Issa, R. R. A. (2016). From simulation to monitoring: Evaluating the potential of mixed-mode ventilation (MMV) systems for integrating natural ventilation in office buildings through a comprehensive literature review. *Energy and Buildings*, *127*, 1008-1018. DOI: https://doi.org/10.1016/j.enbuild.2016.06.054

Sánchez-García, D., Bienvenido-Huertas, D., Pulido-Arcas, J. A. & Rubio-Bellido, C. (2023). Extending the use of adaptive thermal comfort to air-conditioning: The case study of a local Japanese comfort model in present and future scenarios. *Energy and Buildings*, *285*, 112901. DOI: https://doi.org/10.1016/j.enbuild.2023.112901

Sánchez-García, D., Rubio-Bellido, C., Martín del Río, J. J. & Pérez-Fargallo, A. (2019). Towards the Quantification of Energy Demand and Consumption through the Adaptive Comfort Approach in Mixed Mode Office Buildings Considering Climate Change. *Energy and Buildings 187*, 173-85. DOI: https://doi.org/10.1016/j.enbuild.2019.02.002

SENER, Secretaria Nacional de Energía. (2021). Comisión Nacional Para el uso Eficiente de la Energía. *Infografía Confort Térmico*. Recuperado de: https://www.gob.mx/conuee/acciones-y-programas/estadisticas-energeticas-en-las-viviendas-mexicanas

Tsolkas, C., Spiliotis, E., Sarmas, E., Marinakis, V. & Doukas, H. (2023). Dynamic energy management with thermal comfort forecasting. *Building and Environment*, *237*, 110341. DOI: https://doi.org/10.1016/j.buildenv.2023.110341

Yau, Y. H. & Chew, B. P. (2012). A review on predicted mean vote and adaptive thermal comfort models. *Building Services Engineering Research and Technology*, *35*(1), 23-35. DOI: https://doi.org/10.1177/0143624412465200