Indoor thermal comfort in the tropics

By Carolina M. Rodriguez[1] and Marta D'Alessandro[2]

[1] **Architecture Programme, Universidad Piloto de Colombia, Bogotá, Colombia** (carolina-rodriguez1@unipiloto.edu.co)

[2] **Architecture, Built Environment and Construction Engineering Department (ABC), Polytechnic University of Milan, Italy**

Context

The current demographic growth indicates that by 2050, nearly 50% of the world's population will reside in the tropics, which hosts some of the most populated and hottest regions on earth (Edelman et al. 2014). As a consequence, the global demand for air conditioning (AC) multiplies every year, particularly in middle-income and low-income countries with warm climates (JRAIA 2017). This leads to increases in energy consumption, carbon emissions and environmental damage (Yang et al. 2014), with the aggravation that many of these regions are located in territories of high vulnerability to climate change. These conditions make the tropics a strategic frontier to investigate indoor thermal comfort (ITC), energy use and sustainable development. However, research on these fields in tropical countries is very limited compared to the rest of the world. Various academic articles have highlighted this issue, but no previous literature review has comprehensively studied it before. The review article summarised here (Rodriguez and D'Alessandro 2019) uses critical comparison and cross-analysis of data from various sources. These include 54 general reviews on thermal comfort, 61 field studies from ASHRAE databases, 75 selected documents on thermal comfort in the tropics, as well as records from 111 tropical countries, 33 mega and large cities and 43 fast-growing cities. The findings from this work reveal significant boundaries of research in terms of volume, origin, impact, focus and content. It also underlines research gaps for further development.

Methodology

The review was carried out through the analysis of six different samples during two stages: a broad review and a focused review (Figure 1). The first stage compiled evidence from multiple review papers on ITC (sample 1) and available information on the ASHRAE RP-884 database and the ASHRAE Global Thermal Comfort Database II (sample 2). The second stage (samples 3-6) concentrated on collecting and studying selected information on ITC in the tropics and related general data.

A multiple-reviewers' system was set in place to collect and evaluate the information, which was mostly limited to peer-review documents in scientific journals, databases from recognised organisations and established standards. The tools used for the bibliometric search were Scopus, Web of Science, Engineering Village and Google Scholar. Mendeley reference manager was the chosen tool for classifying and coding documents, and Excel pivot tables were used for statistical analysis.

ITC research trends and gaps

General bibliometric searches evidenced that the study of thermal comfort has received significant academic attention, especially since the beginning of this century. However, ITC research in the tropics is still minimal for 84% of countries, 39% of mega and large cities (MLC) and 95% of fastest-growing cities (FGC). Most of the academic data focus on very few countries, such as Singapore, Malaysia, India and Brazil. Tropical Africa was identified as the region with less ITC research overall, closely followed by tropical America and the Caribbean.

As the equatorial zone gets most of the sun exposure, it is often assumed as being hot and humid, when in fact it hosts vast environmental and climatic diversity. According to the data studied for the review, by 2030 most population in the tropics will likely live in climates categorised as Aw followed by BSh, Am, and Cwb, in the Köppen-Geiger Climate Classification System. However, the climates that have been studied the most are Cwa and Af. Aw has been relatively investigated, but little research was found for other

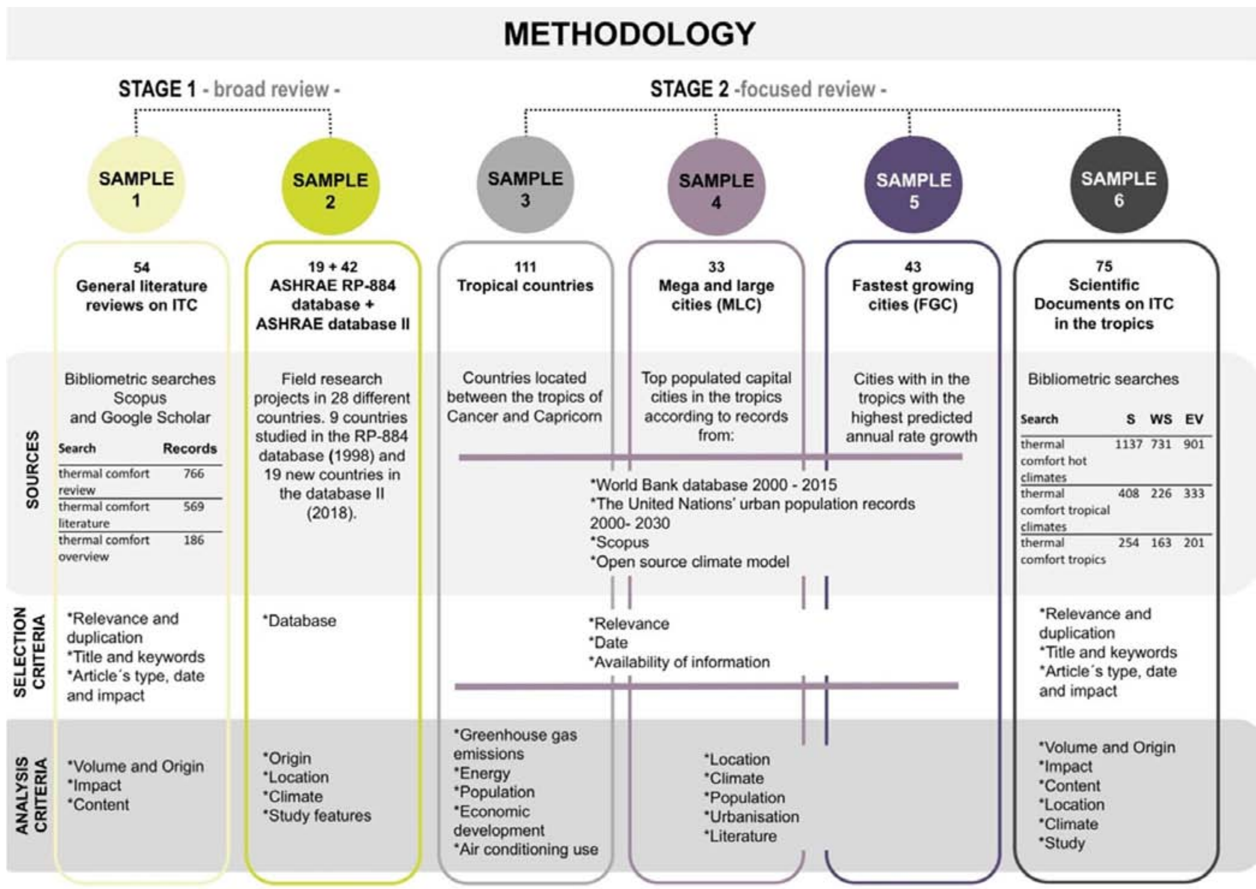

Figure 1. Methodology map.

climates in the B and C categories (Figure 2). During the review, marked climatic and geographical differences between areas classified within the same Köppen-Geiger category were noticed. For example, there was some variance between average temperatures, more dispersion between rainfall data and a very wide spread between altitude values. This generates uncertainties regarding the suitability of this classification for the study of thermal comfort.

Established thermal comfort standards such as the ASHRAE Standard 55, the ISO 7730 or the CSN EN 15251 are the most commonly used worldwide, despite being explicitly developed for northern latitudes in the United States and Europe (Olesen, 2004). These standards include two main models for assessing thermal comfort in buildings: the static model developed by Fanger (1970) and the adaptive model generated from a collection of studies (de Dear et al., 1997). The former focuses on the assessment of set physiological variables related to the heat exchange between humans and the environment; while the latter includes other dynamic variables related to human behaviour and outdoor climate. As both models were initially promoted by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), it is claimed that their content and wording may suggest the superiority of mechanical conditioning over other alternatives.

Some authors argued that the static model has often overestimated the thermal sensation of occupants, especially in naturally ventilated (NV) buildings (Humphreys and Hancock, 2007). Therefore, the adaptive model is deemed to be more suitable for these cases. The adaptive model was developed and updated using information from two databases: the ASHRAE RP-884 database published in 1998 comprising 23 field research projects (de Dear et al., 1997) and the ASHRAE Global Thermal Comfort Database II released in 2018 including 42 field research projects (Földváry Ličina et al., 2018). A closer look at these databases evidences their limited amount of information from tropical regions and climates of Africa, South America, Central America, and the Caribbean. Only 23% of the studies considered climates in tropical areas. Most of them were office buildings, and a relatively small percentage were NV buildings, particularly in the first database (Figure 3).

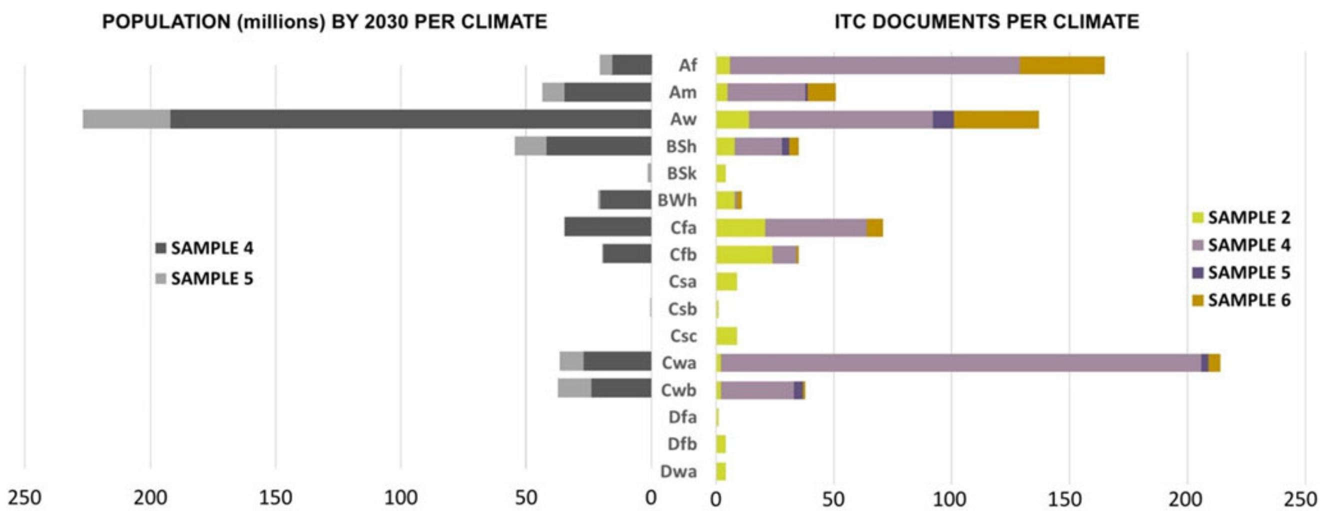

Figure 2. Population (million people) per climate in samples 4 and 5 compared to ITC documents per climate in samples 2,4,5 and 6.

Even when there is still no academic consensus on the applicability of any of these models within the tropics, many countries have directly implemented them without any adaptation to local economic, political, cultural or geographic conditions. However, there is now compelling evidence that these standards are not the most appropriate for buildings in tropical regions (Kwong et al., 2014). This is mainly because the perception of neutrality and comfort is subjective and can vary significantly between different climates and seasons (Zain et al., 2007) and amongst occupants according to age, (Zomorodian et al., 2016) gender (Karjalainen 2012) and cultural background (Karyono 1996). Consequently, alternative models to assess thermal comfort in buildings with natural ventilation or mixed ventilation have emerged in various regions, many of which are inspired by the adaptive model. For example, a model for hot and humid climates in general (Toe and Kubota, 2013); models for particular regions in Southeast Asia (Mishra and Ramgopal, 2015), México (Oropeza-Perez et al., 2017) and Brazil (Cândido et al., 2011); or specific models for residential buildings in different climatic zones of eastern China (Yan et al., 2017) and office buildings in hot and humid climates of India (Indraganti et al., 2014).

Results regarding comfort temperatures

Most of the studied data confirmed that people in tropical hot and humid regions are generally quite tolerant to high indoor temperatures, heat stress (Lu et al., 2018) and humid environments (Zhang et al., 2010), while they have a lower tolerance to cold conditions than predicted (Lu et al., 2018). Temperature comfort ranges can vary from 22 to 27°C in Brazil (Caetano et al., 2017), 24.6 to 28.4°C in Madagascar (Nematchoua et al., 2018), 19.6 to 28.5°C in India (Manu et al., 2016) and 27.1 to 29.3ºC in Singapore (Wong and Khoo 2003). In Mexico, research suggested that people are capable of standing temperatures over 30°C, as long as they have control over avenues of adaptation (Oropeza-Perez et al., 2017).

Literature from tropical regions in China suggests that the ability to adapt is effective in the range of 10 to 35°C outdoor temperature, but it is limited beyond this range (Yan, et al. 2017). In this study, occupants' thermal sensation and acceptance were perceived differently according to the ventilation mode. Higher acceptable temperatures were found in NV buildings, while overcooling appeared to be a common phenomenon in office spaces, being the leading cause of thermal discomfort and energy waste (Chen and Chang, 2012). Furthermore, research in Thailand (Srisuwan and Shoichi, 2017) suggested 28°C as the neutral temperature for NV spaces and 25°C for AC spaces. On the contrary, comfort ranges varied from 25.4 to 26.5°C in Ghana (Koranteng and Mahdavi, 2011) and from 19.7 to 24.7°C in Zambia (Sharples and Malama, 1997) under NV mode, while the temperature range was wider (between 25.4 and 30.5°C) for MV spaces (Koranteng and Mahdavi, 2011). A study in Nigeria (Efeoma and Uduku, 2014) showed that when combining NV and MV systems, acceptable comfort temperature could reach up to 32.9°C.

Results regarding relative humidity

Conflicting views were found on the impacts of relative humidity (RH) on thermal comfort. Some studies indicated that high levels of humidity could cause

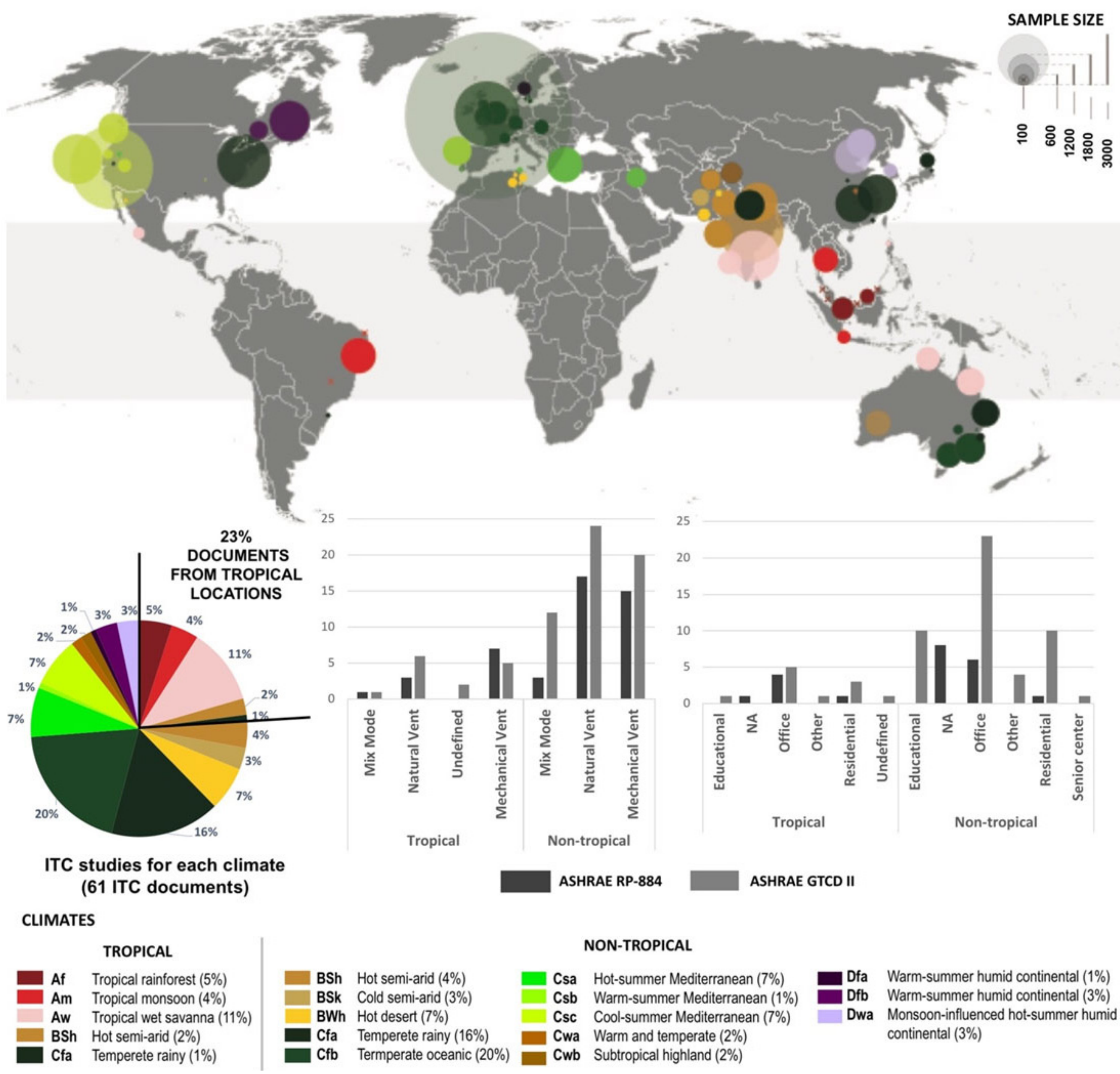

Figure 3. Sample 2, type of climate and location of the samples included in the ASHRAE RP-884 database and the ASHRAE Global Thermal Comfort Database II.

an adverse effect (Jing et al., 2013; Zhang et al., 2017). Therefore, it was suggested that optimal ranges could lie between 50 and 60% RH (Yau et al., 2011). Other studies argued that high relative humidity affects the thermal sensation of the occupants only when the indoor temperature is relatively high (26–27°C) (Yamtraipat et al., 2005). It was also found that the effect of RH on the thermal sensations could be typically minimal to negligible (Lu et al., 2018; Givoni et al., 2006). Therefore, indoor high relative humidity might be acceptable in the humid tropics, with optimum comfort close to 73% (Djamila et al., 2014). Literature from Thailand recommended a comfort zone with temperatures ranging from 25.6 to 31.5°C and RH between 62.2 and 90.0%. Further research based on the ASHRAE RP-884 database proposed an alternative RH-inclusive adaptive model that significantly extended the range of acceptable indoor conditions regarding humidity (Vellei et al., 2017).

Results regarding common adaptive practices

The most common adaptive practices found to improve comfort in hot and humid climates were: increasing the indoor air velocity, reducing clothing insulation and changing activity (Djamila et al., 2013; Mishra and Ramgopal, 2014; Gou et al., 2018). For example, a study from Brazil established different acceptable ranges, from 24 to 27°C with less than 0.4 m/s; from 27 to 29°C with 0.41 to 0.8 m/s, and 29 to 31°C with more than 0.81 m/s (Cândido et al., 2011). Regarding clothing insulation, a study in Cameroon (Nematchoua et al., 2014) identified that ranges could vary from 0.36 to 1.45 clo according to the season (wet or dry). These results were confirmed by different Chinese studies (Luo et al., 2015; Zhang et al., 2018) that indicated a 0.3 clo for the summer season and a range between 0.27 and 1.2 clo for the no-summer season in the city of Guangzhou. Clothing resistance of 0.78 clo on average was found within wet tropical climates (Am type) for 22.4–26.7°C comfort temperatures; while in tropical hot, humid climates (Aw type) it was 0.67 clo on average for 24.3–27.8°C comfort temperatures. No similar study was found in the sample regarding the specific impact of metabolic rates (met) on temperature acceptability. It was noticed that most comfort evaluations in NV environments adopted the range of 1.0–1.3 met, recommended by the adaptive model. Although, a study highlighted that met could noticeably change according to seasonal variations, as a result of physical activities usually being more intense in the dry than in the rainy season (Nematchoua et al., 2014).

There was evidence in the sample that climate adaptation was directly related to particular economic and physiological factors. For example, in office buildings occupants are generally inclined to favour the use of AC systems, while in housing, the preference is to increase air velocity by opening the windows or using electrical fans (Hwang et al., 2009). Therefore, housing residents generally tolerate higher temperatures because they have more adaptive options available (e.g. opening windows, changing their clothes, drinking beverages or using fans) (Djamila et al., 2013; Zhang et al., 2018). Additionally, they are usually responsible for cooling costs. The degree of the agency had been frequently cited as a critical factor influencing psychological adaptation to the thermal environment (Zhang et al., 2017). Furthermore, a study in hot and humid areas of southern China (Zhang et al., 2018) suggested that neutral and acceptable temperatures were significantly different between rural occupants and urban occupants due to variances in the local culture, expectations and environmental cognition.

Studies indicated that occupants frequently exposed to AC environments tend to acclimatise and adapt relatively quickly to lower temperatures (Ismail and Barber, 2001), but develop less tolerance to extreme thermal conditions and show a desire for "thermal indulgence" (Indraganti, 2011). Additionally, abrupt thermal changes caused when moving out of AC spaces and into hot-humid climates, or vice versa could cause discomfort by producing up to 2°C variations in skin temperature (Dahlan and Gital, 2016).

Summary

It is argued in the feature review that improving research efforts on ITC is not only relevant for the particular regions where there is a shortage of studies, but also for humanity in general. As tropical countries rank amongst the most populated and climatically diverse in the world, how ITC is addressed now will have long-term global implications on sustainable development, energy use, climate change, CO_2 emissions, and related pollution. The review highlights different variables distinctive to tropical countries which cannot be addressed by applying standards designed for other regions. For example, relative humidity is not a primary variable for the adaptive model, but it is a defining feature in the tropics, being particularly high in wet tropical climates and extremely low in tropical desert regions. Another significant but overlooked variable is the altitude, which defines particular environments in mountain ranges located in the tropics, such as the Andes and the Ghats. Climatic conditions in cities located at high altitude vary significantly during the day due to changes in atmospheric pressure. Altitude also affects the oxygen concentration in the body and the function of the vascular system, resulting in alterations in metabolic rates (Wang et al., 2010; Bernardi, 2012). Furthermore, CO_2 levels are often overlooked as a core variable in thermal comfort. However, they can be found in relatively large concentrations within AC spaces and densely populated urban environments, both common scenarios in tropical regions. High levels of CO_2 have been associated with an over-stimulation of the respiratory system, resulting in increased metabolic rates and heat exchange with the environment, which suggests potential effects on thermal comfort. These and other social variables related to the perception of status, aspirations, and desires are also explored in the review. Additional tables and graphic material accompany the original article and are supplemented by raw and processed data.

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