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The Comfort and Energy Impact of Overcooled Buildings in Warm Climates

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Around 18% of global carbon emissions can be attributed to building heating or cooling, driven by the adoption of “international” thermal comfort standards such as ASHRAE-55, which imply an homogenous indoor environment. We argue that the importation of such standards to warm climates results in indoor cold discomfort due to “overcooling”: a phenomenon anecdotally recognised worldwide but not studied or defined systematically. Unlike under- or over-heating, overcooling is the purposeful over-expenditure of energy, that creates conditions of cold thermal discomfort. We examine data for warm and temperate climates from a global thermal comfort database spanning 27 countries with over 90,000 occupant responses to investigate overcooling of air-conditioned buildings. We suggest that overcooling is best defined by taking the intersection of thermal sensation and preference and, using this definition, we find that 17% of building occupants in the examined data can be classed as being overcooled. We estimate the cooling energy demand of overcooling imposed through the adoption of the ASHRAE-55 standard using computer simulations that move building occupants from being overcooled to comfortable. The results suggest around 15% of cooling energy demand could be saved through a simple upward adjustment of set-point temperatures by 2°C in warm climates. Such an adjustment in the Global South, which contains the majority of the warm regions of the Earth, could have a dramatic impact on the evolution of future cooling energy demand which is expected to triple by 2050.

Keywords: Building Energy; Thermal Comfort; Building Overcooling; Cold Thermal Discomfort; Warm and Hot Climates.

1 Introduction

Currently, around half of the global population resides within buildings which account for 30% of global energy consumption and 28% of emissions [1]. Space cooling is a significant energy end-use within buildings, responsible for roughly 20% of the energy consumed in buildings globally, and 8% as the share of cooling in total energy demand carbon emissions [2]. Within warmer climates, space cooling is not only the largest building energy end use but is also the fastest growing [2]. The majority of built environment growth will occur in warmer climates and hence the annual global energy consumption for space cooling is projected to triple from about 2,000 TWh currently to 6,000 TWh by 2050 [2].

It is remarkable that a proportion of this projected growth in cooling energy demand is being driven not by a growth in the overall installations of air-conditioning, and hence a general increase in comfort for greater parts of the populations in warm regions of the world, but through the unnecessary expenditure of energy, or “overcooling”, that produces uncomfortably cool thermal conditions. Accounts for overcooling span diverse settings such as office buildings [3], shopping malls [4], and institutional buildings [5]. Instances of overcooling were hinted at within the thermal comfort literature as far back as 1991 [6–9]. This literature tends to refer to “overcooling” as excess active cooling of a space, however, the extent to which overcooling is defined and quantified, in terms of thermal comfort has not been systematically studied.

Unmanaged overcooling will lead not only to significant unnecessary energy consumption within a rapidly expanding building stock, resulting in increased cooling energy demand and carbon emissions, but also persistent occupant discomfort leading to negative health effects. In this paper, we investigate the extent of overcooling research in the literature and explore thermal comfort standards and practices to establish a definition of overcooling within the built environment, presently unavailable in the literature. We evaluate data from the ASHRAE Thermal Comfort Database II (ATCD-II), spanning 27 countries with over 90,000 occupant responses against this definition to determine the frequency of overcooling and the deviation from suggested comfort temperatures within warmer climates. The energy implications of this overcooling are then considered for current and possible future climates.

2 Background

2.1 Overcooling research

Complaints of feeling too cold in buildings have become a common modern occurrence across the globe [10–14]. This phenomenon of excessive cooling within the built environment has taken on the term of overcooling. We conduct a literature review of this topic by undertaking a systematic search for the term "overcooling" independently as well as in combination with "buildings", "built environment", "building performance", and "thermal comfort". While a total of 209 papers referring to overcooling were found, only about half (106) pertain to overcooling in relation to buildings and thermal comfort. Of these, 79 consider the issue in-depth (i.e. overcooling is considered within the results and/or discussion sections) and are hence summarised in Table S 1 of the supplementary material. It is noteworthy that 46% of these papers have been published in the last five years, indicating the increasing interest in the topic.

Interestingly, overcooling has also attracted media attention with anecdotal reports from a range of buildings such as offices and shopping centres [3–5]. Here, terms such as "summer freeze" and "freezing" are common, and identify the shared common experience of overcooled spaces in enclosed public buildings of being "too cold" inside, while it is "nice and warm" outside [3–5]. In East Asia, the term "air-conditioningitis" has also been coined to describe the negative health effects arising from the large differences indoor and outdoor temperatures caused by low setpoints in air-conditioned buildings [15]. The sensation of being overcooled has driven occupants to resort to a series of fundamentally unsustainable strategies: opening windows to dump the coolth and admit the very heat that the cooling system was designed to reject, increasing clothing layers during the hot season, and in some instances simply avoiding overcooled spaces in an effort to stay thermally comfortable.

2.2 Definitions of overcooling

Our review of the studies in Table S 1 suggests that the approaches to defining or explaining overcooling in the literature fall into the following three categories, presented in approximate order of the frequency of use:

- Occupant feedback: the most common means of measuring or defining overcooling is by surveying building occupants using a range of thermal comfort metrics (a total of 28 studies out of 79, i.e., 35%). These include: the thermal sensation vote (TSV), seen in 27 studies out of 79 (34%), the Thermal Preference Vote (TPV) in 13 studies out of 79 (16%), the Thermal Acceptance Vote (TAV), seen in 11 studies out of 79 (13%), and the Thermal Comfort Vote (TCV) seen in 6 studies out of 79 (7%) – many studies using more than one. However, as the TAV and TCV indicate occupant acceptance or comfort of a space with no indication of whether the vote is a result of being cold or hot, neither can be considered an effective indicator of overcooling. The TSV is a metric that indicates the occupant's thermal sensation based upon their direct feedback on a seven-point thermal scale ranging from “cold” (-3) via “neutral” (0) to “hot” (+3). On this scale, comfort is usually defined between [-1,+1] in the literature, and an average or individual vote below -1 is considered overcooled [11,16–20]. In studies that use this definition, between 20% to 50% of the observed votes are classified as overcooled [12,16–18,21]. The TPV indicates whether an occupant would like to move towards a warmer or colder thermal environment and is measured on an n-point preference scale indicating a vote of warmer, no change, or cooler, where $n \in \{3, 5, 7\}$. Where the scale is composed of only 3-points [6,19,21,22], the options are simply “cooler”, “no change”, or “warmer”. On 5-point scales [23–27] or 7-point scales [28–30], degrees of preference are introduced using terms such as “slightly”, “more”, and “much more” on either side of “no change”. On such scales, preference votes for warmer conditions in summer would indicate the existence of overcooling.

As a function of air temperature: 25 out of 79 papers (31%) in

- Table S 1 define overcooling as occurring, when the air temperature falls below a predetermined criteria [31–36], usually the setpoint temperature [8,33,37,38]. In addition to single temperature points and temperature ranges, three papers specify degree-time interval metrics such as overcooling degree days which compare designed comfortable air temperatures, including seasonal air temperatures ranges and humidity, with external air temperatures to indicate overcooling [13,38–46].

- Model predictions: during the design stages where occupant feedback is unavailable, thermal comfort metrics such as Predicted Mean Vote (PMV) can be used to assess overcooling risk in much the same way as TSV is used above [39–42,47]. In Table S 1, 22 studies out of 79 (27%) use model predictions to identify overcooling. In such cases, overcooling is described as a PMV below -0.5 since the PMV model usually defines thermally comfortable votes to occur between [-0.5, +0.5] for most building types such as offices [47–49]. The PMV as a model falls under the so-called “steady state” thermal comfort model. Although it is considered to be universally applicable, research in several field studies have suggested that the so-called “adaptive” thermal comfort models better describes thermal comfort in naturally ventilated buildings, and hence restricting the use of PMV to mechanically conditioned buildings. While cold discomfort is certainly possible to measure in naturally ventilated buildings, and may even be present, this would, by definition, not imply an unnecessary expenditure of energy [50–52]. Hence there is little to no reference to cold discomfort from the use of the adaptive models in the literature.

It is pertinent to observe that an internationally standardized idea of thermal comfort has not been proven to universally work across climates and cultures [26,53–58]. This is the reason, for example, that India has chosen to define its own standard rather than co-opt the ASHRAE or European standards. Hence, if we define thermal comfort as the mindful expression of satisfaction with the thermal environment specific to a culture and/or climate, overcooling can be expressed as the cold dissatisfaction with that thermal environment with a similar specificity. Therefore, assessing cold discomfort for a population as a direct factor of their responses is the basis for defining overcooling considered here.

2.3 Definitions of overheating versus overcooling

Since thermal comfort is commonly defined as a mindful expression of one’s satisfaction with the thermal environment [41], deviations from thermal comfort occurring due to either a warm or cold thermal response from occupants would be classified as either overheating or overcooling. Although no single *agreed* definition of overheating exists, the metrics are clearly codified in the literature for temperate climates. It is hence instructive to observe the approach taken for overheating when considering overcooling.

Prevalent definitions of overheating, such as those in CIBSE TM52 and CIBSE TM59, quantify these deviations using various metrics of temperature exceedance. These are (i) the *hours of exceedance*, which defines the acceptable percentage of hours above a defined maximum temperature (ii) the *daily weighted exceedance,* which measures the severity of overheating within any one day and (iii) an *upper limit temperature*, which provides an absolute maximum daily temperature that may not be breached [59,60]. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard 55 recommends $-0.5 < \text{PMV} < +0.5$ and a PMV above this range would be considered overheating [61]. Other definitions are often simpler, such as those used by the Passivhaus standard, which requires no more than 10% of the occupied year over 25°C [62]. Temperature based metrics work well for overheating due to the highly dynamic response of indoor conditions to a changing outdoor environment, which occurs in free-running mode, i.e., in the absence of mechanical control. A significant limitation to a temperature-based approach within these standards is that they assume these temperatures are comfortable to start with as they have been derived from years of studies conducted in cooler climates, i.e., North America and Europe.

However, the problem of overcooling can be bifurcated according to whether (a) the undesirable coolth is the result of the building reacting to changing external conditions (e.g., naturally ventilated buildings in winter) and hence dynamically changing, or (b) the result of purposefully set indoor set-points, derived from thermal comfort standards and delivered through mechanical control. It is primarily the latter with which we concern ourselves in this paper. Hence, the definition of this type of overcooling must be approached directly from the standpoint of thermal comfort. However, if indoor conditions are the outcome of the application of an agreed thermal comfort standard such as the International Organization for Standardization (ISO) 7730 [39], ASHRAE Standard 55 [41], or the European Standard (EN) 16798-1:2019 [63], then why does overcooling occur and how can we understand it? What are the energy and implications of overcooling? What can we do about it? These are questions we aim to address in this paper.

3 Methods

As our goal is to identify the extent of overcooling in the warm season (i.e. summer), particularly in warm climates, we first require an analysis of field thermal comfort data. From this, we aim to initially identify and then codify overcooling. Our second goal is to obtain an estimate of the energy cost of building overcooling, through simulating what might happen if we moved occupants towards occupant derived comfort temperatures that would minimise overcooling. Both approaches are discussed in detail below.

3.1 Source data

The ATCD-II is the largest quality-tested repository of thermal comfort field data available under the Open Database License. ATCD-II is a collection of thermal comfort studies spanning the last 30 years with over 90,000 building occupant responses from 92 different cities across 27 countries, comprising both air-conditioned and naturally ventilated building types. Filtering for air-conditioned buildings results in 30,018 building occupant responses from 42 cities across 17 countries [64]. We further filtered records to include the TSV and TPV as the predominant subjective thermal comfort metrics while recording all six standard indices of thermal comfort, i.e., air temperature (T_a), mean radiant temperature

(T_r), air velocity (A_v), relative humidity (Rh), clothing insulation value (Clo) and metabolic rate (Met). Studies which have small sample sizes (i.e., fewer than 30 occupants) are disregarded leaving 22,119 records for analysis summarized in Table S 2. Table S 2 shows our analysis data grouped by cities, season, and climate zone using the Köppen-Geiger climate classification [65]. To undertake seasonal analysis, which is useful to provide a benchmark for any summertime overcooling by comparing against winter conditions for the same location, hot and cold thermal discomfort distributions are calculated for the summer (i.e., with the potential for cooling demand) and winter (no cooling demand) seasons, for each group of data. In the northern hemisphere, we take summers as May through August and winters as December through February, and the opposite in the southern hemisphere. The summer and winter seasons identify the active cooling season and the no cooling season respectively.

An interesting feature of the data in Table S 2 is that only 17% of the cities and 12% of the studies represent regions of the Global South (i.e., Bangalore, Bangkok, Chennai, Delhi, Hyderabad, and Makati). These proportions would be much smaller if all studies in non-warm regions were included. Given that the greatest future expansion in global built footprint is expected in the Global South – it is expected to add an estimated 75% of the current global built floor space by 2050 [66] – there would seem to be an urgent need for more studies from this region being included in the database. Hence, an indicative list of thermal comfort field studies conducted in air-conditioned buildings in warm climates to 2020 which have not been included in the ATCD-II are summarised in Table S 3.

3.2 Evaluating thermal discomfort

We now turn to the question of how purposeful overcooling is best measured. Of the methods used in the literature (see Section 0), PMV would seem to be least suited given that it is the outcome of a calculation process which uses assumptions about occupant comfort the application of which, in itself, could cause overcooling. Temperature too, is likely to be inconclusive due to the fact that building occupants may perceive comfort at different temperatures even within the relatively uniform conditions of air-conditioned buildings, due to differences in expectation, which may be driven by socio-cultural factors. Indeed, this is now well-recognised in naturally ventilated buildings through the adaptive thermal comfort model where the upper-limit of acceptability in a cold season or climate could be equivalent to the lower limit of acceptability in a warm season or climate in conditions with regular humidity [67–71].

It might seem obvious that either TSV or TPV might be ideal candidates for determining the true state of overcooling. However, alone, neither can be taken as a perfect measure given that of the votes in the ATCD-II with TSV < -1, 17.8% are not accompanied by a TPV indicating the desire for warmer conditions. Likewise, 24.5% of the votes in the database with TPV indicating warmer are not accompanied by TSV < -1 (see **Error! Reference source not found.**). In other words, not all votes indicating a sensation of coolth are accompanied by a preference for warmer conditions, and not all subjects preferring warmer conditions said they were experiencing a feeling of cold discomfort. These inconsistencies suggest that taking either metric on its own is likely to result in an inflated estimate of overcooling. Hence, the safest course would be to define the set of overcooled subjects in buildings (O) as those meeting both conditions. In set-theoretic notation:

$$O = \{(TSV, TPV): TSV < -1, TPV > 1\}$$

Within the filtered ATCD-II, while the majority of TSV data were collected on an ordinal scale, a minority are on an interval scale (14.5% of the database). In this paper, to resolve the disparity in the two TSV scales employed, TSV data on an interval scale were binned to translate votes to the equivalent ordinal scale.

It is notable that TPV in the ATCD-II occurs on a three-point preference scale which represents an equal magnitude between extreme votes on either side of the scale (i.e. the magnitude of -1 = +1). The TSV in the ATCD-II occurs on a seven-point thermal scale, the magnitude of the vote depends on its location on the seven-point thermal scale (i.e. the magnitude of -3≉-1). A cold vote (-3) on a seven-point thermal scale represents a cold thermal sensation that is three times the magnitude of a slightly cool vote (-1). To understand the magnitude of discomfort votes the number of votes against each ordinal point on the TSV scale are weighted as follows: $3 \times n_{TSV=-3}$; $2 \times n_{TSV=-2}$; $1 \times n_{TSV=-1}$; $1 \times n_{TSV=0}$; and similarly for the positive votes.

The TSV classifications are accounted with their weighted magnitudes are classed as either a *cold discomfort* (TSV [-3, -1)), *neutral* (TSV [-1, +1]), or *hot discomfort* (TSV (+1, +3]). We consider the vote of the occupant to indicate *cold discomfort* when the TPV selected by the occupant is “warmer” (out of the three possible options of “cooler”, “no change”, or “warmer”). The opposite is considered for hot discomfort.

Thus, aligned votes (e.g., TSV *cold discomfort* and TPV *cold discomfort*) are combined to represent cold discomfort, neutral comfort, and hot discomfort cases based upon the previous criteria. The cold discomfort percentage (CD) is calculated by normalising against all cases for each study and vice versa for the hot discomfort percentage (HD). Comparing the hot and cold discomfort percentages of each study illustrates the discomfort type and intensities which allows for identifying overcooling. This is important because, in every study, a proportion of votes will fall into both the HD and CD categories. Hence, if overcooling is determined based purely on CD, this will distort the true picture of occupant experience as it is possible that a greater proportion of votes are classed as HD at the same time. Hence, it is only counting cases where CD exceeds HD can we be reliably sure of the presence of overcooling. Naturally, this must be taken alongside information on outdoor temperatures as it is possible CD exceeds HD when outdoor conditions were cool.

3.3 Quantifying the impact of overcooling on building energy

We aim to establish the difference in building cooling energy demand between the observed (i.e. actual) and comfortable (i.e. desired) conditions for the selected studies. To do this, we use dynamic thermal simulations using both the observed temperature setpoints and comfort temperature setpoints for the selected studies in their respective climates to assess cooling energy demand for each study.

Observed temperature setpoints are readily derived from the recorded air temperatures in the ATCD-II. The comfort temperature is derived using the Griffith’s method, which has been employed in several studies in the literature [26,55,72–81]. The calculation is associated with a regression coefficient called the Griffiths constant (G) that is derived from thermal comfort studies in field and laboratory settings [74].

The Griffiths method is utilized here using equation (1) [73,82].

$$T_c = T_r + (0 - TSV)/G \tag{1}$$

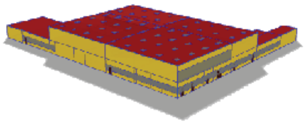
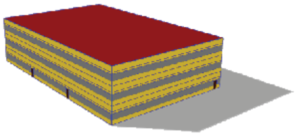
Where T_c (°C) is the comfort temperature and T_r (°C) the indoor globe temperature. There is disagreement in the literature on the most appropriate value for G. Table 1 contains a list of all common values for G derived in the literature, separated by those for warm climates (i.e. Köppen Aw, and Bwh) and other climates. In the literature, overall, the most commonly suggested values for $G \in \{0.25, 0.33, 0.5\}$ [83–87]. Laboratory derived values such as G=0.33 derived by Fanger [47] were initially disputed as they lack support from field studies [74]. An extensive inspection of field studies in the ASHRAE database suggested G=0.5 as suitable [70], and this has been adopted by other studies [70,74,88–92]. However, in the warmer climates of Pakistan [81,89] and India [80,93], $G \in \{0.25, 0.31, 0.33\}$ have been suggested. For this study, we examine the values for G from the literature in Table 1 and consider the weighted average. The Griffiths coefficient is evaluated for all air-conditioned buildings and weighted by the number of occupants (n) where available, and is not accounted otherwise. This results in 0.32 as it is the weighted mean G value for warm climates in Table 1.

Table 1 Derived Griffiths Constant Values from Thermal Comfort Field Studies

Location	n	Year	Climate	Season	Building Ventilation	G	Source
Pakistan	-	1994	Bwh	All	Mechanical	0.250	[74]
Pakistan	-	1994	Bwh	All	Mechanical	0.330	[74]
Hyderabad (India)	100	2008	Aw	Summer + Monsoon	NV	0.310	[73]
Hyderabad (India)	128	2008	Aw	Summer + Monsoon	NV	0.310	[67]
Chandigarh/Roorkee (India)	71	2012	Csa/Cfa	All	NV	0.210	[72]
Shiraz (Iran)	832	2013	Bsh	Summer + Autumn	NV	0.230	[71]
Doha (Qatar)	828	2016	Bwh	Summer	AC	0.389	[26]
Seville (Spain)	891	2016	Csa	All	MM/AC	0.172	[70]
Doha (Qatar)	1174	2017	Bwh	All	AC	0.390	[69]
ASHRAE RP884	-	Multiple	All	All	Multiple	0.508	[66]
IMAC India Database	1849	Multiple	Multiple	All	Multiple	0.250	[67]
Smart Controls and Thermal Comfort (SCAT) Database	-	Multiple	All	All	Multiple	0.513	[66]
Arithmetic Mean AC Buildings						0.306	
Arithmetic Mean All Buildings						0.288	
Weighted Mean AC Buildings						0.322	
Weighted Mean All Buildings						0.300	

We use the well-known EnergyPlus dynamic thermal simulation engine [94] to estimate the impact on cooling energy demand between the use of observed (i.e. standards recommended) and calculated comfort setpoint temperatures. As our goal is to obtain an estimate of the scale of the difference in demand, it would be convenient to use notional building thermal models that can be consistently replicated in different climates, rather than real buildings. The ANSI (American National Standards Institute)/ASHRAE/IES (Illuminating Engineering Society) Standard 90.1 provides such convenient thermal models that have been pre-calibrated and successfully used in similar comparative simulation studies [94,95]. We choose the appropriate prototype building model based upon it having a similar function and building size of the studies that indicate overcooling in Table S 2. The selected studies, i.e. those demonstrating overcooling as per our definition, fall into two categories: medium office and secondary school. The initial simulations consider the observed and comfort setpoint temperatures for each study indicating overcooling in their respective climates. **Error! Not a valid bookmark self-reference.** shows the key characteristics of the chosen models. In all our simulations, we use a setback offset temperature of +2 °C outside building occupancy hours, as recommended by ASHRAE 90.1-2004 [95,96].

Table 2 Summary Description of the ANSI/ASHRAE/IES Standard 90.1 Prototype Building Models.

Building Element	Source	Specification		Sampling
		Secondary School	Medium Office	
Illustration				
Floor Area (m2)	EIA 2005	19,592	4,982	-
Floor to Ceiling Height (m)	EIA 2005	3.96	2.74	-
Floors	EIA 2005	2	3	-
Cooling and Air Distribution System	ASHRAE 90.1-2004	Air cooled chiller unit multizone VAV	Packaged AC unit multizone VAV	-
Cooling System Sizing	ASHRAE 90.1-2004	Auto sized to design day		-
Setpoint Temperatures	ASHRAE 90.1-2004	Cooling only, variable per simulation		-
Setback Temperatures	ASHRAE 90.1-2004	Cooling only, non-occupied hours 2°C increase from setpoint		-
Outside Air Requirement	ASHRAE 1999	Classrooms 7.08 l/s/person	9.44 l/s/person	-
Occupancy	ASHRAE 2004b/ Pless et al. 2007	Classroom 4 m^2/person	18.6 m^2/person	-
Façade Glazing Ratio (FGR)	EIA 2005	0.33	0.33	0.20 - 0.95
Building Base Obstruction Angle	-	0	0	20º - 80º
Heat Loss Parameter (HLP)	ASHRAE 90.1-2004	Code minimum	Code minimum	Code min.-Passivhaus

Additionally, comparison simulations of altered building elements being façade glazing ratio, heat loss parameter, and obstructions are evaluated through varying building temperature setpoints reflecting the observed and comfort temperature setpoints of the energy model which resembles the average from the initial simulations. Further, given a changing climate, we also estimate the impact of future climates on the difference in cooling energy demand between observed and comfort setpoints. Future weather data for building simulation was created using the CCWorldWeatherGen tool [97], which uses the morphing technique to produce weather data in EnergyPlus (.epw) format for a given location into a 2050 equivalent. Future data is derived from the Hadley Centre Coupled Model version 3 (HadCM3) using the Special Report on Emissions Scenarios (SRES) “medium high”(A2) emissions experiment which yields the necessary parameters for the morphing calculations depicting emissions for “business as usual” development [97,98]. The morphing process requires certain variables to alter building simulation weather data files. Here we use data from the Intergovernmental Panel on Climate Change (IPCC) Third

Assessment Report (AR3) as publicly available data from the more recent reports lack the required variables to conduct the morphing calculations. Using publicly available current weather files from several governmental meteorological repositories, future weather files for all locations that indicate overcooling in Table S 2 are established. Comparisons between simulations of the alteration in building elements and future weather are conducted to assess the initial simulation results in real world building conditions. Varying the major contextual building elements such as façade glazing ratio, heat loss parameter, and obstructions illustrate the effect that appropriate cooling setpoints would have on a range of buildings in varying contextual settings both in current and future warmer climates.

The alteration of the three variables for the simulation is based upon random sampling of a domain of 100 simulation cases for each variable. The façade glazing ratio (FGR), heat loss parameter (HLP), and obstructions values were randomly sampled using Latin Hypercube Sampling (LHS) method in this study [99–102]. LHS is deployed in simulation studies for sampling of uncertainty and sensitivity as it produces balanced random sampling of selected variables in the analysis [99–102]. The façade glazing ratio is sampled through a minimum glazing level which provides sufficient daylighting to a maximum of a full glazed building with the façade glazing ratio between of 0.20 to 0.95 for this study [103–105]. The heat loss parameter is evaluated through the building fabric and ventilation loss which is sampled between ASHRAE 90.1-2004 code minimum building fabric and ventilation loss values [106] and best case practices as those values prescribed by Passivhaus design guidelines [107]. Building obstructions in the ANSI/ASHRAE/IES Standard 90.1 prototype models in practice do not exist [106]. For this comparison study Building Obstruction Angles (BOA) are sampled from the base of the simulated building between 20° to 80°, treating each building elevation equally.

4 Results

4.1 Thermal comfort metric assessment

The combined TSV and TPV votes averages for each study in the ATCD-II are plotted according to binned indoor operative temperature (Figure 1). This plot illustrates the pattern of occupant TSV and TPV votes in the entirety of the database (Figure 1). In our combined thermal sensation and preference votes analysis, we observe, as expected, an increased clustering of cold discomfort votes in cooler indoor temperatures, increased clustering of hot discomfort votes in warmer indoor temperatures, and a clustering within a comfortable vote range for both the TSV and TPV when indoor temperatures are between 22°C and 25°C (Figure 1). This analysis supports the use of the combined metric as it illustrates the association of the combined TSV and TPV with expected discomfort voting in varying indoor temperatures. In addition, this metric represents how discomfort is evaluated ignoring contradicting votes only considering comparable TSV and TPV vote to evaluate hot thermal discomfort (HD) and cold thermal discomfort (CD).

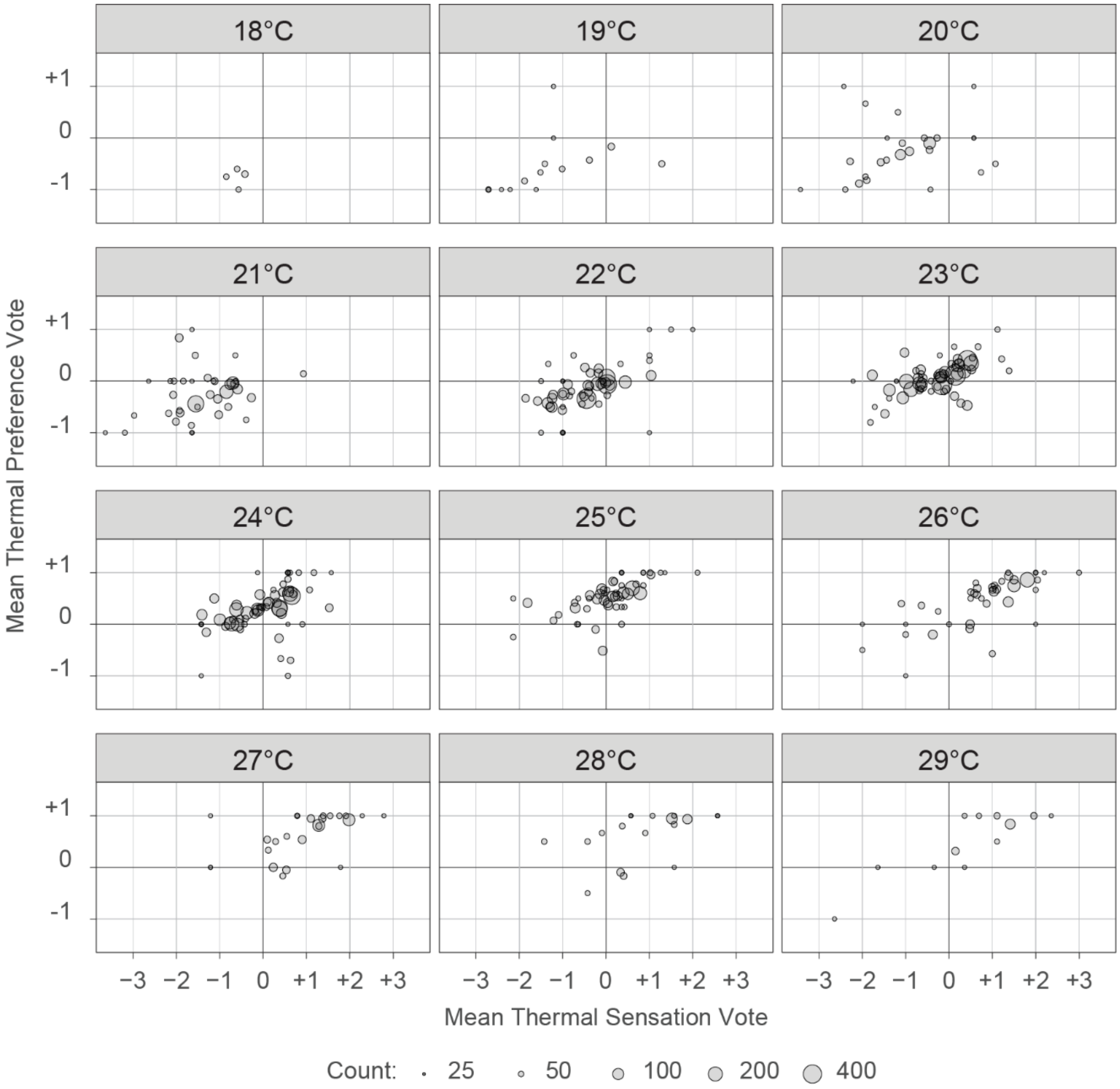
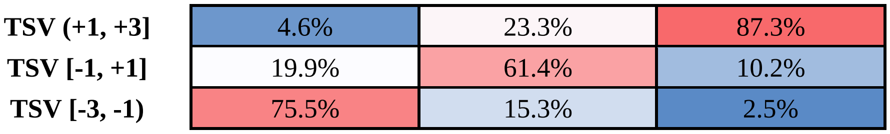


Figure 1 Scatter plot of mean TSV against mean TPV for each study, using data from the ASHRAE Thermal Comfort Database II filtered per Table S 2. Each panel contains data grouped by indoor operative temperature, and the size of the circle represents the sample size of the study. TSV ranges between -3 (cold) to +3 (hot) and TPV ranges between -1 (prefer warmer) to +1 (prefer cooler).

Figure 2 shows the result of the vote alignment percentage analysis conducted on thermal comfort parameters in the ATCD-II, based on our review of existing methods in Section 0. Taking TSV cold (TSV [-3, -1)), neutral (TSV [-1, +1]), and hot (TSV (+1, +3]) and comparing the votes in each TPV of cooler, no change, and warmer as indicators of an occupant's thermal state towards to the environment. In the analysis we observe the greatest indicator of discomfort is the combination of aligned TSV and TPV classifications (e.g., TSV of "cold" and TPV of "warmer", TSV of "neutral" and TPV of "no change", and TSV of "hot" and TPV of "cooler").

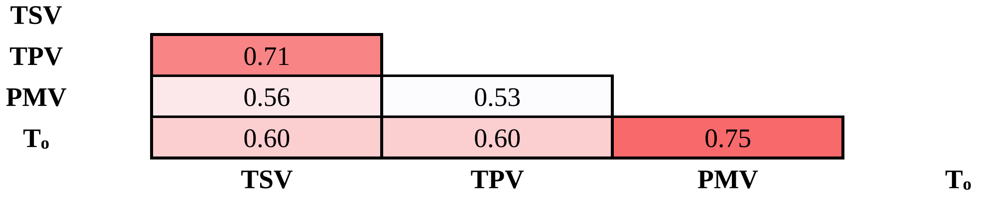


TSV (+1, +3]	4.6%	23.3%	87.3%
TSV [-1, +1]	19.9%	61.4%	10.2%
TSV [-3, -1)	75.5%	15.3%	2.5%

TPV = Warmer **TPV = No Change** **TPV = Cooler**

Figure 2 Vote alignment percentage analysis for thermal comfort parameters in the ATCD-II. Rows shows TSV grouped as cold (TSV [-3, -1)), neutral (TSV [-1, +1]), and hot (TSV (+1, +3]). Columns show TPV of cooler, no change, and warmer. Colours indicate the alignment of the TSV and TPV from extremely aligned (red) to neutral (white) through not aligned (blue), and colour saturation shows the strength of the relationship.

Figure 3 illustrates the correlation analysis conducted for TSV and TPV from a maximum correlation (+1) to a minimum correlation (-1). We observe similar high correlation for both the TSV and TPV as found in the PMV which is used as the ideal method for thermal comfort assessment in thermal comfort standards. The variation between the TSV and TPV differs by 7.5% from the PMV in alignment to T_o from the range (-1 to +1) in Figure 3. This suggests that TSV and TPV are as equipped as the PMV to establish cold thermal discomfort.



	TSV	TPV	PMV	T_o
TSV				
TPV	0.71			
PMV	0.56	0.53		
T_o	0.60	0.60	0.75	

Figure 3 Correlation matrix for the TSV, TPV, PMV, and T_o. The x and y axis presents the various metrics and the operative temperature. Colours indicate the type of correlation, from positive (red) to neutral (white) through to negative (blue), and colour saturation shows the strength of the relationship which occurs on a correlation scale from -1 to +1.

4.2 Thermal discomfort evaluation

The grouped thermal comfort studies account for a total of seventy-two studies in nine different climates conducted over a period of thirty years is shown in Table S 4. Roughly 90% of the extracted thermal comfort data from the ATCD-II in Table S 4 are collected from offices, ~8% from classrooms, and ~2% from other spaces. Much of the data are collected within the summer season (44%) followed by winter (38%), autumn (10%), and spring (8%). There is a disparity in the data in terms of the climate, within the different climate zones in the Köppen-Geiger classification, 17% of the data is collected within tropical climate group (A) Köppen-Geiger climate zone, 7% in an arid climate group (B), 66% in a temperate climate group (C), and 10% in a continental climate group (D). Comparing the warmer climate groups (A and B) to the cooler climate groups (C and D), 24% of the data is in warmer climates compared to the 76% in cooler climates.

Evaluating both the hot thermal discomfort (HD) and cold thermal discomfort (CD) percentages identifies studies which indicate possible overcooling. Studies that represent negative value for (HD-CD) contain a majority of occupants which are voting with a cold sensation (TSV [-3, -1)) and a preference to be warmer indicating cold discomfort which is illustrated in Table S 4 for the ATCD-II.

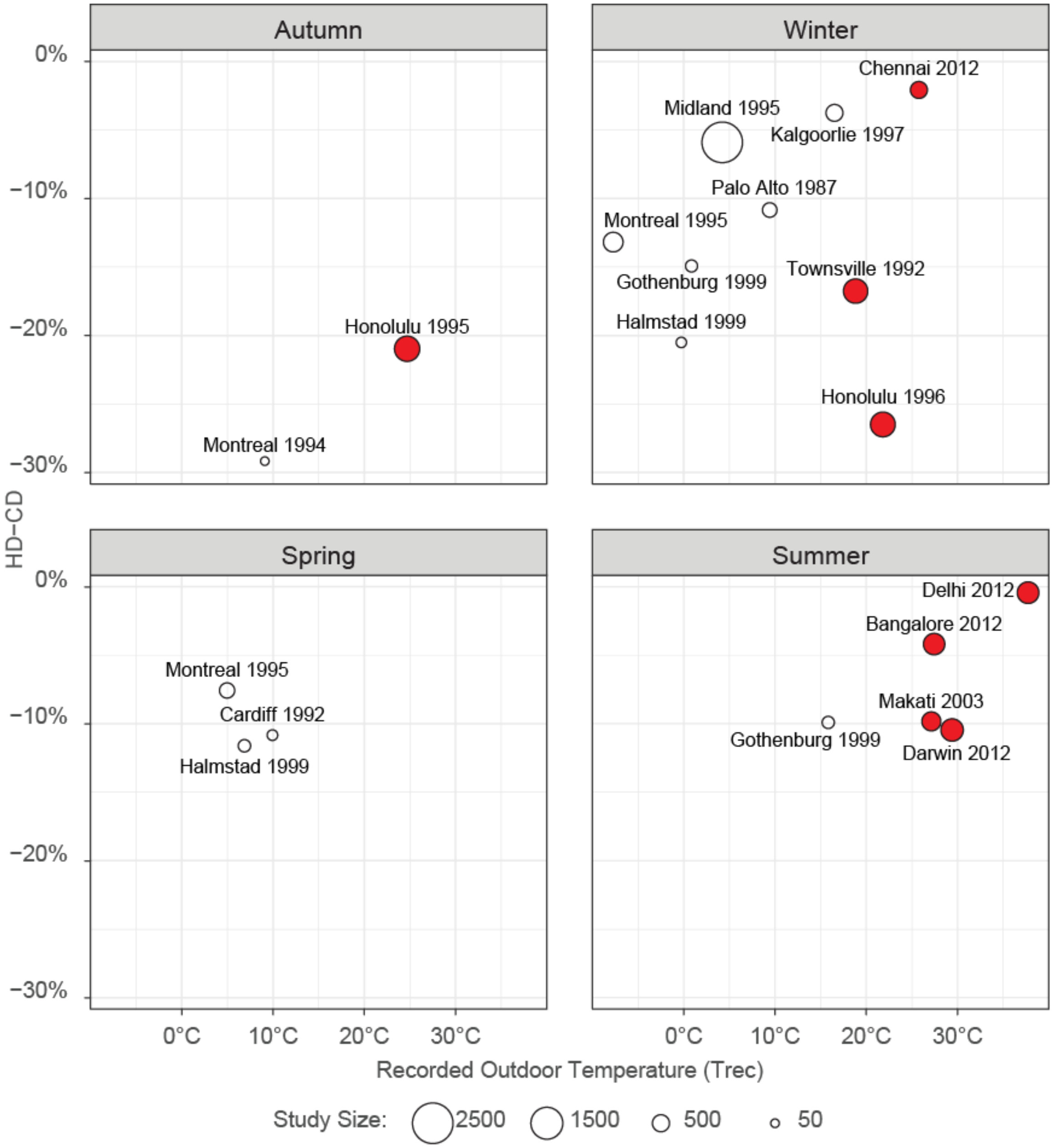
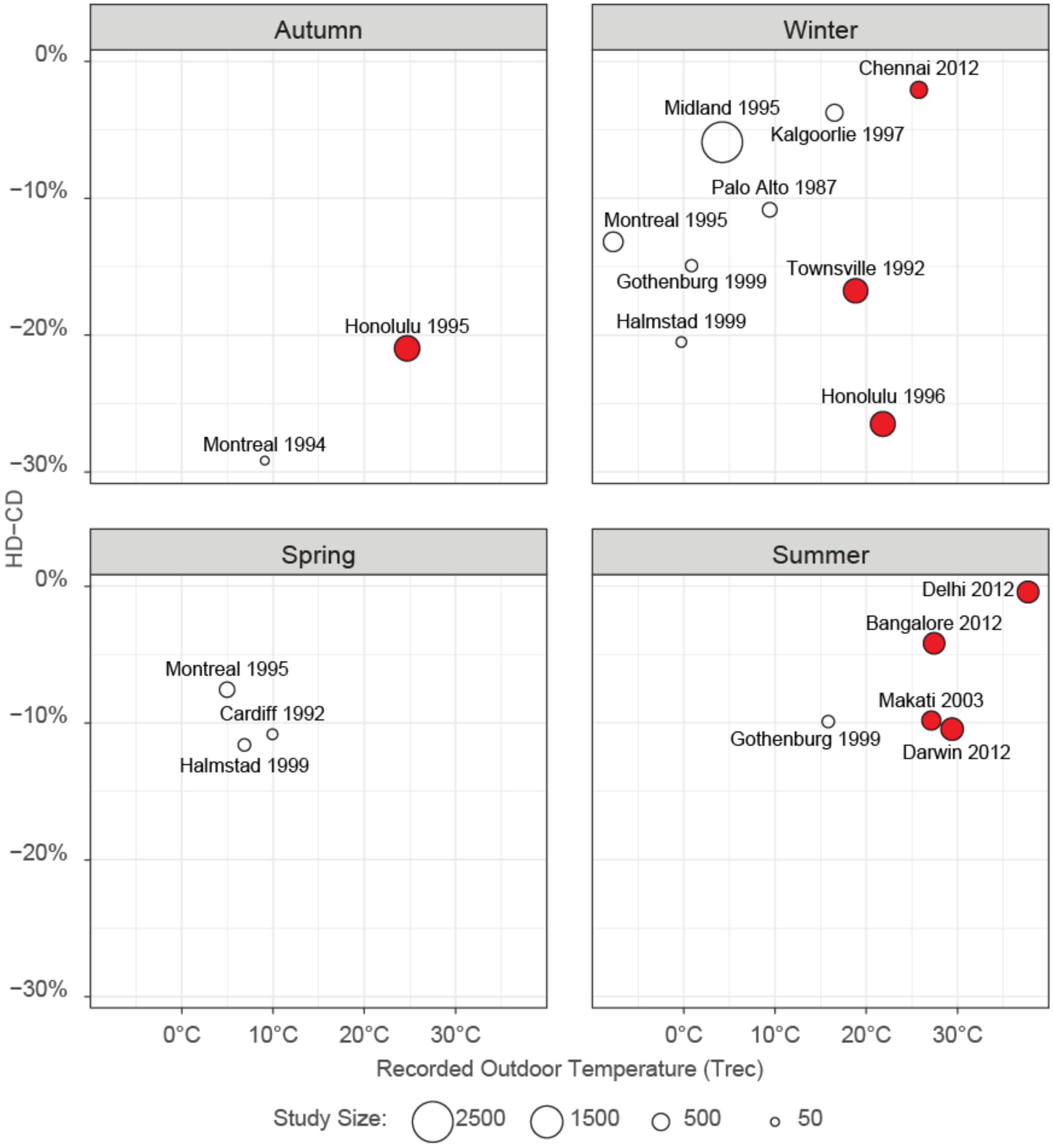
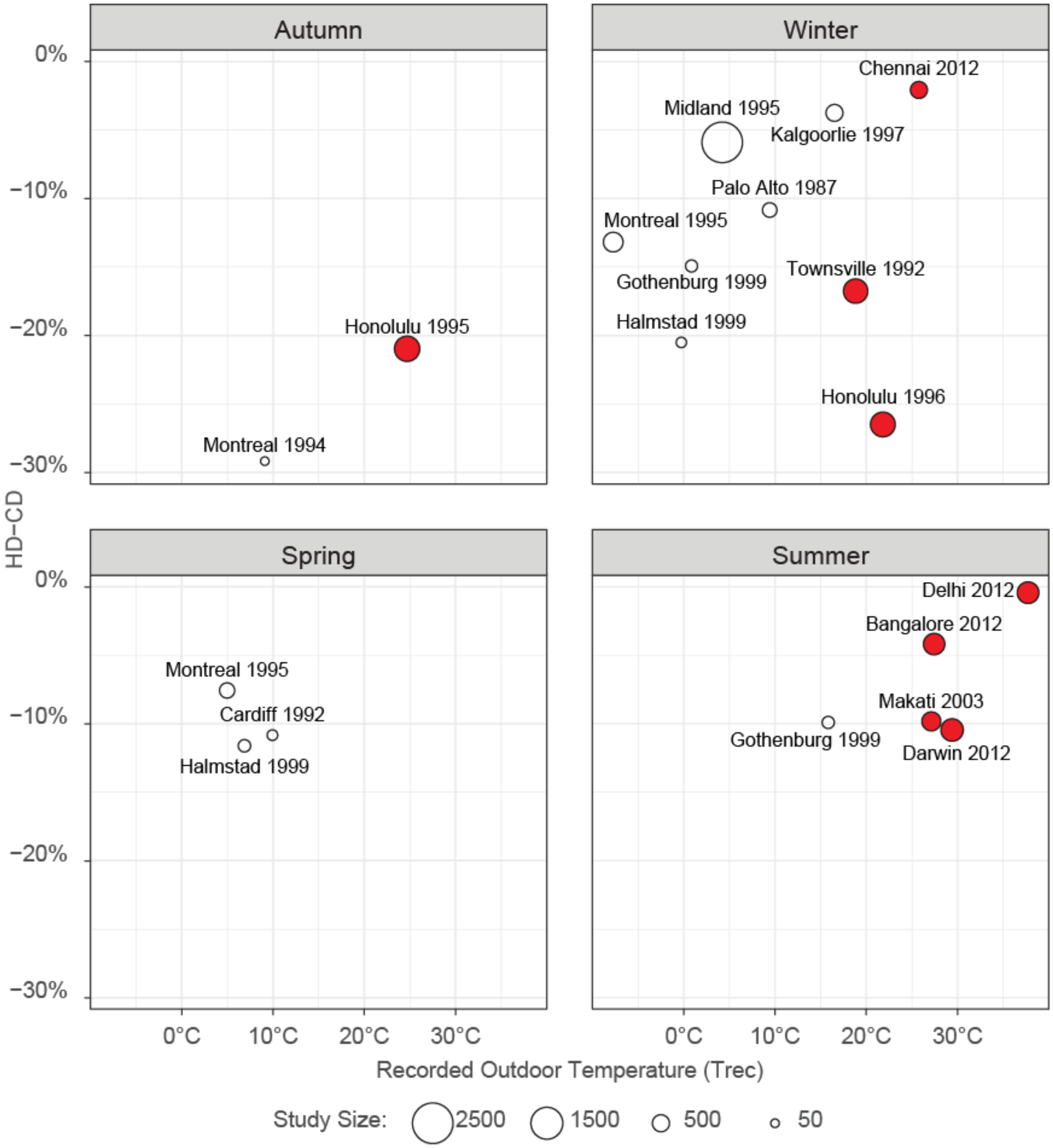


Figure 4 A seasonal cold thermal discomfort analysis of filtered ATCD-II studies illustrating the difference between hot discomfort and cold discomfort against recorded outdoor temperatures (T_{rec}). Studies where HD-CD < 0 and T_{rec} > 18°C are highlighted as studies that have a greater discomfort due to cold indoor conditions.

Out of the 72 studies in Table S 4, 23 indicate a greater cold discomfort percentage in contrast to the hot discomfort percentage which are summarized by their discomfort and corresponding recorded outdoor temperatures in Evaluating both the hot thermal discomfort (HD) and cold thermal discomfort (CD) percentages identifies studies which indicate possible overcooling. Studies that represent negative value for (HD-CD) contain a majority of occupants which are voting with a cold sensation (TSV [-3, -1)) and a preference to be warmer indicating cold discomfort which is illustrated in Table S 4 for the ATCD-II.



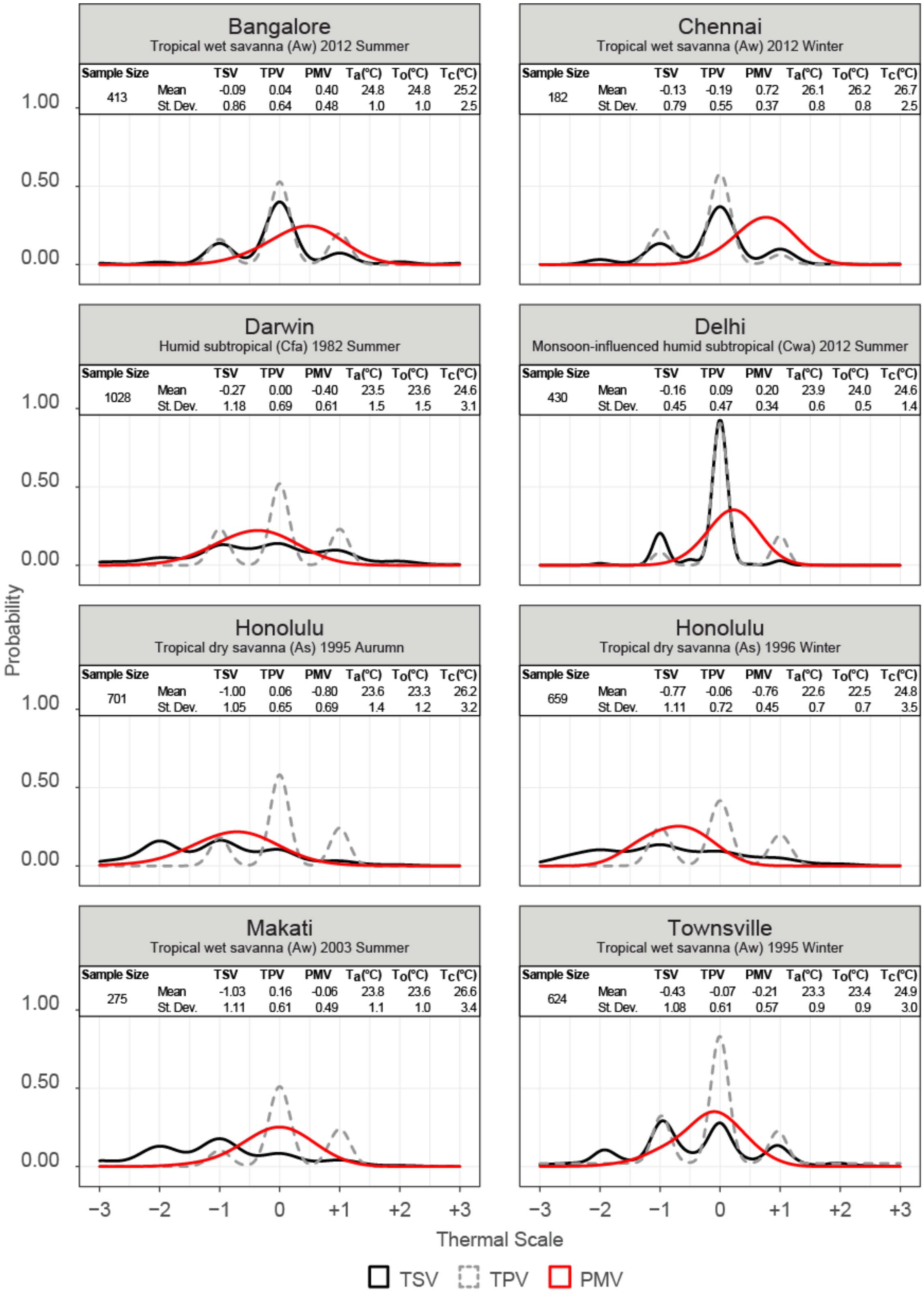
. The outdoor air temperature for each study location is collected from the original journal publications in instances where it is available, from the National Oceanic and Atmospheric Administration and National Centers for Environmental Information (NOAA NCEI) [108] for cities in North America and Europe, Australian Bureau of Meteorology (ABM) [109] for cities in Australia, and the Met Office [110] for cities in the United Kingdom, where temperature information was not available from the source publications. The outdoor air temperature is collected for both the air temperature of the location recorded during the study period (T_{rec}) and the historical average air temperature of the location (T_{his}). Studies with recorded outdoor air temperatures (T_{rec}) lower than 18°C are not indicating of overcooling as the outdoor air temperatures lower than 18°C do not usually necessitate any active cooling to maintain indoor thermal comfort (Evaluating both the hot thermal discomfort (HD) and cold thermal discomfort (CD) percentages identifies studies which indicate possible overcooling. Studies that represent negative value for (HD-CD) contain a majority of occupants which are voting with a cold sensation (TSV [-3, -1)) and a preference to be warmer indicating cold discomfort which is illustrated in Table S 4 for the ATCD-II.



), as it is often used as the base temperature for determining cooling degree days.

The studies in Bangalore, Chennai, Darwin, Delhi, Honolulu, Makati and Townsville all illustrate a higher cold discomfort percentage compared to the hot discomfort percentage for each study, respectively with an average CD-HD of 12.2%. Likewise, we observe a disparity in discomfort when examining data for female occupants at 15.5% CD-HD and 6.15% for male occupants (Table S 5). Cold discomfort is observed across all studies with the mean operative temperature at 23.83±1.04°C and does not vary across female (23.93±1.05°C) and male (23.96±1.05°C) responses (Table S 5).

In addition, all these studies have recorded an outdoor air temperature (T_{rec}) greater than 18°C which would categorize the excess in cooling from an active energy source, classifying them as overcooled. Within the overcooled studies, four of the eight studies that indicate higher cold thermal discomfort percentages occur during summer, i.e. the active cooling season.



Bangalore
Tropical wet savanna (Aw) 2012 Summer

Sample Size		TSV	TPV	PMV	T_a(°C)	T_o(°C)	T_c(°C)
413	Mean	-0.09	0.04	0.40	24.8	24.8	25.2
	St. Dev.	0.86	0.64	0.48	1.0	1.0	2.5

Chennai
Tropical wet savanna (Aw) 2012 Winter

Sample Size		TSV	TPV	PMV	T_a(°C)	T_o(°C)	T_c(°C)
182	Mean	-0.13	-0.19	0.72	26.1	26.2	26.7
	St. Dev.	0.79	0.55	0.37	0.8	0.8	2.5

Darwin
Humid subtropical (Cfa) 1982 Summer

Sample Size		TSV	TPV	PMV	T_a(°C)	T_o(°C)	T_c(°C)
1028	Mean	-0.27	0.00	-0.40	23.5	23.6	24.6
	St. Dev.	1.18	0.69	0.61	1.5	1.5	3.1

Delhi
Monsoon-influenced humid subtropical (Cwa) 2012 Summer

Sample Size		TSV	TPV	PMV	T_a(°C)	T_o(°C)	T_c(°C)
430	Mean	-0.16	0.09	0.20	23.9	24.0	24.6
	St. Dev.	0.45	0.47	0.34	0.6	0.5	1.4

Honolulu
Tropical dry savanna (As) 1995 Aurumn

Sample Size		TSV	TPV	PMV	T_a(°C)	T_o(°C)	T_c(°C)
701	Mean	-1.00	0.06	-0.80	23.6	23.3	26.2
	St. Dev.	1.05	0.65	0.69	1.4	1.2	3.2

Honolulu
Tropical dry savanna (As) 1996 Winter

Sample Size		TSV	TPV	PMV	T_a(°C)	T_o(°C)	T_c(°C)
659	Mean	-0.77	-0.06	-0.76	22.6	22.5	24.8
	St. Dev.	1.11	0.72	0.45	0.7	0.7	3.5

Makati
Tropical wet savanna (Aw) 2003 Summer

Sample Size		TSV	TPV	PMV	T_a(°C)	T_o(°C)	T_c(°C)
275	Mean	-1.03	0.16	-0.06	23.8	23.6	26.6
	St. Dev.	1.11	0.61	0.49	1.1	1.0	3.4

Townsville
Tropical wet savanna (Aw) 1995 Winter

Sample Size		TSV	TPV	PMV	T_a(°C)	T_o(°C)	T_c(°C)
624	Mean	-0.43	-0.07	-0.21	23.3	23.4	24.9
	St. Dev.	1.08	0.61	0.57	0.9	0.9	3.0

Figure 5 Thermal comfort analysis of TSV, TPV, and PMV probability density on the seven-point thermal scale indicating a slight shift of the occupant's votes to the colder (left) side for TSV. Sample size of building occupants polled in the study and the Comfort temperature (T_c) calculations using the Griffiths constants (G) for G= (0.32) are indicated.

In the eight identified studies, the greatest disparity between TSV and PMV on the seven-point thermal scales is observed in Makati with a mean TSV cooler than the mean PMV by 0.97, followed by Chennai at 0.85, and Bangalore 0.49. The average TSV in comparison to the PMV across all studies is substantially lower (Figure 5) with an average TSV of -0.51 and an average PMV of -0.11 indicating a 0.39 warmer difference of the vote on a seven-point thermal scale.

The average operative temperatures observed within the studies range from 22.5°C to 26.2 °C, representing a thermal environment which the PMV might consider comfortable (Figure 5), however, a negative value for the TSV is observed for every study. In some studies, the mean sensation vote falls within an acceptable ±0.5 mean vote, however, a significant minority can find conditions too cold (TSV<-1) which can be not represented when taking average values. Additionally, the TSV alone would not demonstrate the occupants' desired for a warmer condition which is represented when considering the TPV for the occupant votes. Therefore, cold discomfort is most properly described by negative value for (HD-CD) which takes into consideration both the sensation and preference of the occupants. The comfort temperature calculation under the considered Griffiths coefficient G= 0.32 suggests a comfort temperature (T_c) warmer for every study, with an average by 1.5°C than the operative temperature in Figure 5.

4.3 Cooling energy analysis

We observe the comfort temperatures evaluated for all studies to be warmer than the observed temperatures recorded from the mean operative temperature in Table 3. The average observed temperature recorded through all the selected studies is found to be about 24.0°C. The average comfort temperature calculated for all the selected studies is found to be about 25.5°C (Table 3). Our analysis of the selected studies identifies a difference in the observed temperatures to the comfort temperatures ranging from 0.4°C to 3.0°C with an average of 1.5°C warmer (Table 3). The comfort temperature range is notably higher than observed temperatures and the PMV predicts the mean vote for the studies to occur at +0.08 on the seven-point thermal scale indicating slight occupant warming which would recommend more cooling.

As expected, the cooling energy demand for each study simulated demonstrates lower demand when using calculated comfort temperature as the setpoint (Q_c) in contrast to the demand obtained using observed indoor operative temperatures (Q_o) as setpoints (Table 3). The difference ranges from 0.9 kWh/m^2 (3.2% reduction) to 11.0 kWh/m^2 (19.5% reduction) and is proportional to the difference between T_c and T_o, which is greatest in Makati at 3.0°C. We observe an average reduction in cooling energy demand of 6.8% per 1°C increase in setpoint temperature.

Table 3 Comfort Temperature Energy Analysis Summary

Study	HD-CD	Observed Temperature T_o (°C)	T_o Cooling Energy Demand Q_o (kWh/m^2)	Comfort Temperature T_c (°C)	T_c Cooling Energy Demand Q_c (kWh/m^2)	Difference $T_o - T_c$ (°C)	Difference $Q_o - Q_c$ (kWh/m^2)
Bangalore (Aw) 2012 Summer	-4.2%	24.8	28.9	25.2	28.0	0.4	0.9
Chennai (Aw) 2012 Winter	-2.1%	26.2	47.3	26.7	45.8	0.5	1.6
Darwin (Cfa) 1982 Summer	-23.8%	23.4	48.3	24.8	45.1	1.0	3.2
Delhi (Cwa) 2012 Summer	-0.5%	24.0	40.9	24.6	39.1	0.6	1.7
Honolulu (As) 1995 Autumn	-20.5%	23.3	56.4	26.2	45.4	2.9	11.0

Honolulu (As) 1996 Winter	-26.0%	22.5	59.9	24.8	50.3	2.3	9.6
Makati (Aw) 2003 Summer	-9.6%	23.6	50.9	26.6	41.5	3.0	9.4
Townsville (Aw) 1995 Winter	-16.4%	23.4	37.1	24.9	33.2	1.5	3.9

Figure 6 shows the predicted energy demand obtained using LHS across building elements (FGR, HLP, and BOA) for current and future climate conditions. FGR drives the biggest difference in both climates (10.5%), followed by HLP (3.9%), and finally BOA (3.7%). The relationship of cooling energy demand within the different building elements sampled and climates is examined to illustrate the projected range of cooling energy demand presented in varying contextual building conditions in Figure 6. Under all building elements alterations, we observed a reduction in cooling energy demand from the observed to comfort temperature setpoint conditions by an average of 10.4% amounting to 4.1 kWh/m^2 (Figure 6) in current climate conditions. Likewise future climate conditions the average reduction in cooling energy demand under all building elements alterations from observed to comfort building temperature setpoint conditions is 9.8% amounting to 4.7 kWh/m^2 (Figure 6).

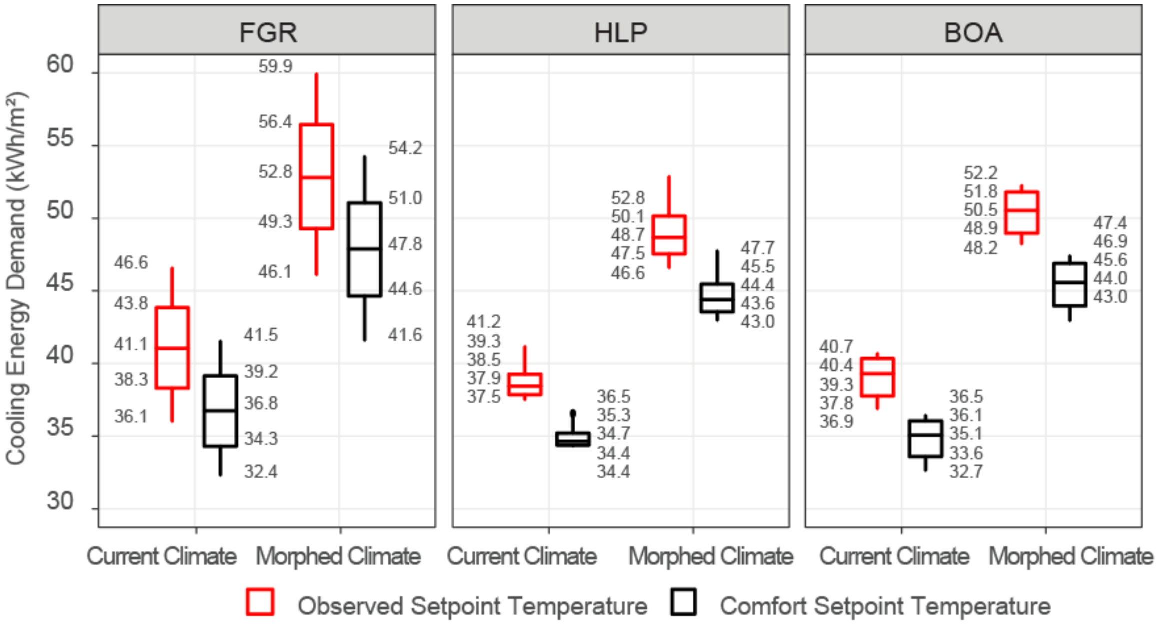


Figure 6 Cooling energy demand simulations for observed and comfort building temperature setpoints in current and future climate conditions with variations in façade glazing ratio, heat loss parameter, and building obstruction angle. The box and whisker plot shows the maximum, minimum, median, and upper and lower quartiles

Examining the HLP and BOA it is apparent that selecting a more appropriate indoor setpoint temperature is more effective in reducing cooling energy demand than a regularly shaded building and best practice building air tightness and insulation. We observe that the minimum cooling energy demand found for a highly obstructed building (BOA = 80°) – i.e. one in which cooling energy demand will be low compared to an equivalent building with BOA of 20° – is 36.9 kWh/m^2 at an indoor setpoint temperature of 24.0°C. In contrast, the maximum cooling energy demand for a building with BOA of 20° at a higher setpoint temperature of 25.5°C is only 36.5 kWh/m^2 under current climate conditions (Figure 6). The difference between the average observed and comfort temperature setpoint condition simulations is 4.2 kWh/m^2 for the entirety of the randomly sampled simulations for BOA in the current climate conditions.

Additionally, we can see from the results that the minimum cooling energy demand (37.5 kWh/m^2) in a highly insulated and airtight building at a colder setpoint temperature of 24.0°C is greater than the maximum cooling energy demand (36.6 kWh/m^2) in a typical insulated and airtight building at a warmer setpoint temperature of 25.5°C in the current climate. The difference between the average observed and comfort setpoint condition simulations is 3.7 kWh/m^2 for all the randomly sampled simulations for HLP in the current climate conditions. This trend is additionally observed in future climates but at a reduced impact suggesting that the manipulation of indoor temperature setpoints to achieve comfort and reduced cooling energy demand is less effective as the climate gets warmer.

5 Discussion

We have seen that coupling TSV and TPV is the safest means of determining occupants' thermal attitude in relation to overcooling, as the combination clearly identifies both the subjective sensation and preference eliminating the possibility of ambiguity and misinterpretations. Observations comparing the TSV and TPV to the PMV within the identified studies clearly illustrates the disjunction between PMV and occupant thermal response in warmer climates.

The PMV can indicate inaccurate thermal comfort assumptions as it takes into consideration the occupants' physical characteristics ignoring cultural aspects. An extension to the PMV was later established by Fanger and Toftum for buildings with no air-conditioning in warmer climates as collected field data in these climates would misalign with the model [50]. This extension featured the introduction of an "expectancy factor" that resulted in a shift of the PMV distribution to the left on the seven-point thermal scale. This would shift the PMV from a +1.0 to a +0.5 with an expectancy factor of 0.5, which changes the occupants predicted vote from feeling warm to comfortable [50]. The existence of the PMV extension to accommodate for mispredictions in warmer climates alludes to the issue with overestimating warmer thermal discomfort in warmer climates. Further, PMV calculations tend to represent a normal distribution of discomfort assuming occupant of a certain climate would react to hot and cold thermal discomfort proportionately. Within comparable air temperatures, warmer climate overcooling occurrences outweigh those of cold climates. Within both climates a differing perception of thermal discomfort is indicated, suggesting a cultural link to thermal comfort. A global implementation of thermal comfort as in the PMV across varying climates assumes that "comfort" is homogeneous across all climates and cultures. However, more frequently we discover that the application of an international comfort standard yields different results in climates that differ from the climate originally intended.

The impact of overcooling is not merely on energy and discomfort, but also carbon emissions as every unit of energy expended in unnecessary overcooling is also adding carbon to the atmosphere. Globally, fossil fuels accounted for roughly 65% of total power generation with an average emission factor of 0.505 kgCO^2/kWh in 2016 [2]. With the studies examined here, emission factors vary within the range 0.620

kgCO^2/kWh in Australia to 0.751 kgCO^2/kWh in Hawaii, which are both greater than the global average (Table 4).

Table 4 Summary of Average Carbon Intensity of Electricity Generated for Overcooled Studies

Region	Study	kgCO$_2$/kWh	Source	Year
Global	-	0.475	[111]	2017
Hawaii	Honolulu	0.751	[112]	2017
India	Bangalore	0.718	[113]	2017
	Chennai			2017
	Delhi			2019
Australia	Darwin	0.620	[114]	2019
Philippines	Makati	0.712	[115]	2017

Although the global trend in power generation carbon intensity is decreasing, a significant future increase in cooling energy demand is expected. This increase is estimated to triple current cooling energy demand by 2050 because of increased air conditioning use, urbanization, population growth, and a warming climate.

To estimate the carbon penalty of overcooling from the examined studies, a country wide energy model that accurately reflects the varying building typologies in terms of their quantities and size alongside their operation is needed. Additionally, power generation carbon intensities for the electrical grids connected to these buildings would need to be determined for periods of air conditioning utilization for all the studied locations. As much of these data are presently unavailable, a general assumption of the global cooling trend can be applied instead. Based upon available documentation of the future of cooling energy consumption from IEA reports [2], we speculate that the overall carbon emission volumes will remain significant since reductions in grid carbon emission factors will be offset by the mass utilization of air conditioning both in quantity and duration in both developed and developing regions given estimates of future growth and warming [2].

Space cooling accounts for 2,000 TWh of global energy use at present, equating to around 8% of global carbon emissions. At the simplest level, if we assume 17% of the expended energy is wasted in overcooling, then we obtain an estimate of 1.3% of current global carbon being emitted unnecessarily due to overcooling based on global carbon intensity presented in Table 4. Not all buildings in the world are likely experience overcooling, e.g., air-conditioned buildings in temperate climates where delivered internal temperatures are more likely to match expectations, or many residential buildings, therefore, this is likely to be an overestimate of the impact of overcooling on global carbon.

We can postulate, that given overcooling is purposeful waste and thus has the potential to be mitigated rather simply by the adjustment of thermostats, what proportion of our future carbon budget might be saved by eliminating overcooling. To estimate this, recall that the majority of future space cooling will come from the Global South where demand can be considered to be largely unsaturated. Hence, the estimated tripling of space cooling demand to 6,000 TWh by 2050 will be driven largely by the Global South which is unlikely to decarbonise electricity grids at the same rate as the industrialised parts of the world. If we assume (a) a 1:3 split of space cooling demand from non-domestic to domestic buildings (b) overcooling to occur only in non-domestic buildings and (c) a linear growth business-as-usual scenario, then 6,800 TWh of delivered space cooling over the 30 year period of 2020 to 2050 can be estimated to be due to overcooling. If the world halves its present carbon intensity for electricity by 2050 – for example India and China are expected to be “net zero” well after this date – this equates to 1.6 BtC by 2050, which is 0.7% of the available carbon budget for a 67% chance of limiting global temperature rise to 1.5 °C [116]. While the assumption of all non-domestic buildings to be overcooled is likely to result in an overestimate, this may be balanced in future by the overall warming trend and the fact that many residential buildings, especially those controlled centrally, may be wastefully cooled. While the debate around precisely what our carbon budget actually is remains unresolved, it is instructive that the simple behavioural change implied by an adjustment of thermostats to eliminate overcooling registers at all on the likely scale of the planet’s total carbon budget for the next thirty years.

And it is not merely the impact on energy demand or carbon. Overcooling causes thermal discomfort which will also have knock on effects for health and wellbeing. Common health problems associated with overcooling are cold-like symptoms, fatigue and headaches, some of which can turn chronic due to prolonged exposure for those with other morbidities or advanced age. Disruption in fine motor skills due to a stiffening of muscles when temperatures drop, can affect many everyday activities. These can result in increased absenteeism, loss of productivity and lead to further waste in terms of staff costs, which account for 90% of a typical institutional or business costs.

We observe a significant gender disparity in cold discomfort, with females experiencing about three times higher cold discomfort (measured as CD-HD) compared to males. This reinforces the need to consider both comfort and discomfort across gender, cultures, and climates and supports other recent work in this area [117].

Finally, we believe there is a shortage of thermal comfort studies within warmer climates which have the necessary thermal comfort parameters to obtain a fuller understanding of thermal comfort in these climates. Hence, further research on space cooling culture in these geographies and climates is called for, as current urbanization trends within developing warmer climate regions are expected to significantly exacerbate the issue of overcooling.

6 Conclusion

Population growth which is driving growth in the total number of buildings and the increased availability and affordability of space cooling systems has not only made space cooling the largest consumer of energy in warm climates but also the fastest growing. Without a proper interpretation of overcooling within the built environment, attempts in its reduction would be unfeasible, resulting in increased occupant discomfort, energy consumption, and environmental degradation.

We observe that the safest means of identifying overcooling is to ensure that both the thermal sensation and preference votes coincidentally point towards cold discomfort during the warm season, and that the overall percentage of votes expressing cold discomfort exceed those with warm discomfort. We find that eight studies in the global thermal comfort database meet this definition and all occur in warm climates. In these studies, an average of 17% votes can be classed as overcooled using this definition.

Using computer models, we estimate that this overcooling accounts for about 12% of delivered cooling energy demand which is *wastefully* delivered. Additionally, we find that the opportunity cost for mitigating this waste is low, i.e. through the use of a more climate and culture specific definition of thermal comfort. The simplest embodiment of this would be an upwards adjustment of set-point temperatures by on average 1.5 °C. We estimate that the reduction in cooling energy demand resulting from such an adjustment is likely to be greater than most good-practice passive design measures such as better heat loss parameters and shading, now and in the future. This is not to say that passive design measures are not needed, quite the opposite, but rather that the impact of poorly specified indoor environments is of a greater scale than is often appreciated. Indeed, a thought experiment suggests that the quantity of this unnecessary demand is such that it is likely to register on the scale of the entire planet's carbon budget to 2050.

Thus, we find that a departure from a "universal" interpretation of thermal comfort towards a climate and culture specific application would serve to not only avoid the waste of energy and carbon, but also improve health and well-being. Localisation of thermal comfort is already underway in some parts of the Global South, such as India's recent IMAC model. Even in places that might appear climatically similar, there is emerging evidence that cultural factors mediate expectations and can play an important role[118]. However, the presence of only a small number of studies from the Global South in the thermal comfort database combined with the expectation that these regions are likely to nearly double global built floor space by 2050, suggests that a rapid move towards more widespread localisation is now needed.

7 Acknowledgement

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