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The Future of Thermal Comfort in a Warming World

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Abstract:

Building cooling energy demand in the warmer climates of the world is increasing due to population growth and built environment expansion. Currently, cooling energy demand is increasing at a rate of 8% per annum, and this is projected to increase more rapidly with global warming. However, much of this demand is driven by unsustainably low indoor building temperature set points, that are also fundamentally seen as undesirable by most building occupants. In this study, we examine the effect of this “overcooling” in a changing climate using data from Qatar as a case study of a location with high average and peak external temperatures. Field data from 4 buildings in public and private settings demonstrate that cold discomfort is about 20 percentage points higher than warm discomfort due to excessive air-conditioning. Computer energy simulations using morphed future weather data and the extrapolated effect of observed low internal building temperatures, demonstrate that overcooling exacerbates the effect of a warming world by 16 percentage points. In other words, the use of more climatically appropriate thermal comfort standards that avoid unnecessary overcooling could reduce 28% of global carbon emissions in a future warmed world. As anecdotal evidence of excessive cooling in other warm climates demonstrates that the effects of overcooling are true, the reduction of building overcooling results in a greater achievement of thermal comfort, a decrease in cooling energy consumption, and a decline in carbon emissions across the warm climates of the world.

Keywords: Thermal Comfort, Warm Climates, Overcooling, Building Energy, Space Cooling

1 Introduction

1.1 Environmental Crisis

Environmental degradation is the negative change of the environment through actions that result in an undesirable environmental change, which is caused by actions such as the pollution, destruction, and depletion of the natural resources (UNEP, 2007). The rate at which the environment has been deteriorating is increasing yearly. Negative impacts such as climate change, global pollution, and the loss of biodiversity are linked to environmental degradation (Stocker et al., 2013). Current biodiversity loss is a thousand times larger than the natural level. The documented loss is roughly three quarters of wild animals and half of plant life as a result of habitat destruction and over-usage of natural resources (Stocker et al., 2013). Increased air, land and sea contamination is observed globally as a result of pollution. The increase in pollution has led to larger occurrences of diseases, allergies, and in some cases death (I. C. Change, 2014). The current change in the climate is correlated with endangering environmental phenomena such as increased precipitation changes, rising sea levels, and global warming. Researchers explain that the current trend in climate change is a direct result of the increase of greenhouse gas production such as carbon dioxide, which has increased 40% within the last century and a half (I. C. Change, 2014).

1.2 Human Population and Built Environment Expansion

The human population globally is experiencing rapid growth facilitated by advances in health care, food production, material manufacturing, transportation, and construction. The rapid population growth and the shift from a rural to urbanized life contributes to the large built environment expansion. As a result of the growing urbanized human lifestyle, human-made carbon emissions increase yearly resulting in global warming (UN, 2011). By 2050, the urban population is estimated at 85% for developed regions and 60% for developing regions (Stocker et al., 2013).

1.3 Global warming

Global warming is the gradual rise in the average surface temperature of the Earth’s climate system. Global warming is a key aspect of climate change, as it has been observed by direct temperature measurements. Climate change and global warming are terms that are frequently used interchangeably (I. C. Change, 2014). The increase in global surface temperatures and its forecasted continuation that is caused by human-made greenhouse gas emissions is considered as global warming, while climate change involves both global warming and its impacts, such as shifts in precipitation. Greenhouse gases such as methane, nitrous oxide, and most importantly carbon dioxide are concluded to influence global warming directly. Simulated climatic modelling projects an increase in global surface temperature by a lower 1.5°C or a higher 4.5°C, depending on the growth rate of greenhouse gas emissions (Stocker et al., 2013).

1.4 Energy Consumption and Cooling

More than half of the global population lives in urban built environments. The built environment accounts for the consumption of roughly 40% of the total energy produced primarily from non-renewable energy sources (EIA, 2019). The non-renewable energy focused consumption generates about a third of global carbon emissions (Stocker et al., 2013) (IEA, 2018).

In the built environment, space conditioning is a significant energy use sector about 16% globally (IEA, 2018). Space cooling is the largest end-use of energy consumption in warm climates, consumption as high as 40% of the building energy could be used for space cooling, (IEA, 2018). Space cooling energy demand globally is projected to triple by 2050 (IEA, 2018). As the largest expansion of the built environment will be in inherently warmer climate developing regions. Space cooling energy demand in warmer climatic regions will witness the greatest increase. As space cooling is a means of establishing habitable built environments, understanding space cooling and the associated energy consumption through thermal comfort in a warming world presents the opportunities for its optimization.

2 Background

2.1 Measuring Thermal Comfort

Thermal comfort is a significant component of building design in the context of the built environment. Thermal comfort impacts building occupant satisfaction and energy demands. Standards exist for achieving and maintaining thermal comfort throughout the built environment. The International Organization for Standardization (ISO) 7730 (ISO, 2005), the ASHRAE Standard 55 (ASHRAE, 2010), the European Standard (EN) 15251 (CEN, 2007), and the CIBSE (The Chartered Institution of Building Services Engineers) Environmental Design Guide (CIBSE, 2015) are examples of entities that address the guidelines and regulations of thermal comfort in the built environment. Assessing thermal comfort involves the combination and evaluation of physical and subjective metrics. The physical metrics evaluate the thermal environment of a space. Physical parameters such as the air temperature, the mean radiant temperature, the air velocity, the relative humidity, the occupant clothing insulation value, and the metabolic rate, are considered in assessing the thermal comfort within a building (ASHRAE, 2010; CEN, 2007; CIBSE, 2015; ISO, 2005). Additionally, the thermal sensation and preference votes are subjective metrics for assessing thermal comfort within a building. Thermal comfort models such as the predicted mean vote attempt to identify the thermal sensation of a building's occupant through evaluating physical parameters (ASHRAE, 2010; CEN, 2007; CIBSE, 2015; Fanger, 1970; ISO, 2005; Toftum & Ole Fanger, 2002). Assessing thermal comfort in principle depends on assessing subjective thermal comfort metrics such as the thermal sensation and preference vote through occupant responses or calculations.

In thermal comfort studies, subjectively assessing building occupant's thermal sensation in each environment involves gathering the thermal sensation vote given by occupant responses. The thermal sensation vote as a metric most accurately describes the occupant's thermal sensation response as it takes into consideration any prejudices based upon age, sex, body mass, metabolic rate, clothing, and thermal adaptation (ASHRAE, 2010; CEN, 2007; ISO, 2005). The thermal sensation vote is most commonly gathered on a seven-point thermal scale from cold (-3) to hot (+3) (ASHRAE, 2010; CEN, 2007; ISO, 2005). In addition, a subjective metric like the thermal sensation vote is the thermal preference vote. The thermal preference vote assesses the occupant's thermal preference by indicating the desire to be warmer, cooler, or to have no change. The thermal preference vote conveys an accurate description of the occupant's thermal preference as it directly indicates their thermal preference in the given environment. The thermal preference vote is gathered on a preference scale of warmer, cooler, and a no-change (ASHRAE, 2010; CEN, 2007; ISO, 2005). The thermal sensation gathers the building occupant's response on a thermal scale. The thermal preference vote can either represent a desire of cooler, warmer, or no change either aligning with the thermal sensation vote or not. The agreement of both the thermal sensation and preference vote on either the cold or hot thermal discomfort identifies the occupant's thermal attitude towards a given space.

2.2 Comfort Temperature

Evaluating a groups' thermal sensation votes in relation to the existing internal temperature through the Griffiths method can establish the proposed comfort temperature for that group (Baker & Standeven, 1997; Griffiths, 1990; Humphreys, 1998; F Nicol et al., 1994; Fergus Nicol & Roaf, 1996; Oseland et al., 1998). The Griffiths method assumes that the comfort temperature represents a neutral vote (0) on a thermal scale. The relationship between the comfort temperature on a thermal sensation scale in relation to the internal temperatures is represented by a coefficient in the Griffiths method (Griffiths, 1990). The Griffiths coefficient is identified as the Griffiths constant with the values for the constants generally applied being 0.25, 0.33 and 0.50 (F Nicol et al., 1994; Rijal et al., 2010). The size of the group of votes and the Griffiths constant affect the accuracy of the evaluated comfort temperature. Thermal comfort studies evaluate the comfort temperatures by employing several Griffiths constants (Bouden & Ghrab, 2005; Indraganti, 2010; F Nicol et al., 1994; Rijal et al., 2010).

2.3 Energy Performance Simulation

EnergyPlus is a software that simulates whole building performance through building systems operations and thermal equations in an energy model under given parameters. EnergyPlus facilitates the manipulation of parameters such as the building schedule, the envelope of the building, the systems for space conditioning, etc. Through these manipulations, EnergyPlus allows for the evaluation and optimization of the performance of buildings (Crawley et al., 2000). Additional parameters are constants in the energy simulations as effects of the environment, such as climatic conditions included in simulations as weather data (Crawley et al., 2000). In the building energy simulations, weather data are common parameters. Weather data files contain for an annual period, hourly combined weather trend data (Crawley, 1998). To correctly evaluate the associated building energy demand for maintaining habitable building conditions the weather data reflects the existing climatic conditions in the energy model.

Global warming presents a change in the climatic conditions resulting in changes in building energy demand. With the change of the climate, space conditioning demands in either cooling or heating can be significantly altered. To assess future impacts on energy demand in the built environment the morphing method of current weather data to suggest future climatic conditions based on carbon emission data is applied (Belcher et al., 2005). The morphing method joins the existing weather data with global emission scenarios to reflect the average weather in the future while maintaining the existing weather patterns from the source weather data. The morphing method results in morphed weather data that are considered in building thermal simulations of future climatic conditions (Belcher et al., 2005).

3 Methods

The field study conducted collected thermal comfort data in Doha through field visits of various buildings. Buildings were selected that represent a large office working environment which range from private to public organizations. The timing of the field data collection was scheduled during the summer of 2019 as the summer periods within warmer climates heavily rely on active cooling systems to offset the heat. Data collection started on June 14th and ended on August 20th of 2019, with a total of 4 visits to 4 buildings during this period.

Qualitative metrics such as the thermal sensation vote and the thermal preference vote were collected in questionnaires. The questionnaires collected were presented to the occupants in an English and Arabic format. Explanations of the data collection and procedures of input were made available upon the beginning of the data collection. Consent of the building's occupant was acquired for their participation.

A questionnaire incorporating standardized thermal comfort questions found in ISO 7730 was used for collecting occupant responses. The questionnaire was made anonymous for the occupants to maintain anonymous responses. Additionally, the questionnaire established the use of a continuous scale on several thermal comfort questions. The distribution of the questionnaire was made to occupants of the building that have been in a prolonged seated position to ensure a stable metabolic level that corresponds to seating.

The environmental parameters collected within the field study were the air temperature, mean radiant temperature, relative humidity, and air velocity. The environmental parameters are measured using calibrated thermal environment measurement sensors which conform to ISO 7730. The air temperature and relative humidity measurements are collected using the Swema HC2A-S air humidity probe, mean radiant temperature measurements are collected using the Swema 05 767370 globe temperature sensor, and the air velocity measurements are collected using the Swema 03 767360 anemometer. The measurements of the environmental parameters are taken as spot readings at the desk of each building occupants' workplace. This is conducted for each occupant that is included in the study. In addition, to the physical measurement, a note of the time, date, building setpoint temperature, and external weather conditions are made. Further, images are captured of any observable indications of excessive cooling in additive clothing or alteration to cooling system equipment.

3.1 Establishing the Thermal Discomfort Classifications

Combining warm or cool thermal discomfort votes in the thermal sensation and preference vote metrics establishes the thermal discomfort classification. The location of the thermal sensation vote on a seven-point thermal scale describes the votes discomfort. A thermal sensation vote above (+1) is warm thermal discomfort, below (-1) is cool thermal discomfort, and in between represents neutral thermal comfort. Additionally, the identification of the thermal preference vote on a thermal preference scale describes the vote's discomfort. A thermal preference vote of cooler is warm thermal discomfort, a vote of warmer is cool thermal discomfort, and a vote of no change represents neutral thermal comfort. The combination of both the warm thermal discomfort occurrences in the thermal sensation and preference votes account for a definite warm thermal discomfort classification as identified by the occupant. In addition, the combination of both the cool thermal discomfort occurrences in the thermal sensation and preference votes account for a definite cool thermal discomfort classification as identified by the occupant. For each study, the warm and cool thermal discomfort classifications are evaluated for the definite combinations ignoring periphery and contradicting combinations.

3.2 Establishing the Thermal Discomfort Distributions

The warm and cool thermal discomfort distributions within a given building are evaluated by accounting for the warm and cool thermal discomfort classification percentages in each building respectively. Calculating the warm thermal discomfort distribution percentage involves accounting for all responses that are classified as a warm thermal discomfort against the total responses in the study. Moreover, calculating the cool thermal discomfort distribution percentage involves accounting for all responses that are classified as a cool thermal discomfort against the total responses in that study. For each building, the warm and cool thermal discomfort distributions are calculated.

3.3 Comfort Temperature Calculations

The Griffiths method is used to evaluate the proposed comfort temperature for each building using equation (1) (Griffiths, 1990; F Nicol et al., 1994).

$$Tcg = Tg + (0 - TSV) / G \tag{1}$$

The evaluated comfort temperatures Tcg 0.25, Tcg 0.33, and Tcg 0.50 are the comfort temperature by Griffiths' method (°C) with the associated Griffiths coefficient (G) respectively (Griffiths, 1990). The Griffiths coefficient applied is 0.50 as it conforms with thermal comfort research and represents the lowest comfort temperature (F Nicol et al., 1994; Rijal et al., 2010). The internal temperatures are taken from Tg (°C). The thermal sensation vote (TSV) is collected from each occupant's response.

3.4 Building Energy Simulations in Current and Morphed Climatic Conditions

Applying EnergyPlus as a whole building energy simulation program and the ANSI/ASHRAE/IES standard 90.1 large office prototype building model, comparative simulations are conducted (DOE, 2019). The ASHRAE climate zone variant of the ANSI/ASHRAE/IES standard 90.1 large office prototype building model is selected for Doha based upon the classification in the ASHRAE climate zone and subtype (DOE, 2018). Additionally, the weather data for Doha's climate is acquired from the ASHRAE weather data center (ASHRAE). The weather data is imported from the data center in EnergyPlus Weather Format (EPW) in the simulation for each model (Crawley, 1998). The comparison study is conducted by simulating the operation of a building in Doha in the initial temperature conditions from the collected setpoint temperatures and the proposed comfort temperature conditions by use of Griffiths method rounded to the nearest 0.5°C. The application of the temperature conditions is through creating different building cooling setpoint schedules. The schedule uses the initial temperatures and the proposed comfort temperatures with a two-degree (°C) setback after working hours for each building respectively. The buildings are simulated in the current climatic conditions to represent the energy demand for both the initial and comfort temperature schedules. The simulated building energy demand is calibrated to current building energy use intensities for cooling demand and whole building energy demand provided by the Qatar national energy provider's calculated energy use intensity averages (Kahramaa, 2014, 2017).

Comparing the simulations for the buildings represents the energy demand difference between the two scenarios. Further, the same process is followed with the morphed climatic conditions. Representing future climatic conditions to assess the projected energy demand requires the morphing of current weather data (Belcher et al., 2005) Current weather data in an EnergyPlus Weather Format (EPW) is morphed based on emission projections to represent the future climatic conditions in 2050 using the climate change world weather file generator tool (CCWorldWeatherGen) (Jentsch et al., 2013). The (CCWorldWeatherGen) tool relates the Intergovernmental Panel on Climate Change Third Assessment Report (IPCC TAR) model summary data of the Hadley Centre Coupled Model version 3 (HadCM3) experiment (C. Change, 2001) to generate the climatic conditions. This application facilitates the application of the "morphed" weather data that represent the climatic conditions in 2050 in energy simulations. Comparably, the comparison simulation in the morphed climatic conditions is conducted by simulating the operation of the buildings in Doha in the initial temperature conditions from the setpoint temperatures and the rounded comfort temperature conditions by use of Griffiths method. Furthermore, The building energy demand difference between the morphed and unmorphed scenarios are evaluated based upon the calibration of the unmorphed simulations to known building energy use intensities in Qatar (Ayoub et al., 2014; Kahramaa, 2014, 2017; Krarti et al., 2017).

4 Results

4.1 Thermal Comfort Conditions in the Doha Built Environment

The buildings examined during the filed visit of Doha represent typical buildings in Qatar. All buildings are actively cooled and heated through building centralized air conditioning systems and maintain non-operable windows throughout as dust is an issue in desert climates. During the data collection period from June 14th to August 20th of 2019, the average external temperatures ranged from 42°C to 45°C as the high dry bulb temperature and from 39°C to 43 °C as the low dry bulb temperature (Table 1). The total occupant response collected was 165, 40 female responses and 125 male responses are included from the buildings surveyed (Table 1). The average age of the building occupants was 38 years.

Table 1 Doha Buildings Study Summary

Study Name	Code	Occupants Surveyed	Occupants Responses	Average Age	Day of Visit	Setpoint (°C)	High Tdb (°C)	Low Tdb (°C)
Public Building 1	**BPU1**	**39**	**11 (F) 28 (M)**	**38**	**6/17/2019**	**22.0**	**42**	**39**
Public Building 2	**BPU2**	**36**	**24 (F) 12 (M)**	**39**	**7/17/2019**	**22.0**	**45**	**39**
Private Building 1	**BPR1**	**55**	**5 (F) 50 (M)**	**36**	**8/20/2019**	**23.5**	**43**	**39**
Private Building 2	**BPR2**	**36**	**1 (F) 35 (M)**	**48**	**7/15/2019**	**24.0**	**45**	**43**

Observing the thermal comfort conditions in the Doha built environment identifies slight variations in the public and private buildings (Table 2). The mean internal temperatures recorded in the study are observed to be in range with the temperature setpoints with minimal deviation (Table 1,2). In public buildings, the observed internal temperatures are cooler than private buildings which is also observed in the average TSV and TPV values as cooler votes. The PMV values for the buildings are in majority within acceptable ranges and the PPD does not exceed 15% (Table 2). Clothing values recorded in the study are observed to be in the range of 1.27 to 0.94 CLO with slight deviation (Table 2). As the study involved seated occupants within office settings the assumed MET value is 1.20 (Table 2).

Table 2 Doha Buildings Study Thermal Comfort Summary

Study Name	Size	TSV	TPV	PMV	PPD	Ta (°C)	Tg (°C)	Rh (%)	Av (m/s)	CLO	MET
BPU1	**39**	**-0.76**	**-0.11**	**0.35**	**11.45**	**22.10**	**22.42**	**52.03**	**0.13**	**1.18**	**1.20**
Std. Dev.		**1.42**	**1.43**	**0.43**	**5.58**	**1.60**	**1.42**	**6.18**	**0.14**	**0.23**	**1.20**
BPU2	**36**	**-1.31**	**-0.16**	**0.24**	**9.03**	**21.65**	**21.47**	**58.22**	**0.20**	**1.27**	**1.20**
Std. Dev.		**1.40**	**1.27**	**0.38**	**2.74**	**0.31**	**0.20**	**4.73**	**0.21**	**0.31**	**1.20**
BPR1	**55**	**-0.31**	**0.06**	**0.66**	**15.00**	**24.75**	**24.84**	**38.77**	**0.18**	**1.09**	**1.20**
Std. Dev.		**1.36**	**1.03**	**0.19**	**4.72**	**0.76**	**0.64**	**1.91**	**0.22**	**0.14**	**1.20**
BPR2	**36**	**-0.67**	**0.15**	**0.31**	**9.61**	**23.74**	**24.02**	**43.64**	**0.12**	**0.94**	**1.20**
Std. Dev.		**1.06**	**0.90**	**0.35**	**4.43**	**0.86**	**0.81**	**2.07**	**0.09**	**0.25**	**1.20**

4.2 Thermal Discomfort Conditions in the Doha Built Environment

Observation of the thermal comfort conditions of the buildings in the Doha built environment identifies several indications of excessive active building cooling. An elevated cool thermal discomfort in contrast to warm thermal discomfort is observed in all buildings based on the collected occupant responses. The elevated cool thermal discomfort percentage is greater in public buildings compared to private buildings (Figure 1-8). Considering the highest evaluated comfort temperatures by the Griffiths method, the suggest comfort temperatures evaluated are on average higher from the building setpoint temperature by a range of 1.5-2 °C (Table 3). The PMV observed in the buildings predicts the thermal sensations to be on average in the acceptable PMV range. However, the PMV illustrates higher thermal sensation in contrast to the range of observed thermal sensation votes (Table 3).

Table 3 Public Building 1 Thermal Comfort Summary

Study Size	Item	TSV	TPV	PMV	Ta (°C)	Tg (°C)	Tc 0.50 (°C)	Tc 0.33 (°C)	Tc 0.25 (°C)
39	Mean	-0.76	-0.11	0.35	22.60	22.42	23.95	24.74	25.48
	Std. Dev.	1.40	1.42	0.43	1.40	1.40	2.29	3.61	4.91
	Max	3.00	2.40	0.93	24.67	25.63	28.47	31.56	34.47
	Min	-3.00	-3.00	-1.08	19.81	19.63	17.50	14.41	11.50

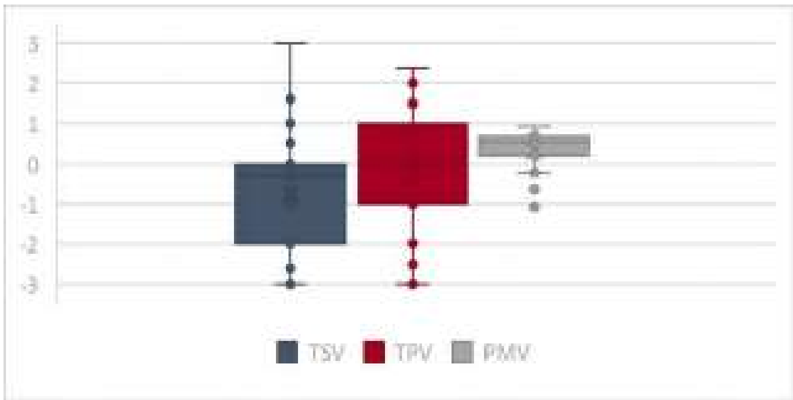


Figure 1, Thermal sensation vote, thermal preference vote, and predicted mean vote distribution on the seven-point thermal scale for Public Building 1

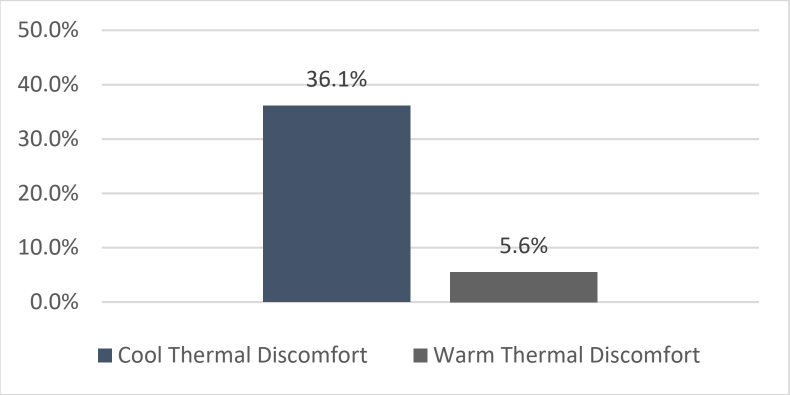


Figure 2, Percentage comparison of thermal discomfort based upon the combined thermals sensation and preference metric for Public Building 1

Table 4 Public Building 2 Thermal Comfort Summary

Study Size	Item	TSV	TPV	PMV	Ta (°C)	Tg (°C)	Tc 0.50 (°C)	Tc 0.33 (°C)	Tc 0.25 (°C)
36	**Mean**	**-1.31**	**-0.16**	**0.24**	**21.65**	**21.47**	**24.09**	**25.45**	**26.72**
	Std. Dev.	**1.38**	**1.26**	**0.37**	**0.31**	**0.20**	**2.76**	**4.18**	**5.51**
	Max	**3.00**	**2.00**	**0.65**	**22.71**	**21.89**	**27.77**	**30.86**	**33.77**
	Min	**-3.00**	**-3.00**	**-0.65**	**21.24**	**21.09**	**15.64**	**12.55**	**9.64**

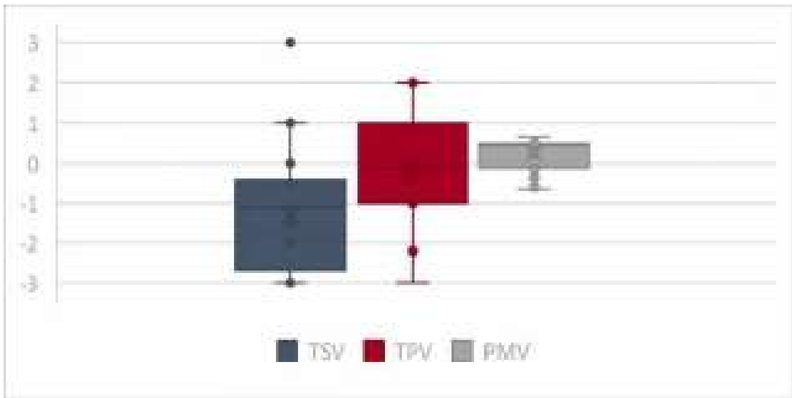


Figure 3, Thermal sensation vote, thermal preference vote, and predicted mean vote distribution on the seven-point thermal scale for Public Building 2

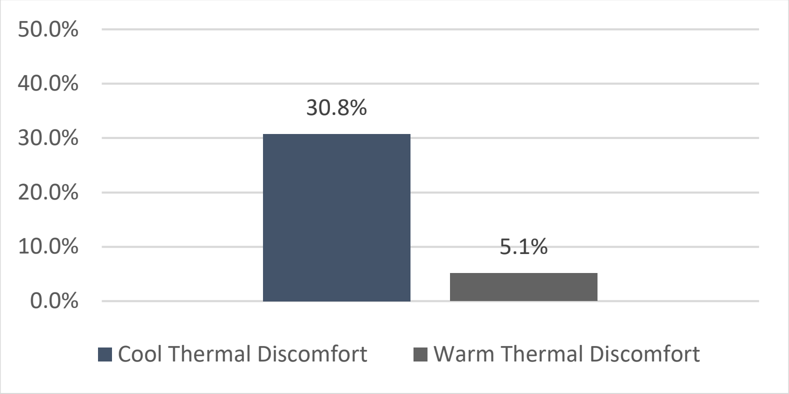


Figure 4, Percentage comparison of thermal discomfort based upon the combined thermals sensation and preference metric for Public Building 2

Table 5 Private Building 1 Thermal Comfort Summary

Study Size	Item	TSV	TPV	PMV	Ta (°C)	Tg (°C)	Tc 0.50 (°C)	Tc 0.33 (°C)	Tc 0.25(°C)
55	**Mean**	**-0.31**	**0.06**	**0.66**	**24.75**	**24.84**	**25.46**	**25.78**	**26.09**
	Std. Dev.	**1.35**	**1.02**	**0.19**	**0.75**	**0.63**	**2.76**	**4.12**	**5.42**
	Max	**3.00**	**2.00**	**0.94**	**25.76**	**25.71**	**31.63**	**34.72**	**37.63**
	Min	**-3.00**	**-2.00**	**0.08**	**23.64**	**23.98**	**18.40**	**15.31**	**12.40**

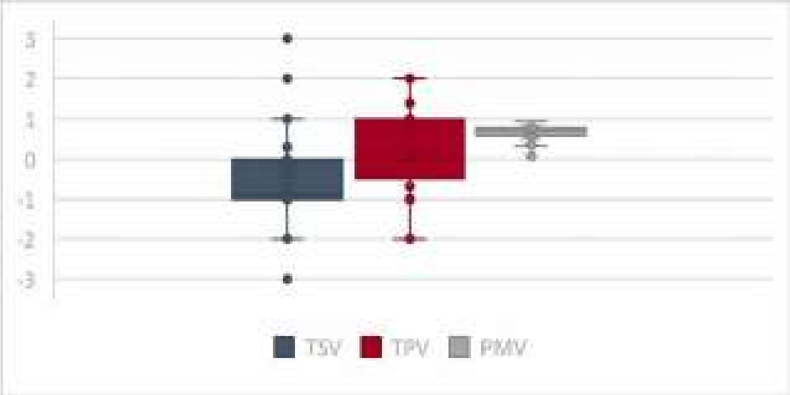


Figure 5, Thermal sensation vote, thermal preference vote, and predicted mean vote distribution on the seven-point thermal scale for Private Building 1

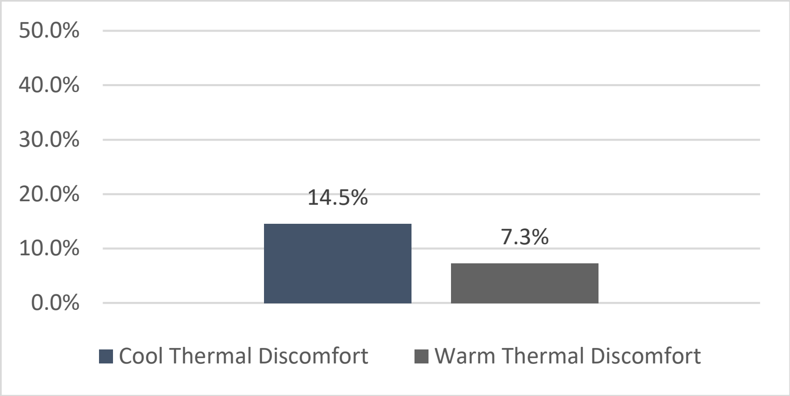


Figure 6, Percentage comparison of thermal discomfort based upon the combined thermals sensation and preference metric for Private Building 1

Table 6 Private Building 2 Thermal Comfort Summary

Study Size	Item	TSV	TPV	PMV	Ta (°C)	Tg (°C)	Tc 0.50 (°C)	Tc 0.33 (°C)	Tc 0.25 (°C)
36	**Mean**	**-0.67**	**0.15**	**0.31**	**23.74**	**24.02**	**25.35**	**26.04**	**26.68**
	Std. Dev.	**1.05**	**0.89**	**0.35**	**0.85**	**0.80**	**2.26**	**3.29**	**4.29**
	Max	**1.00**	**2.00**	**0.79**	**24.73**	**24.99**	**30.81**	**33.90**	**36.81**
	Min	**-3.00**	**-2.00**	**-0.31**	**22.34**	**22.30**	**21.41**	**20.48**	**19.61**

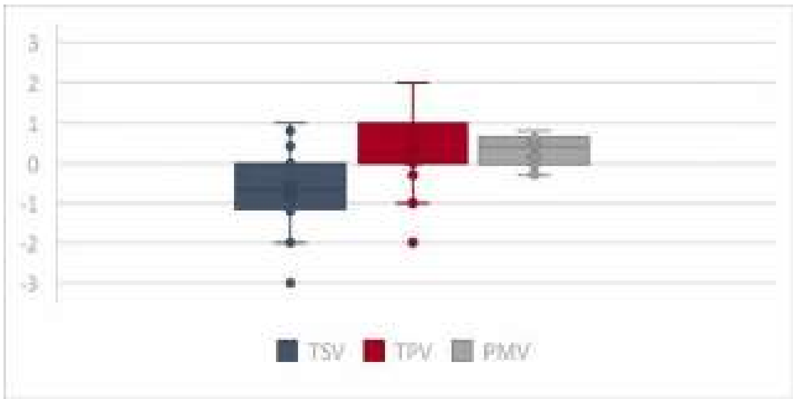


Figure 7, Thermal sensation vote, thermal preference vote, and predicted mean vote distribution on the seven-point thermal scale for Private Building 2

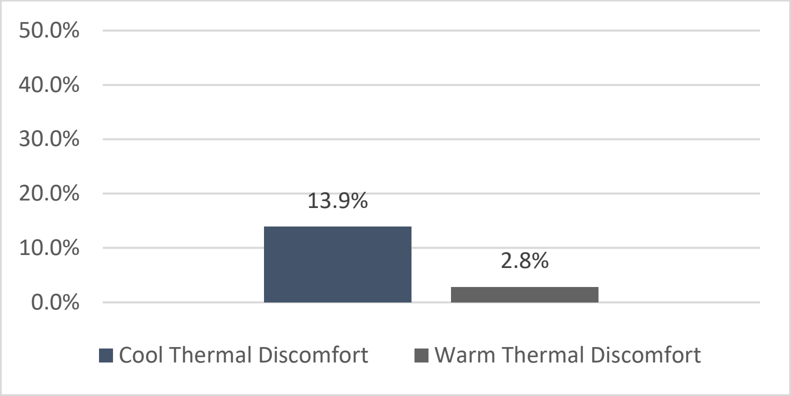


Figure 8, Percentage comparison of thermal discomfort based upon the combined thermals sensation and preference metric for Private Building 2

4.3 Unconventional Observations of Overcooling

Observing the thermal comfort conditions through thermal comfort metrics in the buildings have identified hints of excessive cooling. In addition, unconventional evidence of excessive cooling is observed during the field visits. Observed alterations of the cooling system equipment are attempts by occupants to minimize the cooling in the offices they occupy. Elements such as napkins, papers, and cardboard are used to reduced or block the cooler airflow from the ducts (Figure 9).

Figure 9, Images of observed occupant alterations to building air cooling distribution systems

Also, additional garments and jackets are used frequently in the cold office setting as methods of warming. These garments and jackets can be found in offices as if they are part of the permanent office fixtures. Further, the garments would also remain in the offices and not be taken home later once the occupant left the office at the end of the day (Figure 10).

Figure 10, Images of occupant’s garments in offices as additional insulation for warming when needed

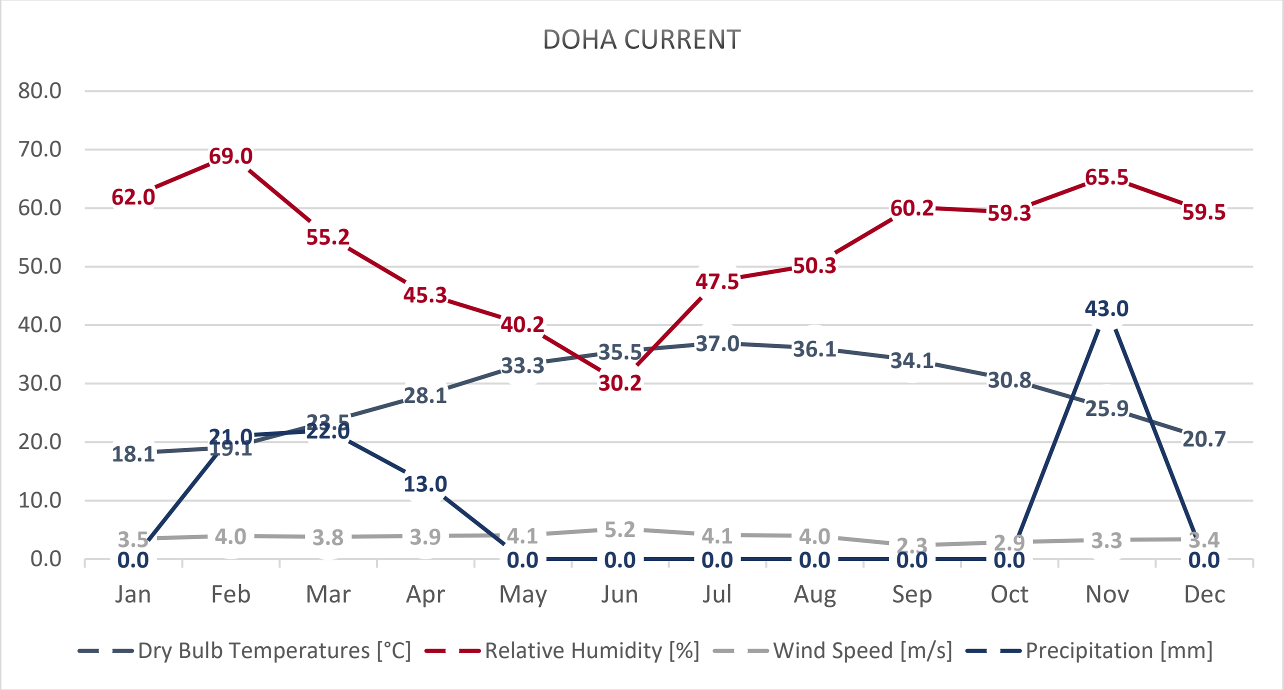
Discussions with the building occupants during the field visits have noted accounts of behavioural adjustments as measures of gaining heat in the cold environment. Occupants resort to taking several breaks throughout the workday outside the building to heat their bodies. In addition, occupants have stated relying on hot beverages to keep warm.

4.4 Current and Morphed Climatic Conditions

Observing the current and morphed climatic conditions of Doha depicts the climatic warming in 2050. The current climatic conditions of Doha represent an average external temperature ranging from 35.5 - 37.0 °C during the summer season and 18.1 – 25.9 °C during the winter season (Table 7). The relative humidity follows an opposite pattern of higher humidity range from 59.5 – 69.0 % during the winter season and lower humidity range from 30.2 – 50.3 % in the summer season (Table 7). As Doha is a desert climate, precipitation is minimum throughout the year increasing slightly in the winter monsoon season (Table 7).

Table 7 Doha Current Monthly Climatic Conditions

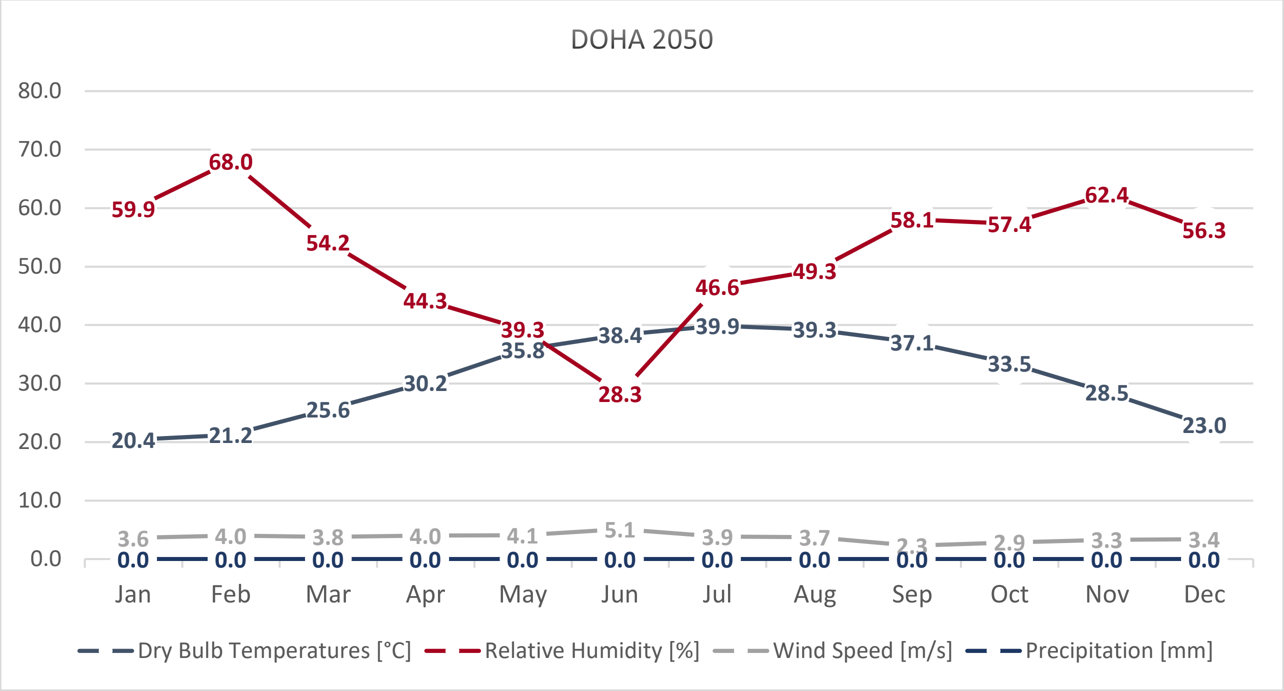
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dry Bulb Temperatures [°C]	18.1	19.1	23.5	28.1	33.3	35.5	37.0	36.1	34.1	30.8	25.9	20.7
Relative Humidity [%]	62.0	69.0	55.2	45.3	40.2	30.2	47.5	50.3	60.2	59.3	65.5	59.5
Air Velocity [m/s]	3.5	4.0	3.8	3.9	4.1	5.2	4.1	4.0	2.3	2.9	3.3	3.4
Precipitation [mm]	0.0	21.0	22.0	13.0	0.0	0.0	0.0	0.0	0.0	0.0	43.0	0.0



The morphed climatic conditions of Doha illustrate an increase in the average external temperatures ranging from 35.8 - 39.9 °C during the summer season depicting an average increase in temperature by 2.70 °C from the current conditions. The winter season temperatures range from 20.4 – 28.5 °C during the winter season depicting an average increase in temperature by 2.45 °C from the current conditions (Table 8). The relative humidity follows a similar opposite pattern of higher humidity during the winter season and lower humidity in the summer season with an average of 2 % decrease in relative humidity as temperatures are higher throughout the year and can hold more moisture (Table 8). Moreover, precipitation is minimum throughout the year increasing slightly during the monsoon season (Table 8).

Table 8 Doha Morphed Monthly Climatic Conditions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dry Bulb Temperatures [°C]	20.4	21.2	25.6	30.2	35.8	38.4	39.9	39.3	37.1	33.5	28.5	23.0
Relative Humidity [%]	59.9	68.0	54.2	44.3	39.3	28.3	46.6	49.3	58.1	57.4	62.4	56.3
Air Velocity [m/s]	3.6	4.0	3.8	4.0	4.1	5.1	3.9	3.7	2.3	2.9	3.3	3.4
Precipitation [mm]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0



4.5 Energy Consumption in Warm and Warmer Conditions

Examining the simulated energy use for the initial setpoint temperature scenario results in an average energy use intensity of 127.7 KWh/m^2 for the total building energy demand and roughly 38.3 KWh/m^2 for a 30% cooling energy demand (Table 9). Qatar's national energy provider Kahrama's annual energy statistics report states an average energy use intensity of 131.9 KWh/m^2 for typical office buildings (Kahramaa, 2014, 2017). In addition, the U.S. Department of Energy (DOE) Standard Benchmark Energy Utilization Index states an average of 115.6 KWh/m^2 for office buildings within the 1A, 2A, and 2B ASHRAE climate zones. The difference between the simulated energy use for the initial setpoint temperature scenarios and the Qatar and DOE averages for office buildings is below 10%. The proximity of the simulated energy use to measured averages validates the energy models for further comparisons.

Table 9 Doha Buildings Energy End-Use Summary in Current Climatic Conditions

Building Designation	BPU1	BPU2	BPR1	BPR2	Qatar 2014	Qatar 2017	USDOE 1A	USDOE 2A	USDOE 2B
Average Total Energy Use (KWh/m2)	**133.8**	**133.8**	**123.0**	**120.1**	**135.3**	**128.5**	**113.5**	**119.8**	**113.5**
Average Cooling Energy Use (KWh/m2)	**40.1**	**40.1**	**36.9**	**36.0**	**40.6**	**38.6**	**34.1**	**35.9**	**34.1**

Observing the simulated energy demand for the initial and comfort temperature scenarios in both current and morphed climatic conditions of Doha represents the current and projected energy impact of excessive building cooling in Doha. The average cooling energy end-use for the buildings in current climatic conditions is 284.4 MWh accounting for an average of 44.6 % of the total energy demand (Table 10).

Table 10 Doha Buildings Energy End-Use Summary in Current Climatic Conditions

	BPU1		BPU2		BPR1		BPR2	
Energy End Use	**Energy (MWh)**	**Portion (%)**	**Energy (MWh)**	**Portion (%)**	**Energy (MWh)**	**Portion (%)**	**Energy (MWh)**	**Portion (%)**
Heating	**6.3**	**0.95%**	**6.3**	**0.95%**	**0.9**	**0.15%**	**0.6**	**0.09%**
Cooling	**306.0**	**45.90%**	**306.0**	**45.90%**	**268.6**	**43.82%**	**257.0**	**42.96%**
Interior Lighting	**83.7**	**12.55%**	**83.7**	**12.55%**	**83.7**	**13.65%**	**83.7**	**13.99%**
Exterior Lighting	**12.5**	**1.88%**	**12.5**	**1.88%**	**12.5**	**2.05%**	**12.5**	**2.10%**
Interior Equipment	**208.4**	**31.25%**	**208.4**	**31.25%**	**208.4**	**33.99%**	**208.4**	**34.83%**
Exterior Equipment	**3.3**	**0.49%**	**3.3**	**0.49%**	**3.3**	**0.53%**	**3.3**	**0.55%**
Fans	**46.6**	**6.98%**	**46.6**	**6.98%**	**35.6**	**5.80%**	**32.8**	**5.48%**
Pumps	**0.0**	**0.01%**	**0.0**	**0.01%**	**0.0**	**0.01%**	**0.0**	**0.01%**
Total End Uses	**666.8**		**666.8**		**613.0**		**598.2**	

Comparing the initial and comfort temperature building cooling scenarios illustrates an increase in energy demand on average by 16.1% with the associated average of 2.0 °C increase in internal temperature (Table 11). In addition, the average increase in the internal temperature by 1.5 °C is associated with a 12.6% increase in energy demand for cooling (Table 11).

Table 11 Doha Buildings Initial and Comfort Temperature Cooling Energy Demands in Current Climatic Conditions

	Initial Temperature		Comfort Temperature		Difference		
	Temperature (°C)	Energy (MWh)	Temperature (°C)	Energy (MWh)	Temperature (°C)	Energy (MWh)	Change (%)
BPU1	22.0	306.0	24.0	257.0	2.0	49	16.01%
BPU2	22.0	306.0	24.0	257.0	2.0	49	16.01%
BPR1	23.5	268.6	25.5	224.6	2.0	44	16.38%
BPR2	24.0	257.0	25.5	224.6	1.5	32.4	12.61%

In morphed climatic conditions, comparing the initial and comfort temperature scenarios represent an average energy demand increase by 14.5% associated with an average of 2.0 °C increase in internal temperature (Table 12). Additionally, the increase in the internal temperature by 1.5 °C is associated with an energy demand increase by 11.4% for cooling (Table 12).

Table 12 Doha Buildings Initial and Comfort Temperature Cooling Energy Demands in Morphed Climatic Conditions

	Initial Temperature		Comfort Temperature		Difference		
	Temperature (°C)	Energy (MWh)	Temperature (°C)	Energy (MWh)	Temperature (°C)	Energy (MWh)	Change (%)
BPU1	22.0	386.6	24.0	331.1	2.0	55.5	14.36%
BPU2	22.0	386.6	24.0	331.1	2.0	55.5	14.36%
BPR1	23.5	344.3	25.5	293.1	2.0	51.2	14.87%
BPR2	24.0	331.1	25.5	293.1	1.5	38	11.48%

Comparing the initial temperature scenarios in current and morphed climatic conditions represent an average cooling energy demand increase by 27.4% associated with the warming of the climate alone (Table 13).

Table 13 Doha Buildings Initial Temperature Cooling Energy Demands in Current and Morphed Climatic Conditions

	Current Climate		Morphed Climate		Difference		
	Temperature (°C)	Energy (MWh)	Temperature (°C)	Energy (MWh)	Temperature (°C)	Energy (MWh)	Change (%)
BPU1	22.0	306.0	22.0	386.6	0	80.6	26.34%
BPU2	22.0	306.0	22.0	386.6	0	80.6	26.34%
BPR1	23.5	268.6	23.5	344.3	0	75.7	28.18%
BPR2	24.0	257.0	24.0	331.1	0	74.1	28.83%

5 Discussion

Through the collection of the thermal sensation vote and the thermal preference votes, it is observed that the thermal sensation and preference vote depict an elevated cold thermal discomfort level in the buildings surveyed. These are indications of the occupants representing a cold thermal discomfort through the physical manipulation of the environment. In addition, Elevated levels of excessive cooling are apparent through the occupant’s clothing and manipulation of the cooling systems within the buildings. This result aligns the findings in the questionnaire to the occupant’s manipulation of the environment to maintain a warm body temperature in additive clothing and cooling system alterations.

The comfort temperatures found for the selected buildings all represented internal temperatures that are higher than the observed internal temperatures. This is an initial indication that occupants prefer warming internal temperatures. Additionally, the observed cooler thermal discomfort votes in the thermal sensation and preference metric align with the notion of a cold internal building temperature. Further, the observation of increased cooling is the underlying logic for the ongoing cultural conversations around occupants being cold in their workspaces. The increased level of cold thermal discomfort is associated with an excessive cooling of the building located within the warm climate of Doha. As the climate of Doha is a warm climate the only means of cooling is from active systems, therefore the excessive cold thermal discomfort is a result of resource use in a form of energy. Considering the increased warming phenomena of the globe, warmer temperatures imposed on buildings will increase resulting in additional energy use to cool the building. The current wasteful use of energy in overcooling buildings in the warm climate of Doha consumes as much energy as predicted by the effect of global warming alone. The understanding of cooling in the expanding warm climate built environment is considered relativity recent and requires additional research.

As the majority of developed regions are concentrated in heat demanding cooler regions, cool demanding warmer climates have been historically overlooked. There exists a shortage in complete current thermal comfort studies within warmer climates. Further research representing current space cooling culture is called for as current urbanization trends within developing warm climate regions are expected to significantly increase the issues of overcooling. In addition to being the largest sector of energy consumption within warm climate built environments, space cooling is likewise the fastest growing. Research around global space cooling projects a significant increase in future cooling demand. This increase is linked to population growth, the built environment expansion, and the increase in the availability and affordability of space cooling systems. Without a proper interpretation of overcooling within the built environment, attempts in its reduction would be unfeasible. Unresolved, overcooling will result in increased building occupant thermal discomfort and contribute to developing regions' energy consumption, considerably increasing its associated environmental degradation.

6 Conclusion

A field study is conducted in buildings of Doha to understand the thermal comfort conditions that exist within them. Elevated levels of cold thermal discomfort are observed through physical observations and collected occupant responses. Observing physical manipulations made by the occupants to keep warm to the environment highlights the excessive cooling within the building. Using the combined thermal sensation and preference metric, increased building overcooling in Doha are observed. The impact of overcooling on energy is estimated to be significant as the majority of the built environment expansion will see a focus in warmer climates where cooling demand is greater. In a warming world, global warming and the built environment expansion are expected to raise cooling demand even further. Without the means to reduce overcooling in warm climate buildings, occupant thermal discomfort, wasteful resource consumption, and increased global carbon emissions would persist.

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