Review of adaptive thermal comfort models in built environmental regulatory documents

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Abstract: In recent years, adaptive thermal comfort models have been integrated into several building design and operations regulatory documents. Although the theoretical background of the adaptive thermal comfort models is quite mature, still some ambiguities exist for their application. The objective of this study is to identify the main sources of uncertainty around application of adaptive models and to analyze quantitatively the difference between the adaptive comfort models proposed by the regulatory documents when applied across a spectrum of different climate zones. This paper analyzes the adaptive models in ASHRAE Standard 55, the European EN 15251 (and its revision prEN 16798), the Dutch ISSO 74 and the Chinese GB/T 50785. For each regulatory document, the major variations or sources of uncertainty are investigated: for ASHRAE 55, the length of the calculation period of the prevailing mean of outdoor temperature, and for EN 15251, prEN 16798, and GB/T 50785, the exponential decay weighting factors used in the calculation of the running mean outdoor temperature.

This study shows that, although these regulatory documents have promoted the uptake of adaptive comfort models by practitioners and designers, uncertainties surrounding their application obstruct full exploitation. In response, this paper offers a fine-tuning of some of the adaptive comfort models. However, the issue of adaptive models' applicability in hybrid ventilation or mixed-mode buildings is still to be resolved, as is a rational basis for identifying the operational mode of such buildings when the adaptive models can be applied, because of their intermittent compliance during transition seasons and also extreme weather events.

Keywords: Thermal comfort, Adaptive thermal comfort models, Built environmental regulatory documents, ANSI/ASHRAE 55, EN 15251, prEN 16798-1, ISSO 74, GB/T 50785.

1 Introduction

Thermal comfort is “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” [1], and the creation of a healthy and comfortable indoor thermal environment is the primary aim of architects and engineers. Thus, the issue of defining suitable indoor environmental conditions is the key to increase occupants’ satisfaction and productivity while promoting building energy conservation in regard to space heating, cooling, ventilation, humidification and dehumidification.

1.1 History of thermal comfort models and of their integration in regulatory documents

In order to assess the quality of thermal environment, in 1970 Fanger introduced a steady-state model or rational model of thermal comfort that predicts the average general thermal sensation and dissatisfaction of a large group of human occupants exposed to moderate thermal environments [2]. It computes two comfort indices: the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) [3]. This model was incorporated into the international standard ISO 7730 in 1984 [4], then subsequently in ANSI/ASHRAE Standard 55 in 1992 [5, 6], and more recently into the Chinese GB/T standard 18049 in 2000 [7]. Fanger’s thermal comfort model, simply referred as the PMV/PPD model, was built on experiments involving exposure of subjects to steady-state conditions in thermal chambers. Therefore, this method is intended for application to environments analogous to those of sealed air-conditioned buildings where the steady-state assumption about indoor environmental properties is appropriate and occupants have negligible adaptive opportunity. However, although PMV/PPD offers a rational approach to assess indoor thermal conditions, subsequent studies revealed that when applied in buildings without mechanical cooling systems, the model overestimated occupant discomfort in both cold and warm seasons [8]. Moreover, further research has pointed out that occupants have a positive attitude towards adapting to surrounding conditions through different approaches (i.e. behavioral adjustment, physiological adaptation and psychological expectations), which was not considered during the development of the PMV/PPD model that rather considers the occupants passive *receptors* detecting the surrounding environmental conditions [9-11].

In the 1970s, Nicol and Humphreys [12] hypothesized the existence of a feedback between the occupants’ thermal comfort perception and their behavior in buildings, which may explain why occupants adapt to a much larger range of temperatures in actual buildings than predicted by the PMV/PPD model. Humphreys [13] meta-analysis of published comfort research provided compelling evidence that occupants' thermal satisfaction to the thermal environment in actual buildings was achieved across a much wider band of indoor temperatures than expected on the basis of the deterministic PMV/PPD model. Since then, abundant field studies were conducted in different climate zones and they have consistently reinforced the enhanced thermal adaptability of occupants in naturally ventilated buildings compared to occupants of air-conditioned buildings [14-21]. Therefore, forcing indoor conditions to artificially meet neutrality (PMV = 0) appears a conservative assumption that commits to intense use of energy for space cooling and dehumidification, which may not return any appreciable improvement in occupants' thermal satisfaction. For example, in mechanically cooled buildings, indoor temperature set-points are typically calculated using the Fanger comfort model and relying on standard metabolic activity rates that were determined for an "average male," causing "[…] buildings to be intrinsically non-energy-efficient in providing comfort to females" [22]. The theory of adaptive thermal comfort represents a valuable alternative in an energy-constrained world by simultaneously increasing occupant satisfaction and reducing building energy intensity. A relaxation of indoor requirements towards adaptive comfort prescriptions can be readily implemented in most of the existing buildings, and its effectiveness can be monitored by directly gathering feedback through appropriate post-occupancy feedback surveys. The energy implications are substantial since the vast majority of national building stocks comprise energy-intensive buildings, most of which are equipped with mechanical cooling systems. Concomitant reductions in buildings sector greenhouse gas emissions can therefore play an important role in meeting the goals set by the Intergovernmental Panel on Climate Change (IPCC) and the Unite Nations Framework Conventions on Climate Change (UNFCCC).

Adaptive comfort theory considers that the optimal indoor operative temperature for occupants who can interact with the building and its devices relates primarily to the *outdoor* environmental conditions. This relationship is commonly expressed by a linear equation $T_c = a \cdot T_0 + b$, where T_c is the expected indoor comfort operative temperature (the dependent variable), T_0 is the outdoor reference temperature (independent variable), a is the slope of the function, proportional to the degree of adaption to the regional climatic conditions [23], and b is the y-intercept. Both the values of a and b are statistically fitted to data collected from field studies. The values of a and b are different for each adaptive thermal comfort model and this may be due to the difference in cultural backgrounds, climatic conditions and other contextual factors.

Earlier adaptive models such as Humphreys [21] suggested that the value of T_0 calculated by monthly mean outdoor air (dry-bulb) temperature. In subsequent versions, de Dear, Brager [24] substituted the new effective temperature (ET*) as the outdoor reference temperature in the final report of the ASHRAE RP-884 program, but, in 1998, the ASHRAE committee SSPC 55, striving to balance “scientific evidence with expert judgment, practical experience, [and] pragmatism” [25] re-calculated the ASHRAE adaptive model again using monthly mean of the outdoor air temperature (dry bulb) for the month in question. Subsequently, Nicol and Humphreys [26] used an exponentially-weighted running mean outdoor air temperature as T_o in order to more realistically reflect changing meteorological conditions and their impact on indoor comfort requirements [27, 28]. The running mean reference temperature was first used in EN 15251 [29], then prEN 16798-1 [30], ISSO 74 and GB/T 50785 [7]. Moreover, the 2013 revision of ANSI/ASHRAE 55 followed suit by introducing the so-called “*prevailing mean outdoor air temperature*” as the function for T_o [31].

ANSI/ASHRAE 55:2004 was the first comfort standard that included an adaptive model. The model was developed de Dear and Brager [8] from the database built by the ASHRAE RP-884 project that collected the field data from various climate zones [32]. In the same year, van der Linden, Boerstra [33] introduced a new regulatory document in the Netherlands, the ISSO 74, which also included an adaptive comfort model also developed from the database of the ASHRAE RP-884 project. Next in the history of adaptive regulatory documents, the three-year SCATs project was performed in Europe with the aims of reducing energy consumption in Europe’s air-conditioned buildings and encouraging the use of natural ventilation in buildings by implementing the adaptive approach. Within this project, a new database of field studies carried out in 26 European offices was built and a new adaptive comfort model was proposed and, later, integrated in the new European standard EN 15251 in 2007 [34]. Most recently China has also developed a new standard that integrates an adaptive comfort model to assess indoor thermal environments in unconditioned buildings in 2012 [7]. At present, adaptive comfort theory has been integrated into several regulatory documents, some of which have undergone periodic revisions. Figure 1 presents a graphical timeline of the integration and refinement of thermal comfort models in regulatory documents, and more interpretation of them will be given in the following sections.

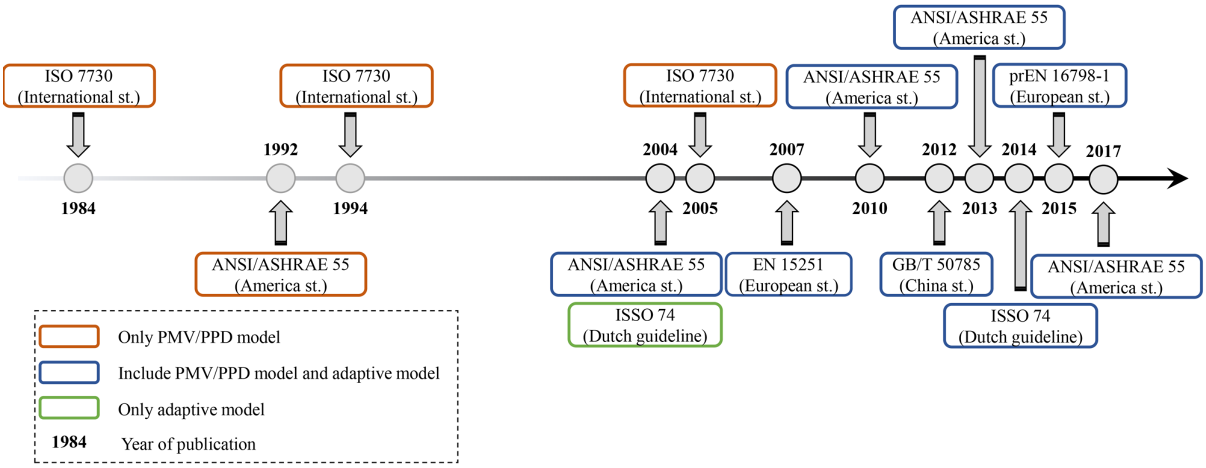


Figure 1: Chronology of the integration and refinement of thermal comfort models in regulatory documents.

1.2 Purpose and organization of the paper

Adaptive comfort theory has undergone a long development process and has gradually improved. For different circumstances, some of these adaptive comfort models were integrated in thermal comfort regulatory documents that have been recast and updated. However, several aspects of these regulatory documents are still ambiguous and there is inconsistency between the norms, for example the application conditions differ for building types and outdoor temperature ranges, and some definitions and related specifications are vague. The purpose of this study is to quantitatively analyze the difference among these adaptive comfort models in the regulatory documents listed above, and to discuss the impact of uncertainty in definitions and calculation methodologies on the indoor environmental conditions of buildings.

This paper is organized into six sections, with research objective and problem statement being specified in first section. The second section offers a review of the development of thermal comfort regulatory documents and the third section outlines the methodology adopted in this study. The fourth section introduces the selection of geographic scope for the application of these regulatory documents. The fifth section reports the main results of the comparative and quantitative analysis and discusses the effects of those definitional and procedural uncertainties on application. The last section draws some summative comments and primary conclusions.

2 Review of the thermal comfort standards

2.1 International ISO 7730 thermal comfort standard

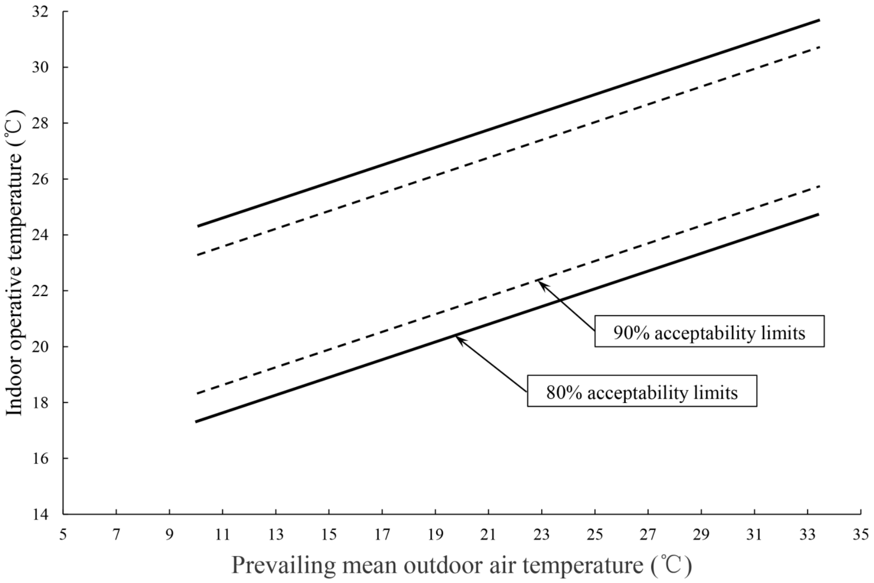
The ISO 7730 [35] was first published in 1984 and introduced the Fanger comfort model in standardization. This standard presents the equations to compute the Fanger thermal comfort indices PMV and PPD. ISO 7730 also offers methods for assessing local thermal discomfort caused by asymmetric radiation, draughts, and vertical air temperature difference. The standard was revised in 1994 and again in 2005 [4]. In the latest version, it introduces three different comfort categories defined for three levels of PPD (A : PPD $< 6\%$ and $-0.2 < PMV < 0.2$; B : PPD $< 10\%$ and $-0.5 < PMV < 0.5$; C : PPD $< 15\%$ and $-0.7 < PMV < 0.7$). Furthermore, it offers a diagram to estimate the air speed required to offset the thermal comfort range to compensate an increase in operative temperature. However, the theory of adaptive comfort is still absent in this latest revision.

2.2 ANSI/ASHRAE 55 adaptive thermal comfort standard

ANSI/ASHRAE Standard 55 provides minimum requirements for acceptable indoor thermal environments and assists engineers to assess the general thermal comfort conditions in a building. It was first published in 1966, and subsequently revised in 1974, 1981, 1992, 2004, 2010, 2013, and most recently in 2017.

There are three significant changes about thermal comfort in the different versions. The first change is the inclusion of the thermal comfort zone determined through the PMV/PPD method in the version of 1992. Before this, the acceptable range of thermal conditions for occupants was defined by a simpler graphic comfort zone [6]. The second change occurred in the version of 2004, which added the adaptive comfort model [8, 25] with the *monthly mean outdoor temperature* as the outdoor reference temperature [36]. The last change occurred in the version of 2013, in which the outdoor reference temperature of the adaptive equation was calculated by the *prevailing mean outdoor temperature* “based on no fewer than seven and no more than 30 sequential days prior to the day in question” [31]. Figure 2 depicts the adaptive comfort ranges of the 2017 versions of the ANSI/ASHRAE 55 [1].

ANSI/ASHRAE 55 is strictly speaking a standard of the American National Standards Institute, and therefore not an international standard. However the adaptive comfort model embedded within ANSI/ASHRAE 55 is deliberately global in scope because the field study research data underpinning it were sourced from 160 different buildings located in dozens of countries spread across four different continents. Therefore this adaptive model is regarded as a global implementation of the adaptive comfort concept.



ANSI/ASHRAE 55:2017

Figure 2: Adaptive comfort models represented in ANSI/ASHRAE 55:2017.

In the ANSI/ASHRAE 55:2017, the acceptable operative temperature ranges are classified into two categories: namely 80% and 90% acceptability. This standard does not specifically mention the type of buildings where the adaptive comfort model can be applied, but it states that the adaptive comfort model may only be applied to occupant-controlled naturally conditioned spaces, where (i) no mechanical cooling system is installed (regardless of its operational status), (ii) no heating system is in operation, (iii) occupants' metabolic rates range between 1.0 met and 1.3 met, (iv) the occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions with a clothing resistance that ranges, at least, between 0.5 clo and 1.0 clo, and (v) the prevailing mean outdoor temperature falls between 10 ºC and 33.5 ºC. If the prevailing mean outdoor temperature is outside this range, mechanical cooling or heating systems have to be installed and operated according to the set-point conditions calculated with the Fanger comfort model.

$$ANSI/ASHRAE\ 55: \begin{cases} \text{Upper 80\% acceptability limit (°C)} = 0.31f(T_{\text{out}}) + 21.3 & (10\text{°C} \le f(T_{\text{out}}) \le 33.5\text{°C}) \\ \text{Upper 90\% acceptability limit (°C)} = 0.31f(T_{\text{out}}) + 20.3 & (10\text{°C} \le f(T_{\text{out}}) \le 33.5\text{°C}) \\ \text{Optimal comfort temperature (°C)} = 0.31f(T_{\text{out}}) + 17.8 & \\ \text{Lower 90\% acceptability limit (°C)} = 0.31f(T_{\text{out}}) + 15.3 & (10\text{°C} \le f(T_{\text{out}}) \le 33.5\text{°C}) \\ \text{Lower 80\% acceptability limit (°C)} = 0.31f(T_{\text{out}}) + 14.3 & (10\text{°C} \le f(T_{\text{out}}) \le 33.5\text{°C}) \end{cases} \tag{1}$$

where $f(T_{\text{out}})$ is the prevailing mean outdoor air temperature ($\overline{t_{pma(out)}}$) in ANSI/ASHRAE 55 of 2013 and 2017, and the mean monthly outdoor air temperature in ANSI/ASHRAE 55 of 2004 and 2010.

The *prevailing mean outdoor air temperature* is defined as the arithmetic average of the mean daily outdoor temperatures calculated over some period of days that have to be "no fewer than seven and no more than 30 sequential days prior to the day in question" [1]. The *mean monthly outdoor air temperature* is defined as "the arithmetic average of the mean daily minimum and mean daily maximum outdoor air temperatures for the month in question" [36]. Besides the arithmetic average of the mean daily outdoor temperatures, ANSI/ASHRAE 55 of 2013 and 2017 also permit a running mean of external temperature when the adaptive comfort model is used. In addition, they permit a weighted, running mean providing the weighting curve decreases towards more distant days. Therefore, the function of $\overline{t_{pma(out)}}$ can be written as follows:

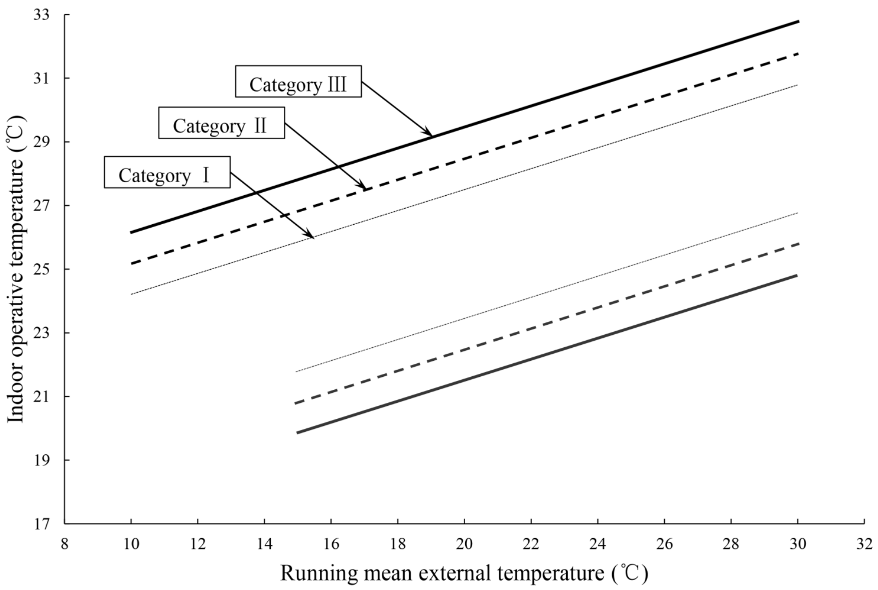
$$\overline{t_{pma(out)}} = (1-\alpha)\cdot\left[t_{e(d-1)} + \alpha\cdot t_{e(d-2)} + \alpha^2\cdot t_{e(d-3)} + \alpha^4\cdot t_{e(d-4)} + \cdots\right] \quad (2)$$

where α is a constant ranging between 0 and 1, and $t_{e(d-1)}$ is the daily mean external air temperature for a time *d* of a series of equal intervals (day).

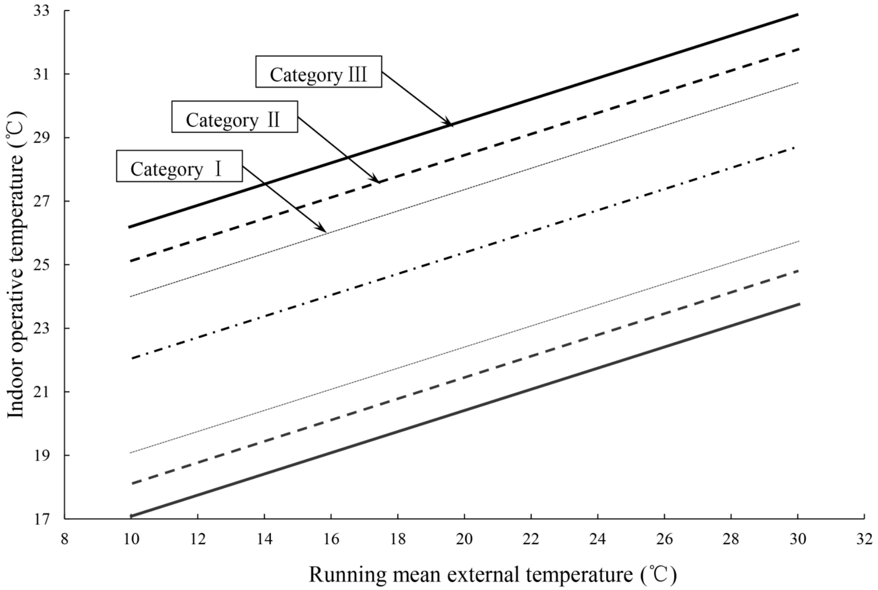
In the last two versions, ANSI/ASHRAE 55 suggests an α-value of 0.9 for those climates where the day-to-day temperature variation is relative minor, such as humid tropics, and a lower α-value of 0.6 for the mid-latitude climates where the day-to-day temperatures variation is more pronounced.

2.3 European EN 15251 and prEN 16798-1 comfort standards

The European standard EN 15251 was firstly published in 2007 [34] and included both the PMV/PPD model and the adaptive comfort method [26, 37, 38] developed from the European SCATs project [39]. A draft revision of EN 15251 came out in 2015 and was renamed with the code prEN 16798-1 [30]. In prEN 16798-1, two changes have been made in the adaptive comfort model. The first regards the lower limit of optimal operative temperature that is 1 ºC lower than the previous version. The second is the available range of outdoor running mean temperature corresponding with lower limit of thermal comfort zone extended from 15 to 30 ºC to 10 to 30 ºC. If the outdoor running mean temperature is outside this range, mechanical cooling or heating systems have to be installed and operated according to the set-point conditions calculated with the Fanger comfort model. The change between the version of 2007 and the draft version of 2015 can be seen in Figure 3.



a) EN 15251



b) prEN 16798-1

Figure 3: Comparison of the difference of comfort models in EN 15251 and prEN 16798-1.

In prEN16798-1, like in EN 15251, there are three comfort categories, and the adaptive comfort model is mainly applied to office buildings, “and other buildings of similar type” that are residential buildings and “conference rooms, auditorium, cafeteria, restaurants, class rooms” [30], not equipped with mechanical cooling systems where occupants engaging in near sedentary physical activities could freely adapt their clothing with the indoor/outdoor thermal conditions. Mechanical ventilation with unconditioned air is allowed, but operable windows must be the primary means of regulating thermal conditions.

$$\text{EN15251}: \begin{cases} \text{Upper limit of Category III (°C)} = 0.33\, f(T_{\text{out}}) + 18.8 + 4 & (10\text{°C} \le f(T_{\text{out}}) \le 30\text{°C}) \\ \text{Upper limit of Category II (°C)} = 0.33\, f(T_{\text{out}}) + 18.8 + 3 & (10\text{°C} \le f(T_{\text{out}}) \le 30\text{°C}) \\ \text{Upper limit of Category I (°C)} = 0.33\, f(T_{\text{out}}) + 18.8 + 2 & (10\text{°C} \le f(T_{\text{out}}) \le 30\text{°C}) \\ \text{Optimal comfort temperature (°C)} = 0.33\, f(T_{\text{out}}) + 18.8 & \\ \text{Lower limit of Category I (°C)} = 0.33\, f(T_{\text{out}}) + 18.8 - 2 & (15\text{°C} \le f(T_{\text{out}}) \le 30\text{°C}) \\ \text{Lower limit of Category II (°C)} = 0.33\, f(T_{\text{out}}) + 18.8 - 3 & (15\text{°C} \le f(T_{\text{out}}) \le 30\text{°C}) \\ \text{Lower limit of Category III (°C)} = 0.33\, f(T_{\text{out}}) + 18.8 - 4 & (15\text{°C} \le f(T_{\text{out}}) \le 30\text{°C}) \end{cases} \tag{3}$$

$$\text{prEN16798} - 1: \begin{cases} \text{Upper limit of Category III (°C)} = 0.33\, f(T_{\text{out}}) + 18.8 + 4 & (10\text{°C} \le f(T_{\text{out}}) \le 30\text{°C}) \\ \text{Upper limit of Category II (°C)} = 0.33\, f(T_{\text{out}}) + 18.8 + 3 & (10\text{°C} \le f(T_{\text{out}}) \le 30\text{°C}) \\ \text{Upper limit of Category I (°C)} = 0.33\, f(T_{\text{out}}) + 18.8 + 2 & (10\text{°C} \le f(T_{\text{out}}) \le 30\text{°C}) \\ \text{Optimal comfort temperature (°C)} = 0.33\, f(T_{\text{out}}) + 18.8 & \\ \text{Lower limit of Category I (°C)} = 0.33\, f(T_{\text{out}}) + 18.8 - 3 & (10\text{°C} \le f(T_{\text{out}}) \le 30\text{°C}) \\ \text{Lower limit of Category II (°C)} = 0.33\, f(T_{\text{out}}) + 18.8 - 4 & (10\text{°C} \le f(T_{\text{out}}) \le 30\text{°C}) \\ \text{Lower limit of Category III (°C)} = 0.33\, f(T_{\text{out}}) + 18.8 - 5 & (10\text{°C} \le f(T_{\text{out}}) \le 30\text{°C}) \end{cases} \tag{4}$$

where $f(T_{\text{out}})$ is the running mean external temperature (θ_{rm}), and this method can be expressed by the following formulation in EN 15251, prEN 16798-1 and ISSO 74:2014.

$$\theta_{\text{rm(ed)}} = (1-\alpha) \cdot [\theta_{\text{ed}-1} + \alpha \cdot \theta_{\text{ed}-2} + \alpha^2 \cdot \theta_{\text{ed}-3} + \alpha^3 \cdot \theta_{\text{ed}-4} + \cdots] \tag{5}$$

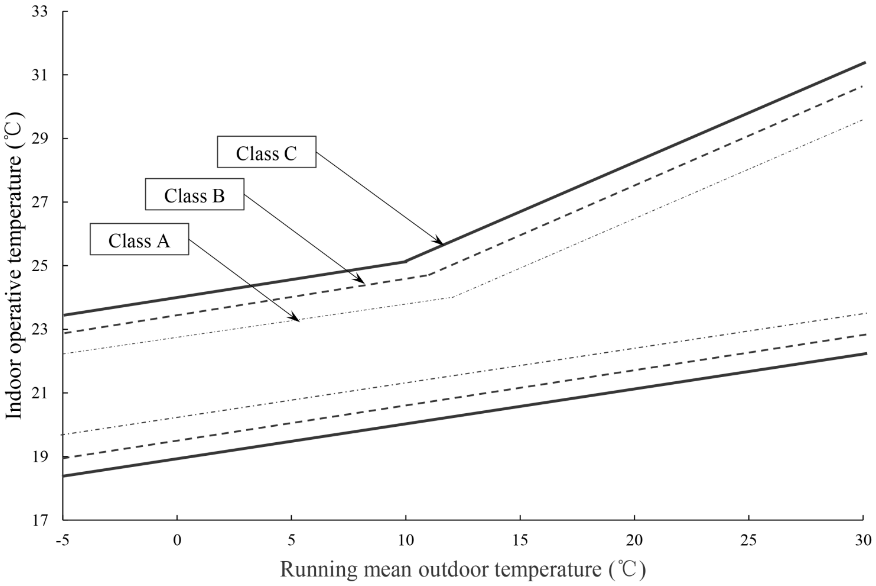
where α is a constant between 0 and 1, recommended 0.8; θ_{ed-n} is daily mean outdoor air temperature for *n*-days prior the day in question. Meanwhile, an approximate equation is provided when the full records of daily running mean external temperature are not available.

$$\theta_{\text{rm(ed)}} = (\theta_{\text{ed}-1} + 0.8 \cdot \theta_{\text{ed}-2} + 0.6 \cdot \theta_{\text{ed}-3} + 0.5 \cdot \theta_{\text{ed}-4} + 0.4 \cdot \theta_{\text{ed}-5} + 0.3 \cdot \theta_{\text{ed}-6} + 0.2 \cdot \theta_{\text{ed}-7})/3.8 \tag{6}$$

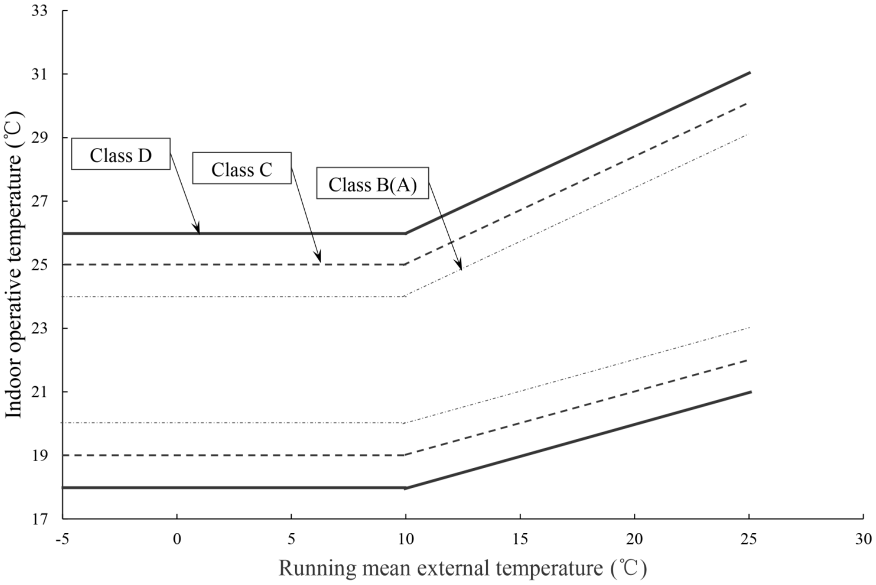
2.4 Netherlands ISSO 74 thermal comfort regulatory document

The adaptive thermal comfort theory was the basis for the Dutch regulatory document ISSO 74. It can be applied for both unconditioned and conditioned spaces. The term *alpha space* refers to "free-running situations in summer with operable windows and a non-strict clothing policy for the occupants", while *beta spaces* are those "which primarily rely on centrally-controlled cooling in summer" in the ISSO 74 [40]. This regulatory document was first published in 2004 [33, 41] and subsequently revised in 2014 [40, 42]. The main differences between the two versions are fourfold: (a) the 2004 version addressed a building as a whole whereas the 2014 version looks at the spaces constituting the building; (b) the adaptive comfort equation in the new version was developed from SCATs European comfort field study database rather than from ASHRAE's RP-884 global field study database, causing the adaptive comfort equation to differ between versions of this regulatory document [40, 42]; (c) the temperature requirements were divided into four classes (i.e., A, B, C, and D) in the new version rather than three classes of the older one; (d) the calculation method of outdoor reference temperature was quite different, and outdoor reference temperature of the new version is defined as recommended in EN 15251.

The updated ISSO 74 adaptive comfort model can be found in Ref.[40, 42]. The figures illustrating the adaptive comfort model in these two papers are distinctly different: the acceptable temperature range in Ref.[40] is clearly broader than that in Ref.[42]. In this study, the figures illustrating of ISSO 74 of 2014 version is based on Ref.[40]. A graphical comparison of the 2004 and 2014 versions of ISSO 74 is shown in Figure 4.



a) ISSO 74:2004



b) ISSO 74:2014

Figure 4: Comparison of the difference of comfort models in the Dutch ISSO 74:2004 and ISSO 74:2014.

Besides, the comparison of the comfort categories presented in the two regulatory documents is reported in **Error! Not a valid bookmark self-reference.**.

Table 1: Comparison of the comfort classes as presented in the Dutch ISSO 74:2004 and ISSO 74:2014.

Document version	**Class**	**Description**	**PPD**	**PMV**	**Acceptance**
2004	Class A	Extra high-quality buildings. This class is appropriate for buildings with relatively sensitive users or building with high requirements as to comfort.	–	–	Min 90%
	Class B	Standard buildings. This class represents a neutral situation for standard offices.	–	–	Min 80%
	Class C	Buildings with an acceptable indoor climate. This class is appropriate for existing buildings or for temporary buildings.	–	–	Min 65%
2014	Class A	“High level of expectation. Select this category as a reference when designing spaces for people with limited load capacity (for instance, sensitive people or persons who are diseased) or when there is a higher demand for comfort”.	Max 5%	–	–
	Class B	“Normal level of expectation. Select this category as a reference when designing or measuring new buildings or in the case of substantial renovations”.	Max 10%	-0.5 to +0.5	–
	Class C	“Moderate level of expectation. Select this category as a reference in the case of limited renovations or when measuring older existing buildings”.	Max 15%	-0.7 to +0.7	–
	Class D	“Limited level of expectation. Select this category as a reference in the case of temporary buildings or limited use (for instance, one to two hours of occupation per day)”.	Max 25%	-1.0 to +1.0	–

Even if the ISSO 74:2014 presents different instructions for the comfort classes A and B, it prescribes that the upper and lower limits of the Class B are to be used for Class A as well, hence we refer to Class B(A) for both Class A and Class B.

$$\begin{matrix}\text{ISSO74: 2004}\\ \mathit{Alpha\ Building}\end{matrix}\begin{cases}\text{Upper limit of Class C (°C)}\begin{cases} = 0.31\,f(T_{\text{out}}) + 22 & (10°\text{C} \le f(T_{\text{out}}) \le 30°\text{C}) \\ = 0.11\,f(T_{\text{out}}) + 23.95 & (-5°\text{C} \le f(T_{\text{out}}) < 10°\text{C}) \end{cases} \\ \text{Upper limit of Class B (°C)}\begin{cases} = 0.31\,f(T_{\text{out}}) + 21.3 & (11°\text{C} \le f(T_{\text{out}}) \le 30°\text{C}) \\ = 0.11\,f(T_{\text{out}}) + 23.45 & (-5°\text{C} \le f(T_{\text{out}}) < 11°\text{C}) \end{cases} \\ \text{Upper limit of Class A (°C)}\begin{cases} = 0.31\,f(T_{\text{out}}) + 20.3 & (12°\text{C} \le f(T_{\text{out}}) \le 30°\text{C}) \\ = 0.11\,f(T_{\text{out}}) + 22.7 & (-5°\text{C} \le f(T_{\text{out}}) < 12°\text{C}) \end{cases} \\ \text{Lower limit of Class A (°C)} = 0.11\,f(T_{\text{out}}) + 20.2 \quad (-5°\text{C} \le f(T_{\text{out}}) \le 30°\text{C}) \\ \text{Lower limit of Class B (°C)} = 0.11\,f(T_{\text{out}}) + 19.45 \quad (-5°\text{C} \le f(T_{\text{out}}) \le 30°\text{C}) \\ \text{Lower limit of Class C (°C)} = 0.11\,f(T_{\text{out}}) + 18.95 \quad (-5°\text{C} \le f(T_{\text{out}}) \le 30°\text{C}) \end{cases} \qquad (7)$$

$$\begin{matrix}\text{ISSO74: 2004}\\ \mathit{Beta\ Building}\end{matrix}\begin{cases}\text{Upper limit of Class C (°C)} = 0.11f(T_{\text{out}}) + 23.95 & (-5°\text{C} \le f(T_{\text{out}}) \le 30°\text{C})\\ \text{Upper limit of Class B (°C)} = 0.11\,f(T_{\text{out}}) + 23.45 & (-5°\text{C} \le f(T_{\text{out}}) \le 30°\text{C})\\ \text{Upper limit of Class A (°C)} = 0.11\,f(T_{\text{out}}) + 22.7 & (-5°\text{C} \le f(T_{\text{out}}) \le 30°\text{C})\\ \text{Lower limit of Class A (°C)} = 0.11\,f(T_{\text{out}}) + 20.2 & (-5°\text{C} \le f(T_{\text{out}}) \le 30°\text{C})\\ \text{Lower limit of Class B (°C)} = 0.11\,f(T_{\text{out}}) + 19.45 & (-5°\text{C} \le f(T_{\text{out}}) \le 30°\text{C})\\ \text{Lower limit of Class C (°C)} = 0.11\,f(T_{\text{out}}) + 18.95 & (-5°\text{C} \le f(T_{\text{out}}) \le 30°\text{C})\end{cases} \tag{8}$$

$$\begin{matrix}\text{ISSO 74: 2014}\\ \mathit{Alpha\ spaces}\end{matrix}\begin{cases}\text{Upper limit of Class D (°C)}\begin{cases}= 0.33\,f(T_{\text{out}}) + 18.8 + 4 & (10°\text{C} \le f(T_{\text{out}}) \le 25°\text{C})\\ = 26 & (-5°\text{C} \le f(T_{\text{out}}) < 10°\text{C})\end{cases}\\ \text{Upper limit of Class C (°C)}\begin{cases}= 0.33f(T_{\text{out}}) + 18.8 + 3 & (10°\text{C} \le f(T_{\text{out}}) \le 25°\text{C})\\ = 25 & (-5°\text{C} \le f(T_{\text{out}}) < 10°\text{C})\end{cases}\\ \text{Upper limit of Class B(A) (°C)}\begin{cases}= 0.33\,f(T_{\text{out}}) + 18.8 + 2 & (10°\text{C} \le f(T_{\text{out}}) \le 25°\text{C})\\ = 24 & (-5°\text{C} \le f(T_{\text{out}}) < 10°\text{C})\end{cases}\\ \text{Lower limit of Class B(A) (°C)}\begin{cases}= 0.2\,f(T_{\text{out}}) + 18 & (10°\text{C} \le f(T_{\text{out}}) \le 25°\text{C})\\ = 20 & (-5°\text{C} \le f(T_{\text{out}}) < 10°\text{C})\end{cases}\\ \text{Lower limit of Class C (°C)}\begin{cases}= 0.2\,f(T_{\text{out}}) + 17 & (10°\text{C} \le f(T_{\text{out}}) \le 25°\text{C})\\ = 19 & (-5°\text{C} \le f(T_{\text{out}}) < 10°\text{C})\end{cases}\\ \text{Lower limit of Class D (°C)}\begin{cases}= 0.2\,f(T_{\text{out}}) + 16 & (10°\text{C} \le f(T_{\text{out}}) \le 25°\text{C})\\ = 18 & (-5°\text{C} \le f(T_{\text{out}}) < 10°\text{C})\end{cases}\end{cases} \tag{9}$$

$$\begin{matrix}\text{ISSO 74: 2014}\\ \mathit{Beta\ spaces}\end{matrix}\begin{cases}\text{Upper limit of Class D (°C)}\begin{cases}= 26 & (-5°\text{C} \le f(T_{\text{out}}) < 10°\text{C})\\ = 0.33\,f(T_{\text{out}}) + 18.8 + 4 & (10°\text{C} \le f(T_{\text{out}}) \le 16°\text{C})\\ = 28 & (16°\text{C} < f(T_{\text{out}}) \le 25°\text{C})\end{cases}\\ \text{Upper limit of Class C (°C)}\begin{cases}= 25 & (-5°\text{C} \le f(T_{\text{out}}) < 10°\text{C})\\ = 0.33\,f(T_{\text{out}}) + 18.8 + 3 & (10°\text{C} \le f(T_{\text{out}}) \le 16°\text{C})\\ = 27 & (16°\text{C} < f(T_{\text{out}}) \le 25°\text{C})\end{cases}\\ \text{Upper limit of Class B(A) (°C)}\begin{cases}= 24 & (-5°\text{C} \le f(T_{\text{out}}) < 10°\text{C})\\ = 0.33f(T_{\text{out}}) + 18.8 + 2 & (10°\text{C} \le f(T_{\text{out}}) \le 16°\text{C})\\ = 26 & (16°\text{C} < f(T_{\text{out}}) \le 25°\text{C})\end{cases}\\ \text{Lower limit of Class B(A) (°C)}\begin{cases}= 0.2\,f(T_{\text{out}}) + 18 & (10°\text{C} \le f(T_{\text{out}}) \le 25°\text{C})\\ = 20 & (-5°\text{C} \le f(T_{\text{out}}) < 10°\text{C})\end{cases}\\ \text{Lower limit of Class C (°C)}\begin{cases}= 0.2\,f(T_{\text{out}}) + 17 & (10°\text{C} \le f(T_{\text{out}}) \le 25°\text{C})\\ = 19 & (-5°\text{C} \le f(T_{\text{out}}) < 10°\text{C})\end{cases}\\ \text{Lower limit of Class D (°C)}\begin{cases}= 0.2\,f(T_{\text{out}}) + 16 & (10°\text{C} \le f(T_{\text{out}}) \le 25°\text{C})\\ = 18 & (-5°\text{C} \le f(T_{\text{out}}) < 10°\text{C})\end{cases}\end{cases} \tag{10}$$

where $f(T_{\text{out}})$ in ISSO 74 of 2014 is the running mean external temperature (θ_{rm})

$$\theta_{\text{rm}} = 0.2 \cdot (T_{\text{ed}-1} + 0.8 \cdot T_{\text{ed}-2} + 0.8^2 \cdot T_{\text{ed}-3} + 0.8^3 \cdot T_{\text{ed}-4} + \cdots) \approx 0.2 \cdot T_{\text{ed}-1} + 0.8 \cdot \theta_{\text{rm}-1} \tag{11}$$

and a simpler expression with just a seven-day horizon is also available.

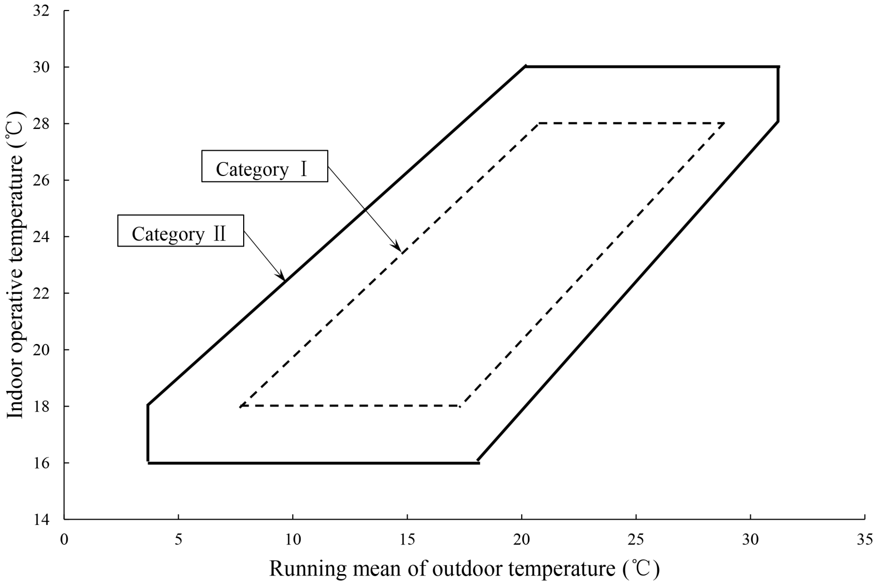
$$\theta_{\text{rm}} = 0.253 \cdot (T_{\text{ed}-1} + 0.8 \cdot T_{\text{ed}-2} + 0.8^2 \cdot T_{\text{ed}-3} + 0.8^3 \cdot T_{\text{ed}-4} + 0.8^4 \cdot T_{\text{ed}-5} + 0.8^5 \cdot T_{\text{ed}-6} + 0.8^6 \cdot T_{\text{ed}-7}) \tag{12}$$

while, in ISSO 74 of 2004, $f(T_{\text{out}})$ is called running mean outdoor temperature $(T_{\text{e,ref}})$ and is an approximate equation with a three-day horizon.

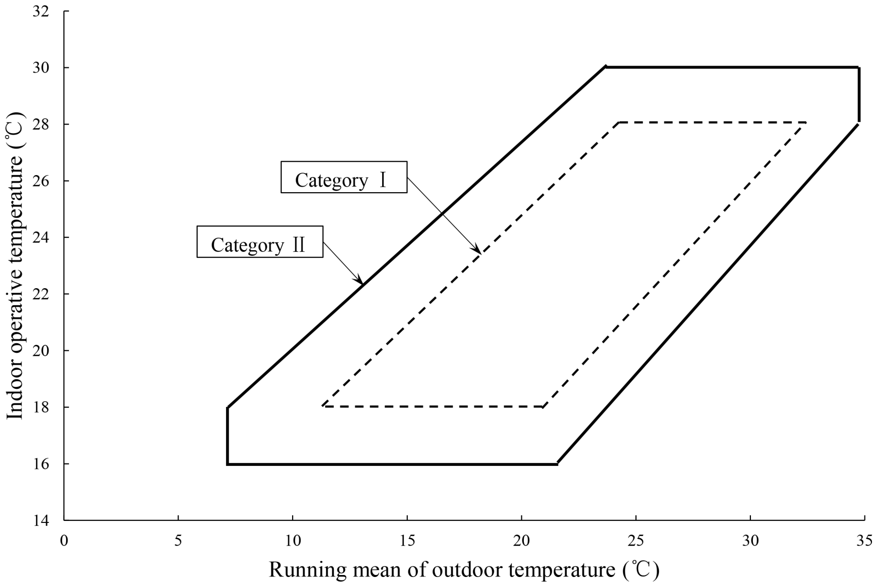
$$T_{\text{e,ref}} = \frac{1 \cdot T_{\text{ed}} + 0.8 \cdot T_{\text{ed}-1} + 0.4 \cdot T_{\text{ed}-2} + 0.2 \cdot T_{\text{ed}-3}}{2.4} \tag{13}$$

2.5 Chinese GB/T 50785 thermal comfort standard

The Chinese GB/T 50785 was issued in 2012 to provide an adaptive comfort model for the evaluation of the indoor thermal environment in free-running buildings at design and operational stages [43]. It offers reference methods specifically for two groups of climate zones in China's five zone climatology: the first comprises the *Severe cold zone* and the *Cold zone*, while the second comprises *Hot summer and cold winter zone*, the *Hot* *summer and warm winter zone*, and the *Mild zone*, and thus it addresses hot and mild climates. This standard does not specifically mention the type of buildings where the comfort model can be applied, but it includes two methods for assessing free-running buildings: a graphical method and a calculation method. The graphical method is based on the adaptive comfort model appearing in ANSI/ASHRAE 55-2004 [7]. For the graphic method, users can select the appropriate model in terms of the climate zone in which the building is located, and the acceptable operative temperature ranges are of two types: Category I represents 90% occupant acceptability and Category II corresponds to 75-to-90% acceptability. Figure 5 shows a graphical representation of these two acceptability ranges in different climate zones as functions of the running mean external temperature and the indoor operative temperature.



a) Thermal acceptability zones for the cold climates



b) Thermal acceptability zones for the hot and mild climates

Figure 5: Acceptable operative temperature ranges for unconditioned buildings.

This figure bears a resemblance to the comfort zone of ANSI/ASHRAE 55 of 2013 version, but they have distinct difference in that Chinese standard has a specific limitation of the upper and lower acceptability thresholds. The maximum 80% acceptability temperature is 30 ºC and the minimum 80% acceptability temperature is 16 ºC.

$$\text{Cold climates}\begin{cases}\text{Upper limit of Category II} = 0.73\, f(T_{\text{out}}) + 15.28 & (18℃ \le T_{\text{UL,II}} \le 30℃)\\ \text{Upper limit of Category I} = 0.77\, f(T_{\text{out}}) + 12.04 & (18℃ \le T_{\text{UL,I}} \le 28℃)\\ \text{Lower limit of Category I} = 0.87\, f(T_{\text{out}}) + 2.76 & (18℃ \le T_{\text{LL,I}} \le 28℃)\\ \text{Lower limit of Category II} = 0.91\, f(T_{\text{out}}) - 0.48 & (16℃ \le T_{\text{LL,II}} \le 28℃)\end{cases} \tag{14}$$

$$\text{Hot and mild climates}\begin{cases}\text{Upper limit of Category II} = 0.73\, f(T_{\text{out}}) + 12.72 & (18℃ \le T_{\text{UL,II}} \le 30℃)\\ \text{Upper limit of Category I} = 0.77\, f(T_{\text{out}}) + 9.34 & (18℃ \le T_{\text{UL,I}} \le 28℃)\\ \text{Lower limit of Category I} = 0.87\, f(T_{\text{out}}) - 0.31 & (18℃ \le T_{\text{LL,I}} \le 28℃)\\ \text{Lower limit of Category II} = 0.91\, f(T_{\text{out}}) - 3.69 & (16℃ \le T_{\text{LL,II}} \le 28℃)\end{cases} \tag{15}$$

where $T_{\text{UL,II}}$ and $T_{\text{LL,II}}$ are the upper and lower acceptability limit of indoor operative temperature in Category II respectively, $T_{\text{UL,I}}$ and $T_{\text{LL,I}}$ is the upper and lower acceptability limit of indoor operative temperature in Category I, $f(T_{\text{out}})$ is the running mean of outdoor temperature (T_{rm})

$$T_{\text{rm}} = (1-\alpha)\cdot(T_{\text{od}-1} + \alpha\cdot T_{\text{od}-2} + \alpha^2\cdot T_{\text{od}-3} + \alpha^3\cdot T_{\text{od}-4} + \alpha^4\cdot T_{\text{od}-5} + \alpha^5\cdot T_{\text{od}-6} + \alpha^6\cdot T_{\text{od}-7}) \tag{16}$$

where $T_{\text{od}-1}$ is daily mean outdoor air temperature for a time *od* of a series at equal intervals (day), and α is a constant between 0 and 1 and recommend using 0.8.

The Chinese standard' calculation method is based on the so-called *adaptive predicted mean vote* (*aPMV*) index that was developed by Yao, Li [44]. The equation for calculating *aPMV* corrects the Fanger's Predicted Mean Vote (*PMV*) with a so-called *adaptive coefficient* (λ) the authors obtained by a statistical elaboration of a selection of thermal comfort field studies carried out in China between 2007 and 2011. For assessment purposes, because the *aPMV* index is derived from Fanger's *PMV*, the calculation method can be applied only when onsite monitoring of all the input parameters to PMV are available (i.e. air temperature, mean radiant temperature, air speed, relative humidity, occupants' clothing insulation levels and metabolic rate).

2.6 Summative comments

All of the comfort regulatory documents presented in this review refer to the exponentially-weighted, running mean external temperature–Eq.(2,5,11,16) as the independent variable (x) in the adaptive comfort equation. This temperature is built on the assumption that more recent days have a stronger influence on the comfort temperature of building's occupants than those in more remote past. This principle is expressed algebraically by multiplying each term of the running mean of the daily outdoor temperature by an exponentially decaying weighting factor. In all formulations, these weighing factors are built upon a constant value commonly indicated with α. All regulatory documents suggest a default value for α, but, in practice, give the analyst freedom to make a different selection. Moreover, the exponentially weighted, running mean external temperature is proposed as an infinite series. EN 15251, prEN 16798-1, and ISSO 74:2014 solve the issue of the series of infinite terms by suggesting approximate equations–Eq.(6 and 12)–for simple calculation of a running mean external temperature. The approximate equations use only three (ISSO 74:2004) or seven terms (EN 15251, prEN 16798-1 and ISSO 74:2014) and fix the values of the exponentially decaying weighting factors. Substantially, they fix the truncation error due to the use of a limited number of terms of the series and compensate by either dividing or multiplying by a constant. The Chinese GB/T 50785 refers to the general series and arbitrarily fixes the number of the sequential days before the day in question to seven. In addition, it recommends an α-value of 0.8, but other options are permissible. Therefore, the truncation error due to the residuals of the series that are not accounted for is left unaddressed, but can be significant, depending on the value chosen for α. A discussion about the truncation error will be presented in Section 5.3.1. On the basis of the aforementioned matters, the optimal adaptive comfort temperatures and comfort or acceptability ranges calculated according to the five standards under investigation will be analyzed to identify similarities and differences. Afterwards, the main sources of uncertainty mentioned above will be discussed to estimate their impact on the final result of calculations.

3 Methodology

The adaptive comfort models were applied to climate data representing various climatic zones around the world. The climates were selected according to the Köppen-Geiger classification [45]. Some of the adaptive comfort models integrated in regulatory documents are generally applied in a specific country or contiguous geographic region at present; for example, EN 15251 and prEN 16798-1 are intended for use exclusively in Europe, ISSO 74 is used in the Netherlands, while GB/T 50785 is intended for exclusive application in China. ASHRAE 55-2017 on the other hand purports to have a global scope of applicability. Therefore, to have at least one city within each of these geographic domains, and to investigate the implications of various adaptive models across diverse climate zones, five cities –Amsterdam, Beijing, Palermo, San Francisco and Shanghai– were selected in this study for deeper analyses (Section 4). To reduce the scenario uncertainty and harmonize the source of meteorological data, Typical Meteorological Years (TMY) were used as outdoor climatic data sources of all cities in this study. The common source of TMY data was the *EnergyPlus*^{TM} website [46].

Optimal comfort temperatures and acceptable temperature ranges were then calculated from each adaptive comfort model for all the five selected cities. Furthermore, the uncertainties due to the weak definition of prevailing mean monthly temperature was investigated for the ANSI/ASHRAE 55, and due to the degree of freedom given to the analyst about the selection of the α-value and the number of days to use for the calculation of the external running mean temperature.

Similarities and differences of temperature time-series are shown graphically and are quantified using four statistical indices: mean bias error (MBE), root mean squared error (RMSE), the coefficient of variation of RMSE (CV(RMSE)), and the standard deviation of the difference of the daily temperature (σ(ΔT)).

MBE is a non-dimensional measure of the overall bias error, or systematic deviation, that is the total percentage error over the evaluation period, for a given temperatures time-series (*x*) of daily outdoor air temperature (*r*), or between two temperature time-series, and it is usually expressed as a percentage:

$$MBE = \frac{\sum_i^N \left(x_i - r_i\right)}{\sum_i^N r_i} \times 100 = \frac{\frac{1}{N}\sum_i^N \left(x_i - r_i\right)}{\overline{r}} \times 100 \tag{17}$$

where N is the number of days in an evaluation period (a year) and $\overline{r}$ is the mean of the daily outdoor air temperature over the evaluation period.

RMSE measures the closeness of a given temperature time-series and the daily outdoor air temperature, or between two temperature time-series.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^N \left(x_i - r_i\right)^2} \tag{18}$$

CV(RMSE) measures the variability of RMSE in relation to the mean of the reference time-series, that is the daily outdoor air temperature or a second temperature time-series.

$$CV\left(RMSE\right) = \frac{1}{\overline{r}}\sqrt{\frac{1}{N}\sum_{i=1}^N \left(x_i - r_i\right)^2} \times 100 \tag{19}$$

σ(ΔT) estimates the standard daily variation of a temperature time-series by calculating the standard deviation of the daily change in temperature. It is a scale-dependent metric.

$$\sigma\left(T_i - T_{i-1}\right) = \sqrt{\frac{1}{N}\sum_{i=1}^N \left(x_i - x_{i-1}\right)^2} \tag{20}$$

where x_i is the daily outdoor temperature in a given day and x_{i-1} is the daily outdoor temperature of the previous day.

Finally, regulatory documents have used so far different approaches for justifying progressive requirements for indoor environment. ANSI/ASHRAE 55 and GB/T 50785 use acceptability to define two classes, ISSO 74:2004 used the quality of a building to define three classes, ISSO 74:2014 uses the degree of expectation for creating four classes, EN 15251 and prEN 16897-1 use a hybrid criterion (fragile occupants and new building or renovation) to define four categories. This makes very challenging to find a common test condition to fairly compare the different adaptive comfort models. Thus, to allow inter-comparison between the various regulatory documents, we referred to the conditions that apply for a common new building, and the 80% acceptability limits are used for ANSI/ASHRAE 55 and GB/T 50785, the Category II is used for EN 15251 and prEN 16798-1, the Class B is used for ISSO 74 of 2004 version and the Class B is used for ISSO 74 of 2014 version. Furthermore, to make clear all the calculation assumptions, they will be displayed before showing the analysis outcomes in the Results and Discussion section.

Table 2: Corresponding thermal acceptability thresholds of each adaptive comfort model selected in this paper.

Standard name	**ANSI/ASHRAE 55**	**GB/T 50785**	**EN 15251 prEN 16798-1**	**ISSO 74:2004**	**ISSO 74:2014**
Category/Class	80% acceptability limit	Category II	Category II	Class B	Class B
PPD	20	25	25	20	10

4 Selection of cities for the standards' application and characterization of their climates

All mentioned regulatory documents on thermal comfort are characterized by different geographical domains. In order to analyze them a number of cities were identified to both comply with geographic scope of at least one of the regulatory document and also fall in a different climate zone as defined by Köppen-Geiger's classification. The five selected cities are Amsterdam, Beijing, Palermo, San Francisco, and Shanghai.

Table 3: Climate characterization of the selected cities.

City name	**Köppen-Geiger classification**	**Subtype**	**Description**
Amsterdam	Marine west coast climate	*Cfb*	Mild and temperate climate, although occasionally quite cool, influenced by its proximity to the North Sea to the west, with prevailing westerly winds and a noteworthy rainfall throughout the year
Beijing	Humid continental climate	*Dwa*	Monsoon-influenced cold and temperate climate with a colder, windier, drier winter that reflects the influence of the Siberian anticyclone, and a higher humidity in the summer due to the

			East Asian monsoon
Palermo	Hot-summer Mediterranean climate	*Csa*	Warm climate with a moderate seasonality characterized by hot and dry summers dominated by the subtropical high-pressure system and winters with moderate temperatures and changeable, rainy weather due to the polar front
San Francisco	Warm-summer Mediterranean climate	*Csb*	Mild year-round climate with little seasonal temperature swings with moist and mild winters and dry summers that reflect the influence of the cool currents of the Pacific Ocean
Shanghai	Humid subtropical climate	*Cfa*	Monsoon-influenced mild and humid climate with a chilly and dry winter due to the influence of northwesterly winds from Siberia and a hot and wet summer due to the East Asian monsoon

The climate of the cities is characterized using the distribution of the dry bulb air temperature in the five corresponding TMY data sets. Dry-bulb temperature is the sole meteorological parameter needed for the application of adaptive comfort models. Figure 6 compares the climates of the five selected cities using box-and-whisker charts.

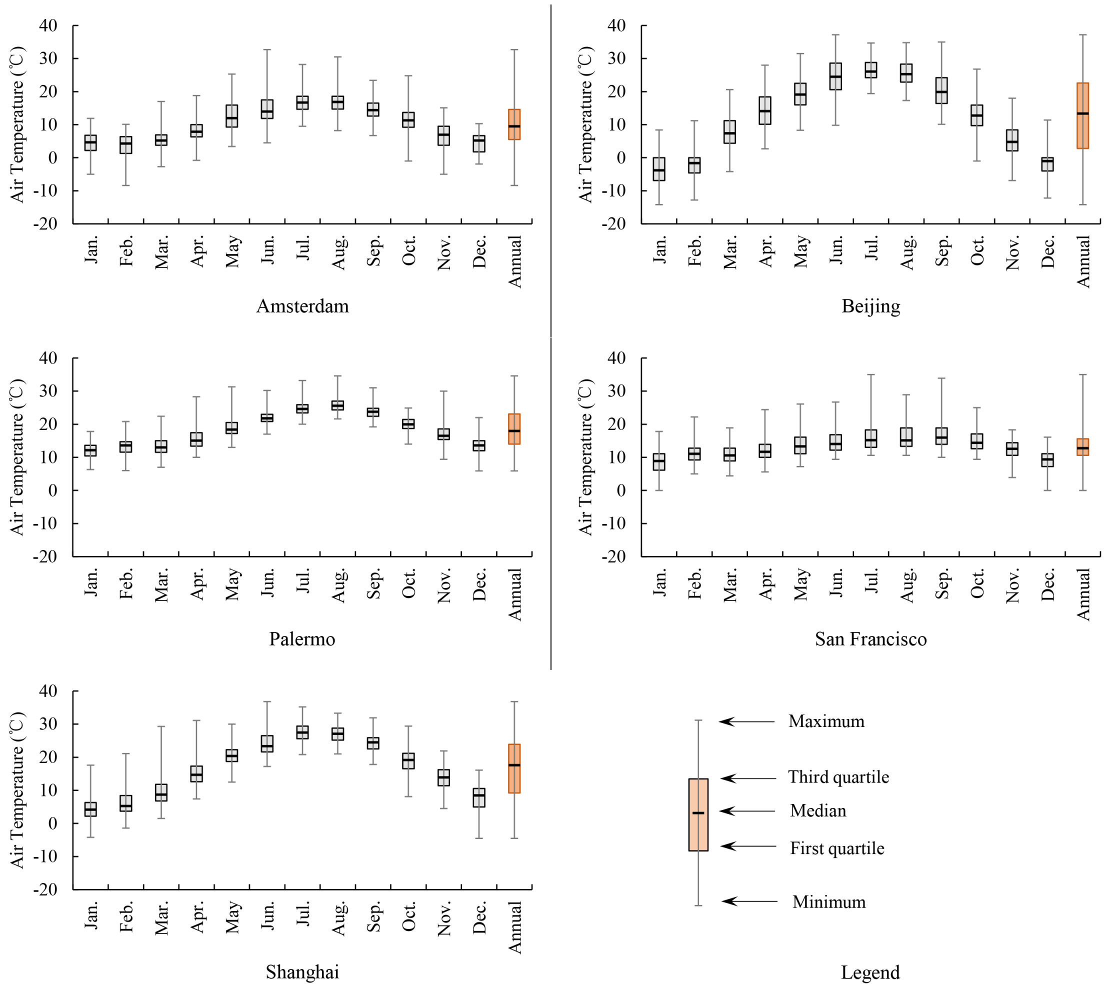


Figure 6: The distribution of outdoor air temperature of the selected cities.

The five cities present dissimilar climate with substantial differences in temperature variability and extreme values. The two Chinese cities present the highest variability. San Francisco and Beijing have basically the same yearly average temperature, but Beijing has a seasonal variability that is double that of San Francisco and, at the same time, records the lowest temperature and the second highest temperature of the sample. San Francisco and Palermo have quite low temperature fluctuations and do not typically go below 0 ºC. Shanghai is affected by the highest temperature peaks, and Amsterdam has the coldest yearly average temperature out of the five cities.

5 Results and Discussion

The adaptive comfort models integrated into thermal comfort regulatory documents are compared in the five selected cities, where applicable. The optimal comfort temperatures and the acceptability ranges are reported for each regulatory document in each city in Section 5.1 and Section 5.2 respectively. After that, the main sources of uncertainty for each adaptive model are discusses in Section 5.3.

5.1 The optimal adaptive comfort temperatures

In this section, the time-series of optimal adaptive comfort temperatures are compared in each of the five selected cities. Furthermore, the applicability of each adaptive comfort model is investigated according to the scopes specified in each of the regulatory document. Adaptive comfort models can be applied if the reference outdoor temperature falls into a given domain; thus, fluctuations of outdoor air temperature result in fluctuations of the adaptive comfort temperature that may cause it to fall outside the prescribed temperature domain in some hours and return into the limits in subsequent hours. This is one of the most critical aspects of the application of adaptive comfort models in practice.

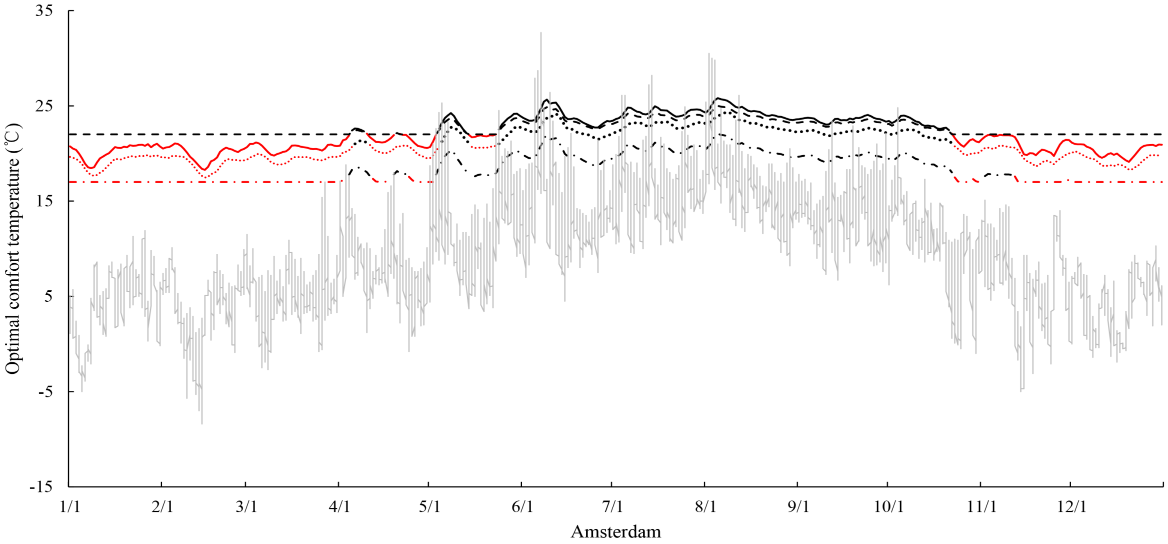
The optimal adaptive comfort temperatures and comfort ranges were calculated according to the most recently published version or publicly available revision of the four analyzed regulatory documents, and all their assumptions are summarized in Table 4.

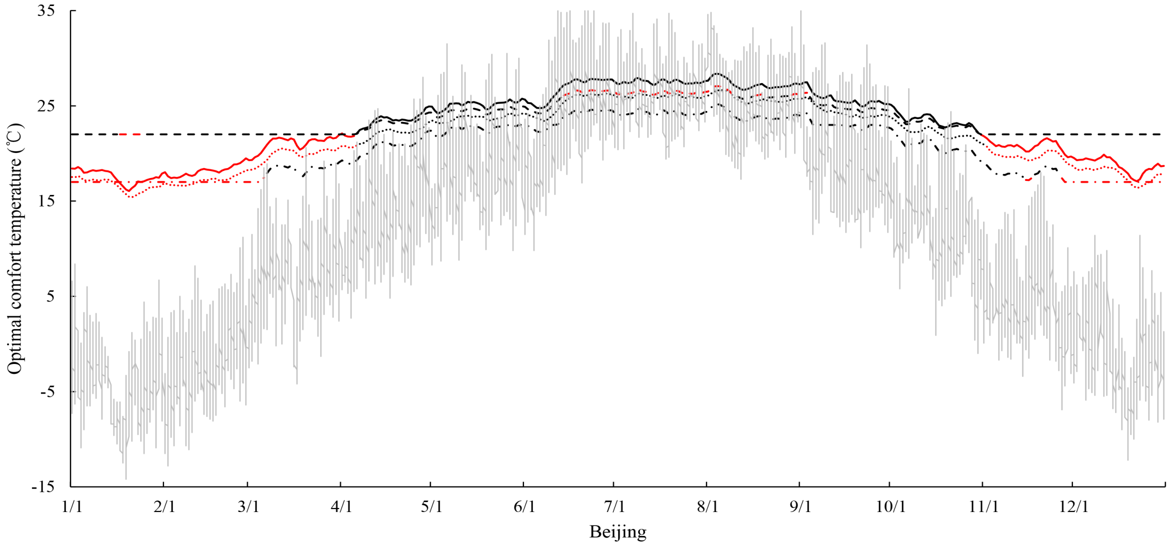
Table 4: Assumptions used to calculate the optimal adaptive comfort temperatures and the comfort limits for each regulatory document.

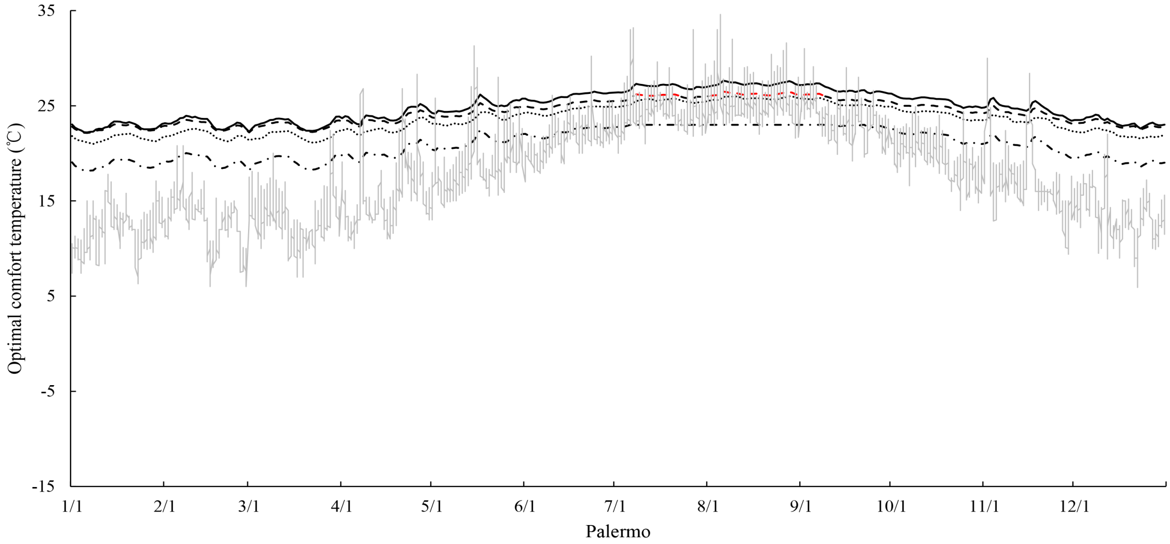
Feature	prEN 16798-1	ANSI/ASHRAE 55	GB/T 50785	ISSO 74
Type of building/space	Buildings without mechanical cooling	Naturally ventilated buildings	Unconditioned buildings	Alpha spaces
Operation	Free-running	Free-running	Free-running	Free-running
Reference outdoor temperature	Approximate running mean	Prevailing mean outdoor air	Running mean of outdoor	Approximate running mean

	external temperature–Eq.(6)	temperature	temperature–Eq.(16)	external temperature–Eq.(12)
Calculation period of the reference outdoor temperature	7 sequential days prior to the day in question	7 sequential days prior to the day in question	7 sequential days prior to the day in question	7 sequential days prior to the day in question
Decay constant in the reference outdoor running mean temperature (α)	0.8	N/A	0.8	0.8

Figure 7 presents a graphical comparison of the optimal adaptive comfort temperatures for 365 days of the five cities' TMY files. It provides, in red, an indication of the period when the reference outdoor temperature falls outside the prescribed temperature domain of a given regulatory document, besides a comparison of the optimal adaptive comfort temperature calculated according to the four analyzed adaptive models.




Optimal comfort temperature (℃)
35
25
15
5
-5
-15
1/1
2/1
3/1
4/1
5/1
6/1
7/1
8/1
9/1
10/1
11/1
12/1
Beijing


Optimal comfort temperature (℃)
35
25
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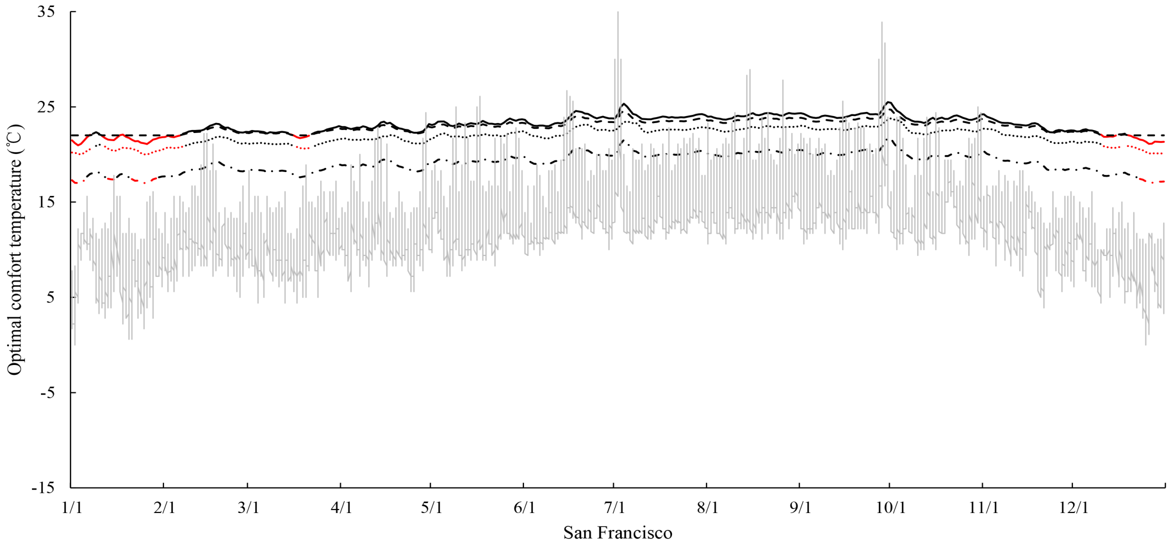
5
-5
-15
1/1
2/1
3/1
4/1
5/1
6/1
7/1
8/1
9/1
10/1
11/1
12/1
Palermo


Optimal comfort temperature (℃)
35
25
15
5
-5
-15
1/1
2/1
3/1
4/1
5/1
6/1
7/1
8/1
9/1
10/1
11/1
12/1
San Francisco

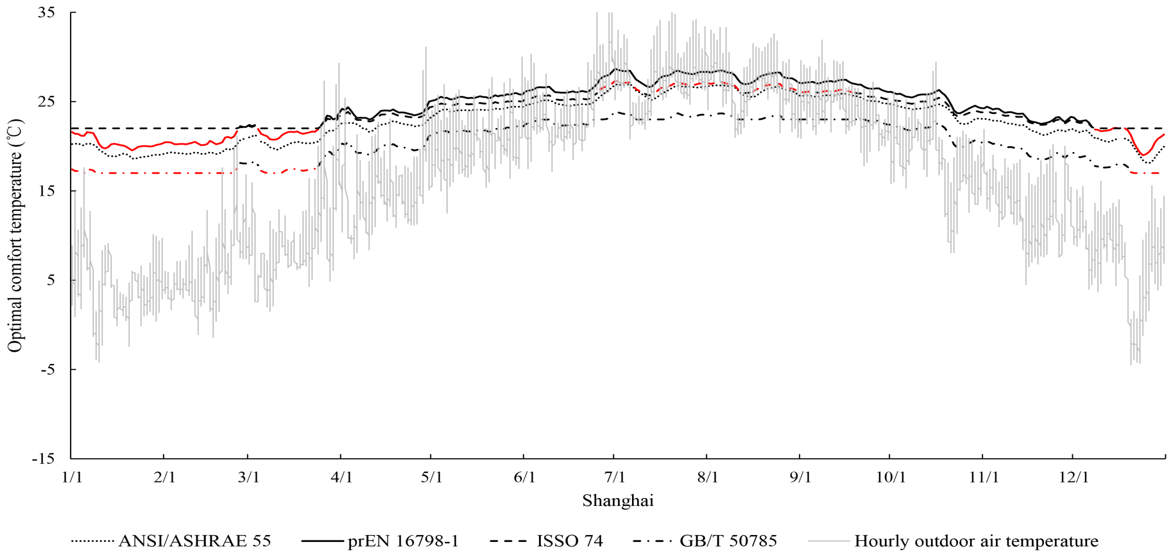


Figure 7: Comparison of the optimal comfort temperature of each adaptive comfort model in the five selected cities. In red, days when the outdoor reference temperature is out of the prescribed temperature domain specified by the given regulatory document.

GB/T 50785 and ISSO 74 do not provide an optimal comfort temperature in their adaptive comfort models, but only acceptability ranges can be defined according to given comfort classes and type of building or space. Therefore, for the purpose of comparison, we have assumed that the optimal adaptive comfort temperatures of GB/T 50785 and ISSO 74 correspond to the arithmetic mean of their upper and lower temperature limits.

Table 5 reports univariate statistics to characterize the time-series of the five cities' optimal adaptive comfort temperature, including mean, median, standard deviation, skewness, and kurtosis, besides the standard daily variation (σ(ΔT)) and the number of applicable days in the TMY year.

Table 5: Description of the optimal adaptive temperature time-series and estimation of their standard daily variation.

City	Metric	prEN 16798-1	ANSI/ ASHRAE 55	GB/T 50785	ISSO 74
Amsterdam	Mean (ºC)	23.8	22.5	19.6	22.7
	Median (ºC)	23.7	22.5	19.7	22.0
	Skewness	0.3	0.2	-0.1	0.9
	Kurtosis	-0.1	-0.1	-0.5	-0.4
	Standard deviation (ºC)	0.8	0.7	1.1	0.8
	Coefficient of variation (%)	3.3	3.2	5.6	3.7
	σ(ΔT) (ºC/h)	0.2	0.2	0.3	0.1
	N. of applicable days	167	167	195	365
Beijing	Mean (ºC)	25.7	24.3	21.9	23.1
	Median (ºC)	25.5	24.1	22.7	22. 0
	Skewness	-0.3	-0.3	-0.5	0.8

	Kurtosis	-1.2	-1.2	-1.0	-0.9
	Standard deviation (ºC)	1.7	1.6	2.2	1.3
	Coefficient of variation (%)	6.5	6.5	10	5.7
	σ(ΔT) (ºC/h)	0.2	0.2	0.2	0.1
	N. of applicable days	208	209	261	287
Palermo	Mean (ºC)	24.9	23.5	21.0	24.0
	Median (ºC)	24.9	23.5	21.1	23.9
	Skewness	0.1	0.1	-0.1	0.2
	Kurtosis	-1.4	-1.4	-1.5	-1.3
	Standard deviation (ºC)	1.6	1.5	1.6	1.1
	Coefficient of variation (%)	6.5	6.5	7.8	4.7
	σ(ΔT) (ºC/h)	0.2	0.1	0.1	0.1
	N. of applicable days	365	365	365	313
San Francisco	Mean (ºC)	23.4	22.1	19.3	22.9
	Median (ºC)	23.4	22.1	19.3	22.9
	Skewness	0.1	-0.3	-0.1	0.1
	Kurtosis	-0.7	-1.0	-0.8	-1.0
	Standard deviation (ºC)	0.7	0. 7	0.9	0. 7
	Coefficient of variation (%)	3.1	3.0	4.7	2.9
	σ(ΔT) (ºC/h)	0.2	0.1	0.2	0.1
	N. of applicable days	305	304	339	365
Shanghai	Mean (ºC)	25.6	24.3	21.4	23.4
	Median (ºC)	25.8	24.4	22.1	23.2
	Skewness	-0.2	-0.2	-0.6	0.4
	Kurtosis	-1.2	-1.2	-1.1	-1.4
	Standard deviation (ºC)	1.9	1.7	1.8	1.
	Coefficient of variation (%)	7.2	7.1	8.5	6.0
	σ(ΔT) (ºC/h)	0.2	0.2	0.2	0.1
	N. of applicable days	265	263	277	289

For all adaptive comfort regulatory documents, except for the ISSO 74, the number of applicable days is higher in Palermo and San Francisco, both of which have warm or mild climates (the yearly outdoor temperatures in Palermo and San Francisco are 18 and 12.8 ºC respectively) with a small variability (the standard deviations of the outdoor air temperature in Palermo and San Francisco are 5.1 and 3.2 ºC respectively). The number of applicable days is the lowest in Amsterdam due to cold (annual mean outdoor temperature in Amsterdam is 9.5 ºC), which pushes the outdoor reference temperature below usable temperature domain for most of the year (Figure 7 and Table 5). Furthermore, except for Palermo and ISSO 74, the periods when the adaptive comfort models can be applied are intermittent during the shoulder seasons.

The optimal adaptive comfort temperature of prEN 16798-1 is consistently the highest of all regulatory documents under review here. In contrast, the optimal adaptive comfort temperature indicated by the Chinese GB/T 50785 is much lower than others during its applicable periods. For example, in Palermo, the optimal adaptive comfort temperature of GB/T is, on average, from 2.6 to 3.9 ºC lower than those calculated with prEN 16798-1, ANSI/ASHRAE 55 and ISSO 74. Also Yang, Xiong [47] (Figure 8 at page 364) found that the optimal comfort temperatures calculated according to EN 15251 overestimate the observed neutral temperature for people in Changsha, China, during the cold and transition months. According to the authors, possible reasons might be that (i) Chinese people “can adapt to the change of outdoor climate condition more quickly” [47] than Europeans by putting on or taking off their clothes according to surrounding conditions, and (ii) the “distinct behavioral adjustment (the physical adaption) and expectation of the occupants (the psychological adaption) caused by the completely different climate conditions between European countries and China” [47]. But there is not a tentative explanation for the cold-bias during the summer months.

Three adaptive regulatory documents, prEN 16798-1, ANSI/ASHRAE 55 and ISSO 74, provide similar optimal adaptive comfort temperatures with RMSE less than 1.5 ºC.

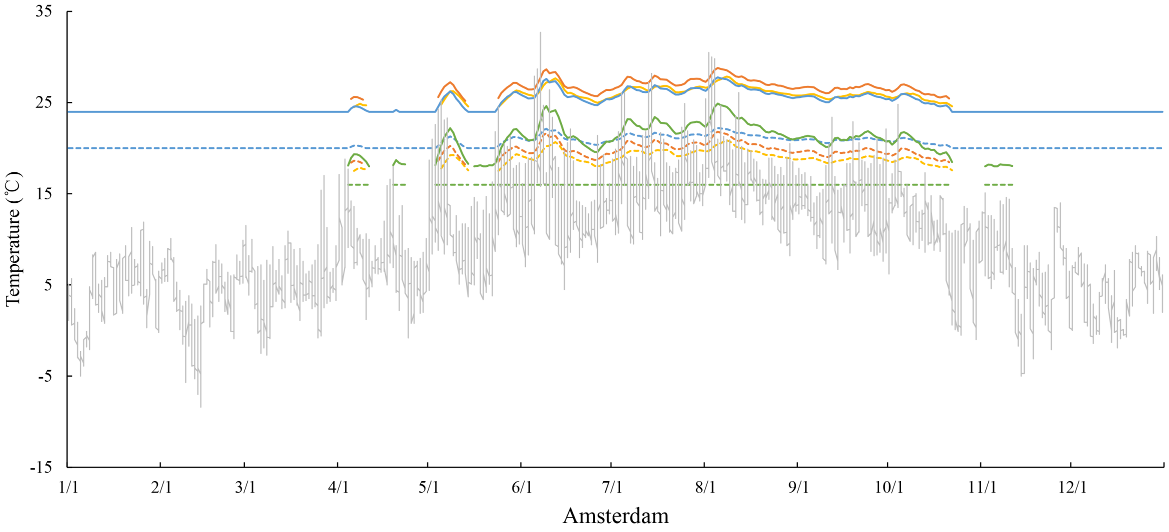
The variability of the optimal adaptive comfort temperature of ANSI/ASHRAE 55 is slightly smaller than those of prEN 16798-1, according to the coefficient of variation indicated in Table 5. In general, ISSO 74 is characterized by the lowest daily optimal adaptive comfort temperature variation; in effect, it has the highest inertial behavior. However, this is influenced by the constant value taken throughout winter months. If the periods when the optimal comfort temperature is constant are excluded from the calculation of daily temperature coefficient of variation of ISSO 74, then ANSI/ASHRAE 55 emerges with the lowest daily temperature variation, followed by the prEN 16798-1, and in third place, ISSO 74. Finally, GB/T 50785 presents the highest values of the daily temperature variation and the largest fluctuation of optimal adaptive temperature when compared with other regulatory documents. These results agree with the findings of Li, Yao [7], Yang, Xiong [47], Liu, Yao [48], who point out that the responses about the thermal environment of occupants who live in free-running buildings in China are strongly affected by the surrounding thermal stimuli and show a fast response adaption to changes in outdoor environment. These aspects are used to explain the large variability recorded in field studies even in short periods of time, for example one day.

In summary, though prEN 16798-1 and GB/T 50785 both use the exponentially weighted running mean external temperature, their disparate adaptive thermal comfort equations differentiate their results. In contrast, the adaptive comfort temperatures calculated by ANSI/ASHRAE 55 and prEN 16798-1, although based on different formulations of outdoor air temperature and processed through different adaptive comfort equations, provide similar optimal adaptive temperatures (the root mean squared error over the evaluation period is just 1.4 ºC in Palermo, which is the largest among the five cities analyzed here). Moreover, the optimal adaptive comfort temperatures recommended by ANSI/ASHRAE 55 exhibit a slightly more inertial behavior compared to those computed using prEN 16798-1 and GB/T 50785. Finally, the Chinese regulatory document computes optimal adaptive comfort temperatures, on average, about 3 ºC lower than the other adaptive comfort models, and the discrepancy enlarges at higher values of the daily outdoor air temperature.

All the analyzed regulatory documents define the scope of adaptive comfort models, which are based on an outdoor reference temperature formulated either as a running mean temperature or prevailing mean outdoor air temperature. Yet none provide any guidance on the correct starting day and duration of calculation period (i.e., season). This is a potential source of uncertainty and leads to confusion regarding which indoor comfort criterion should be adopted in periods when the adaptive comfort models are inapplicable. While de Dear and Brager [25] discuss this issue, no definitive solution has been offered. ISSO 74 and some researchers suggest reverting to the PMV/PPD model when the outdoor reference temperature falls outside the temperature domain specified in the regulatory document, but this would be impractical during highly intermittent periods [49-51]. Moreover, some researchers [52] try to use a horizontal line when the outdoor reference temperature falls outside the temperature domain. However, these suggestions are all extrapolation and lack any theoretical basis.

5.2 The acceptable temperature ranges

The upper and lower comfort limits of the four adaptive models were calculated under the assumptions summarized in Table 4 and presented in Figure 8. Regarding the use of the Chinese adaptive comfort model in the non-Chinese cities, the rules of the Chinese standard GB/T 50176 [53] were applied to Palermo, San Francisco and Amsterdam and deemed to be in the “hot and mild climates” group of GB/T 50785.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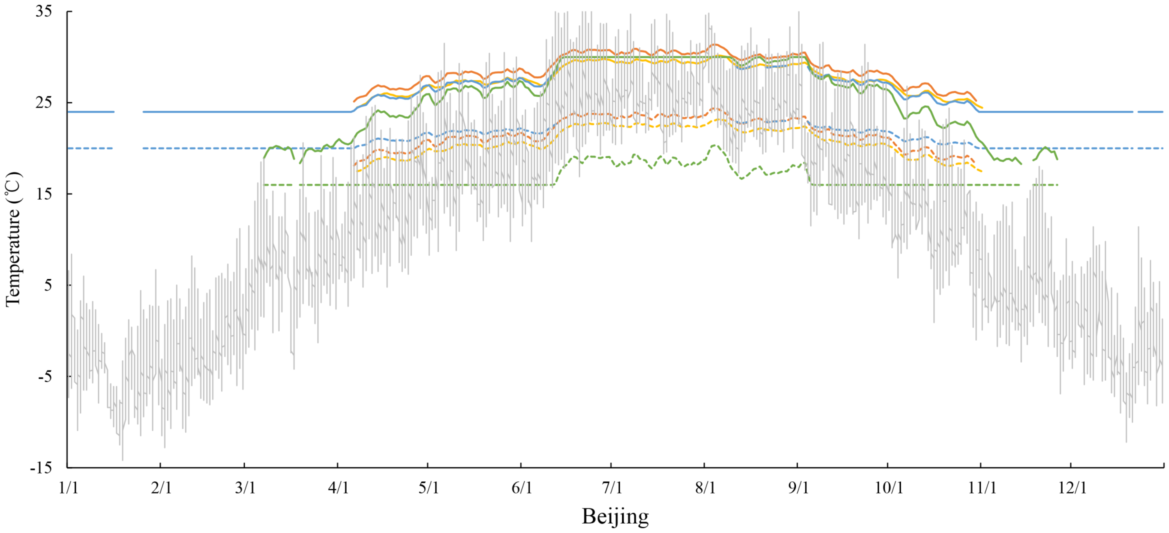
Amsterdam

460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Beijing

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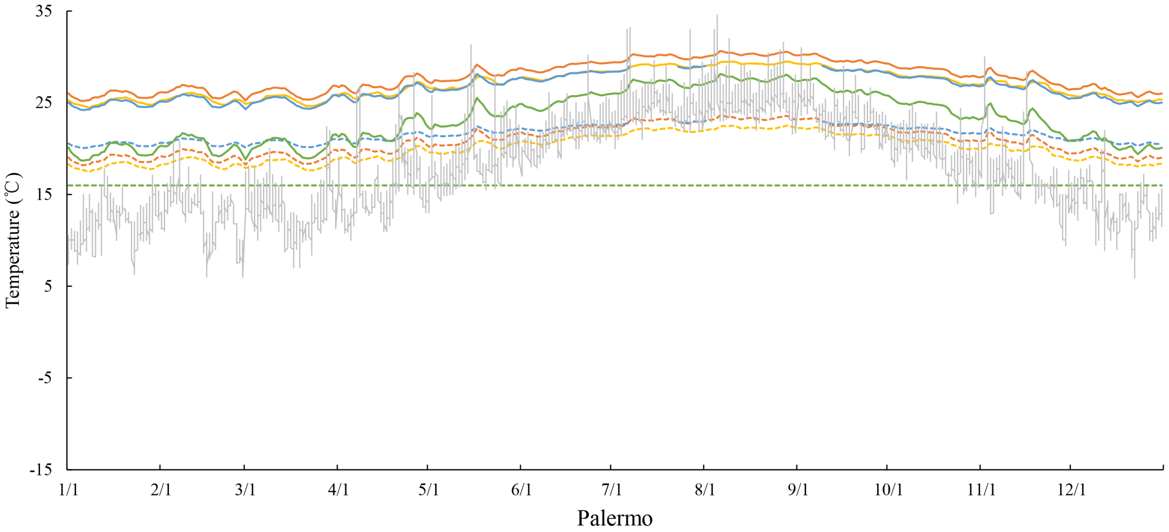
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Temperature (℃)
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Palermo

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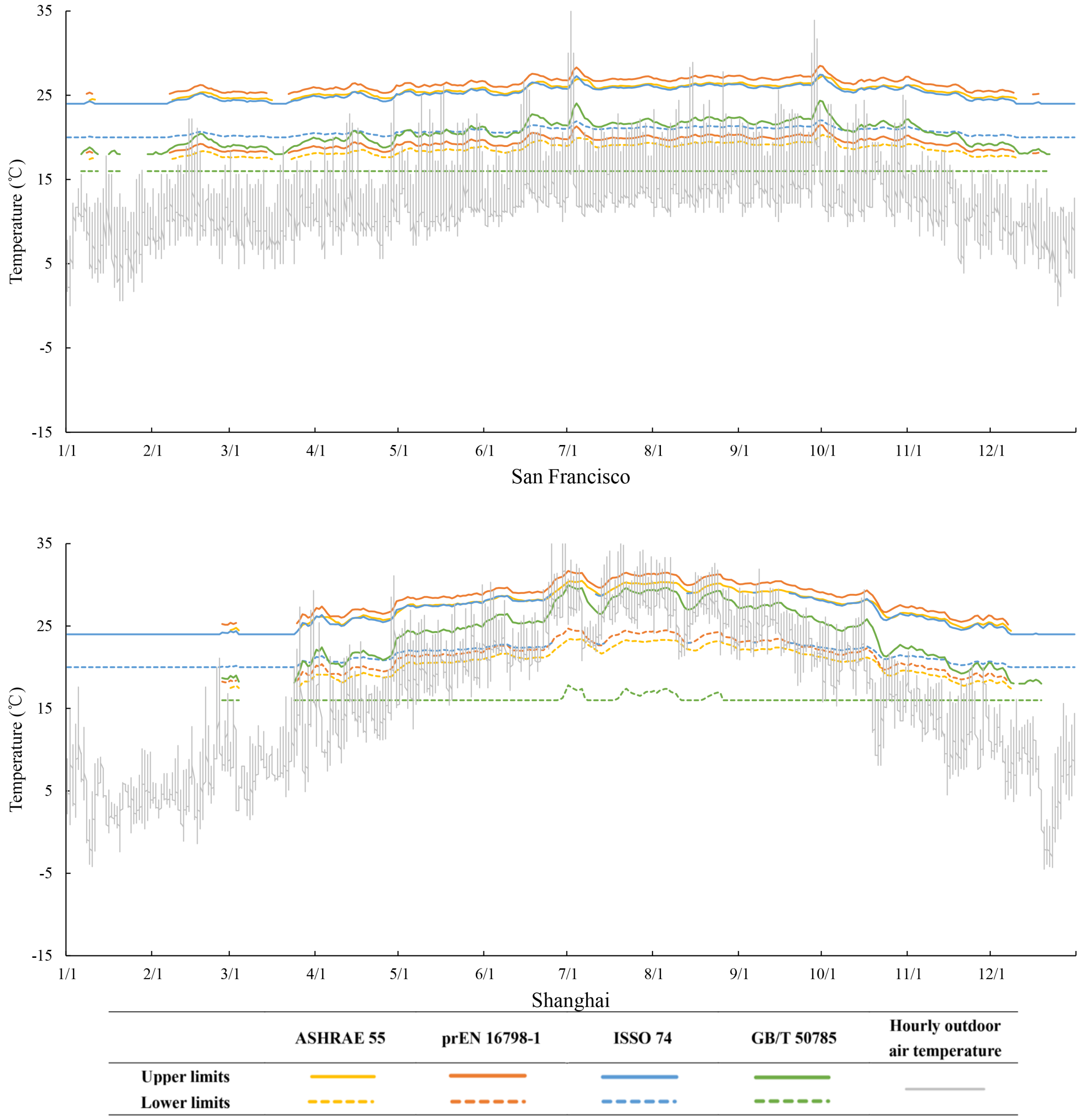

Figure 8: Acceptable temperature ranges applied in different cities according to the different adaptive thermal comfort models.

ANSI/ASHRAE 55, prEN 16798-1 and ISSO 74 all indicate similar acceptable temperature ranges, with discrepancies under 2.5 degree Celsius; this emphasizes the fact that ASHRAE and EN adaptive models provide remarkably similar outputs despite being based on (i) completely different observational databases, (ii) disparate statistical methods used to define their models, (iii) different amplitudes of the compared comfort categories, and (iv) differences in their outdoor reference temperature formulations. Specifically, in all these adaptive comfort models, the upper and lower limits of the comfort ranges are simply offsets of the optimal adaptive comfort temperature by a fixed number of degrees, depending on the chosen comfort category – larger offsets for lower comfort classes (Table 2). It is interesting the shift of 1 ºC of the lower limit of the prEN 16798-1 with respect to EN 15251, which now makes it more consistent with the lower acceptable temperatures in the other adaptive comfort regulatory documents and increases the potential for nighttime ventilative cooling (night purge).

The acceptable temperature range of China's GB/T 50785 stands in stark contrast to the other adaptive comfort regulatory documents but its upper limit, especially in the cities of Beijing and Shanghai, is more consistent with those of the other regulatory documents (within 2 ºC). However, in the other cities, the upper limit of the GB/T 50785 is significantly lower, so much so that in the coldest climate test cases of Amsterdam and San Francisco, the Chinese upper comfort limit approaches their lower limits. This pronounced cold-bias in the Chinese regulatory document would pave the way to heavy reliance on mechanical cooling even for mild indoor operative temperatures lower than 26/27 ºC reference values commonly associated with the conservative Fanger PMV/PPD comfort model.

Regarding the Chinese GB/T 50785 regulatory document's lower limit, it is very low. Even in the hottest periods of the year in the warmer test-case cities, it persists below about 20 ºC and, in all the other periods, it locks onto the fixed lower limit of 16 ºC at which active heating is mandated. The cold-bias in GB/T 50785 increases dramatically the number of hours suitable for the exploitation of night ventilative cooling during summer.

In summary, while the ASHRAE, CEN and Dutch adaptive comfort models provide broadly consistent adaptive comfort ranges, the Chinese variant demonstrates surprising patterns that are further amplified when applied in the non-Chinese cities in this analysis. This phenomenon warrants more detailed investigation but, at this point in time, underlines the importance of constraining the geographic scope of application for the Chinese adaptive model exclusively to China. Nevertheless, the very low Chinese lower limit and the 'arbitrary' 1 ºC reduction in the lower limit in prEN 16798-1 warrant further research to find a compromise between exploitation of summer night ventilative cooling and occupants' overcooling.

5.3 Sources of uncertainty in applying adaptive thermal comfort standards

Three main sources of uncertainty affect both the application of the regulatory documents and interpretation of their calculations. The first arises from the variety of running mean outdoor temperature expressions to choose from each affecting the truncation error mentioned in Section 2.6; the second arises from the variety of prevailing outdoor temperature expressions to choose from in ANSI/ASHRAE 55-2013, while the third source of uncertainty stems from the co-existence of multiple versions of each regulatory document, potentially confounding the interpretation of outcomes if specific versions are not accurately cited.

5.3.1 Uncertainty in the calculation of the running mean outdoor temperature

McCartney and Nicol [37] found that the value of the exponentially decaying weighing factor is not crucial for values of α lower than 0.9. Nicol and Humphreys [26] also found that the correlation with the comfort temperature[1] rises gradually until α = 0.8, but then tapers off beyond that value. EN 15251, prEN 16798-1 and GB/T 50785 recommend an α-value of 0.8 while ANSI/ASHRAE 55:2017 suggests an α-value of 0.9 for those climates where the day-to-day temperatures change relatively slowly, such as humid tropics, and a lower α-value for the mid-latitude climates. ISSO 74 takes the equation of the running mean external temperature from EN 15251 and fixes the α-value at 0.8. Only the Chinese GB/T 50785 specifies a 7-day period prior the day in question to be used in the calculation of the series. Since GB/T 50785 is fixed to seven days and only recommends the α-value, in practice giving the analyst the possibility to change it, varying α implies a change of the exponentially decaying weighing factors, which affects the truncation error. Therefore, in this study, five values of α, 0.2, 0.4, 0.6, 0.8 and 0.9 are applied to the equation with the seven-day horizon proposed in the GB/T 50785 for the climate of Shanghai.

Figure *9* shows the effect of the truncation error in the running mean. Table 6 quantifies differences of the seven-day horizon equation with five α-values applied to Shanghai's daily outdoor air temperature time series.

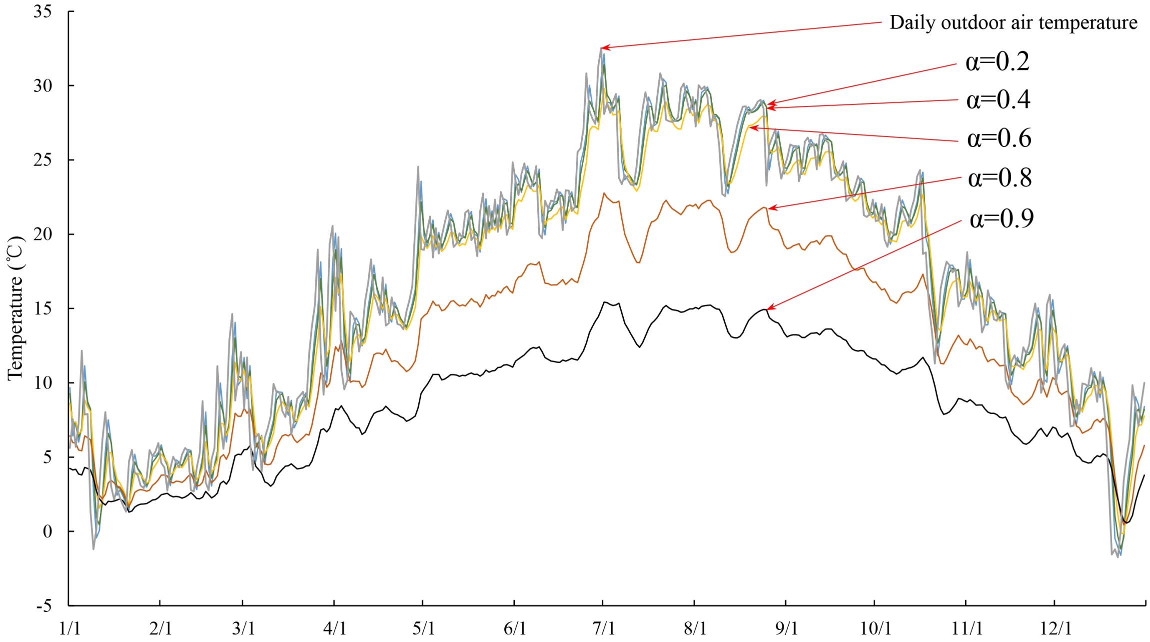

Figure 9: Effect of different α-values on the equation with a seven-day running mean outdoor external temperature, as proposed by GB/T 50785, for the climate of Shanghai, China.

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[1] Neutrality in their analysis was not actually observed but rather estimated by presuming a Griffiths coefficient of half a thermal sensation unit on the 7-point scale for each unit of indoor operative temperature change, and then extrapolating up or down from an observed sensation v temperature data pair to reach the mid-scale sensation vote of "neutral."

Table 6: Differences between the daily outdoor air temperature and the equation with a seven-day horizon for the calculation of the running mean external temperature as proposed by GB/T 50785 calculated for different α-values, for the climate of Shanghai.

Metric	**α-value**				
	0.2	**0.4**	**0.6**	**0.8**	**0.9**
MBE (%)	0.0	-0.2	-2.8	-24.0	-47.8
RSME (ºC)	2.1	2.2	2.3	5.0	9.2
CV(RSME) (%)	12.7	12.9	13.8	30.1	55.0

The value of α, at least with a 7-day time horizon, exerts a major impact on the values taken for the running mean external temperature, which is the only input parameter of the adaptive comfort models. In the case of Shanghai, results come very close to the daily outdoor air temperature for $\alpha = 0.2$ (RSME = 2.1 ºC) or completely shifted, on average by as much as 10 ºC for $\alpha = 0.9$, which close approximates the unweighted running mean outdoor temperature. Table 7 presents more descriptive statistics to characterize the Shanghai time-series. With an increase of α the time-series becomes smoother, indicated by $\sigma(\Delta T)$ decreasing from 1.7 to 0.3 ºC for α set to 0.2 and 0.9 respectively, and approaching a constant i.e., the arithmetic mean, as $\alpha \rightarrow 1$.

Table 7: Characterization of the running mean external temperature as proposed by GB/T 50785 calculated for different α-values, for the climate of Shanghai.

Metric	**α-value**				
	0.2	**0.4**	**0.6**	**0.8**	**0.9**
Maximum (ºC)	32.1	31.4	29.8	22.8	15.4
Mean (ºC)	16.7	16.7	16.2	12.7	8.7
Minimum (ºC)	-1.6	-1.2	-0.2	0.5	0.6
Standard deviation (ºC)	8.4	8.4	8.1	6.3	4.3
Coefficient of variation (%)	50.4	50.1	49.7	49.5	49.4
$\sigma(\Delta T)$ (ºC/h)	1.7	1.3	0.9	0.5	0.30

The impact of α demonstrated in Table 7 and Figure 9 leads us to recommend the adaptive comfort regulatory documents to either specify both the values of α and the duration of the time horizon or the lowest value of the exponentially decaying weighting factor to be considered in the summation. As it stands at the moment we think it imprudent to give the analyst freedom to subjectively “cherry-pick” the α-value because, for example, if the adaptive comfort method is used for the assessment of overheating in buildings, an overheating problem may be opportunistically solved by purposively downsizing α.

Finally, given the importance of α to the dynamic evolution of the running mean outdoor temperature and the absence of systematic studies on this issue, focused research is needed to better understand how to fine-tune the value of α on the basis of the dynamics of the climate regime in question. For example, ANSI/ASHRAE 55:2017 already makes general recommendations for smaller α to be applied in the more changeable weather regimes in the mid-latitudes, and larger for the more stable humid tropics, but as yet, an empirical evidence base to make more specific recommendations along these lines remains missing.

5.3.2 Uncertainty in the calculation of the prevailing mean outdoor temperature

In the original ASHRAE adaptive comfort model the simplest and most ubiquitous outdoor temperature input was used, namely the mean monthly temperature. Since the 2013 version of ANSI/ASHRAE 55, new options for the outdoor reference temperature were introduced while the definition of the comfort classes was not modified. The monthly mean outdoor air temperature inherited form the original version of ASHRAE 55:2004 can now be replaced with the so-called *prevailing mean outdoor air temperature*. However, ANSI/ASHRAE 55 of 2013 and 2017 allows the analyst to arbitrarily select a calculation period ranging from seven through 30 sequential days prior the day in question. Moreover, when the prevailing mean outdoor air temperature is used in conjunction with building performance simulation and calculated from typical meteorological year (TMY) files, ANSI/ASHRAE 55 of 2013 and 2017 recommends, as the preferred expression, a running mean external temperature as defined in EN 15251 and prEN 16798-1. Therefore, ANSI/ASHRAE 55 of 2013 and 2017 offer several options for the outdoor reference temperature, and, in this sub-section, some of them, together with the vestigial ASHRAE 55:2004 monthly mean outdoor air temperature, are calculated for the climate of San Francisco according to the assumptions reported in Table 8 and compared in Figure 10.

Table 8: Assumptions used to calculate the outdoor reference temperature for ANSI/ASHRAE 55.

Category	**ANSI/ASHRAE 55:2013**	**ANSI/ASHRAE 55:2010**
Type of building	Naturally ventilated buildings	Naturally ventilated buildings
Operation mode	Free-running	Free-running
Reference outdoor temperature	Prevailing mean outdoor air temperature–see Section 2.2;	Monthly mean outdoor air temperature–see Section 2.2
Calculation period of the reference outdoor temperature	7, 15, 21, 30 sequential days prior to the day in question; 7-day exponentially weighted, running mean	Calendar month

Constant in the reference weighted running mean outdoor temperature (α)	1 (for monthly means) 0.9, 0.6 (for the exponentially weighted means)	N/A

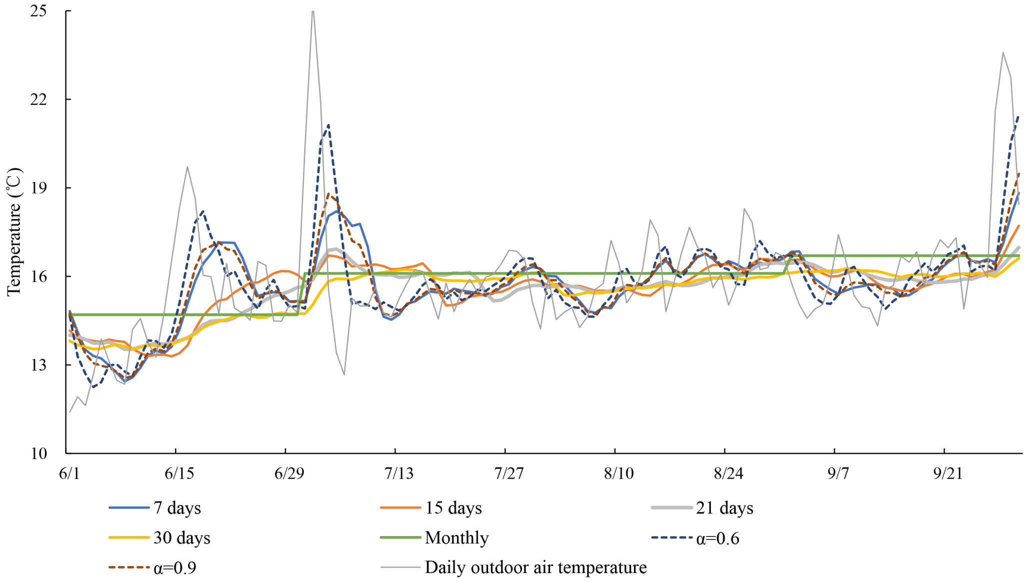

Figure 10: Comparison of the different option to calculate the outdoor reference temperature according to ANSI/ASHRAE 55:2017 (Only the period from 1st June to 30th September is shown for readability purposes).

For the purpose of visualizing the outdoor temperature metric calculations, all versions of the prevailing mean outdoor air temperatures, the monthly mean outdoor air temperature, along with the running mean outdoor air temperature series are compared with respect to the daily outdoor air temperature in Table 9.

Table 9: Comparison between several options of the prevailing mean outdoor air temperature and of the monthly mean outdoor air temperature (Metrics calculated with respect to the daily outdoor air temperature).

Outdoor reference temperature	**Calculation period**	**MBE (%)**	**RSME (ºC)**	**CV(RSME) (%)**	**σ(ΔT) (ºC)**	**Number of applicable days**
Prevailing mean outdoor air temperature	7 days prior the day in question	0.0	1.9	0.5	0.4	304
	15 days prior the day in question	0.0	1.9	0.5	0.2	308
	21 days prior the day in question	0.0	1.9	0.5	0.1	310
	30 days prior the day in question	0.0	2.0	0.6	0.1	310
Monthly mean outdoor air	Calendar month	0.0	1.7	0.5	0.3	303

temperature						
Running mean external temperature	$\alpha = 0.6$	0.0	1.6	0.5	0.7	309
	$\alpha = 0.9$	0.0	1.8	0.5	0.4	302

The various options for calculating the outdoor reference temperature offered by ANSI/ASHRAE 55:2017 differ in terms of variability, smoothness, and number of applicable days. The values of MBE calculated with respect to the daily outdoor air temperature, as expected, indicates that the monthly mean outdoor air temperature is the only option that is systematically biased. For the prevailing mean outdoor air temperature, RSME and CV(RSME) show an increase of both the deviation and variability of the outdoor reference temperature with respect to the daily outdoor air temperature with the increase of calculation period, meaning the longer averaging horizons amplify the hour-by-hour differences with respect to the daily average outdoor air temperature. As expected, longer averaging horizons reduce the fluctuation of the prevailing mean outdoor air temperature, and σ (ΔT) provides a quantification of this effect: increasing the averaging horizons from seven day to 30 days prior the day in question causes a diminution of daily fluctuation by more than three times. Furthermore, expanding the analysis to the other options to compute the outdoor reference temperature, the running mean external temperature has the highest hourly changes, especially when α is set to 0.6 and is the option most closely resembling the daily outdoor air temperature with the lowest deviation (RMSE = 1.63 ºC) and variability (CV(RMSE) = 0.45 %). Finally, also the number of applicable days changes slightly specifically it increases with the length of the averaging horizon in the prevailing mean outdoor air temperature. The value of α has an impact on the number of applicable days as well.

6 Conclusions

The theoretical background of adaptive thermal comfort models has matured and their empirical validation evidence has accumulated in the research literature [54]. As a result, several adaptive thermal comfort models have been integrated into various national and global comfort regulatory documents in recent years. Regulatory documents are fundamental to the acceptance and implementation of a concept in architectural and engineering practice. However, although regulatory documents are updated on a regular basis, there remain some ambiguities in the application of adaptive thermal comfort models in the design and operation of buildings.

In this paper, we investigated the five regulatory documents that have incorporated an adaptive thermal comfort model (ANSI/ASHRAE 55, EN 15251, prEN 16798-1, ISSO 74 and GB/T 50784) by looking for similarities, differences and sources of uncertainty. After a broad-brush review of these five regulatory documents, their adaptive comfort models were used to compute the acceptable indoor temperature ranges in five different climates around the world (Amsterdam, Beijing, Palermo, San Francisco and Shanghai) by adopting their Typical Meteorological Year files of representative hourly meteorological observations. Next, a statistical analysis characterized all the temperature time-series and quantified discrepancies between the adaptive comfort ranges calculated by the adaptive comfort regulatory documents. Finally, several sources of uncertainty affecting the application of the regulatory documents in practice and the interpretation of the results were analyzed and discussed.

Despite the obvious differences between these regulatory documents, such as the source region and culture of the raw thermal comfort field study data from which they were derived, the equation of adaptive comfort model, the definition of comfort categories or classes, and the calculation method of the outdoor reference temperature, several similarities do exist among most of them. This reinforces the robustness of the adaptive comfort theory underpinning all of the regulatory documents.

ANSI/ASHRAE 55, prEN 16798-1(and hence EN 15251), and ISSO 74 use different approximate equation to calculate the outdoor reference temperature and use different adaptive comfort equations, and yet they yield similar optimal adaptive comfort temperatures. The Chinese GB/T 50785 -is the clear outlier in this analysis, with a very discrepant optimal adaptive comfort temperature that is, on average, 3 ºC lower than the others. This significant difference probably results from the Chinese regulatory documents' fundamentally different theoretical basis, namely adaptive PMV model [55], in contrast to the other four regulatory documents in this analysis, which were derived from regression analyses of rigorously quality controlled thermal comfort field research databases.

Under the calculation assumptions adopted in this study, ANSI/ASHRAE 55, prEN 16798-1, and ISSO 74 provide comparable acceptable temperature ranges, but the Chinese regulatory document shows unusual patterns in comparison with the others.

The input variable for adaptive comfort regulatory documents, namely outdoor reference temperature, plays an important role in the calculation of the acceptable comfort temperature. Currently, two main functions are proposed in regulatory documents to evaluate the effect of outdoor environment in adaptive comfort model, which are the running mean external temperature and the prevailing mean outdoor temperature. Uncertainties arise from the freedom ceded by the regulatory documents to the analyst to pick their preferred α-values, and also to the number of days prior the day in question to consider in their calculation of outdoor reference temperature. According to the analysis in this paper, both sources of uncertainty have a significant impact on the optimal adaptive comfort temperature and hence thermal comfort ranges. Therefore, it is suggested that further research be conducted into the time constant of human thermal adaption processes so that future versions of the regulatory documents prescribe the calculation horizon for the outdoor reference temperature and provide a guideline for the selection of the climatologically appropriate α-value(s). This will minimize the subjective influence of the analyst who might, for example, cherry-pick the input parameters of the adaptive comfort model to artificially “solve” an overheating or overcooling problem in the design or operation of a building, but in so doing, exacerbate the thermal discomfort endured by the building’s occupants.

7 Acknowledgements

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