Develop big-data model and dataset originated from public health to study thermal comfort

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Abstract

The recent study shows that big data analytics on an integrated health and thermal comfort datasets could help us better understand human's demands for the thermal environment. This study modifies the health-temperature datasets by considering three systematic influencing parameters: socioeconomic development, population density, and climate temperature. The modified health-temperature modeling/dataset could better explain the observed discrepancies between the thermal comfort neutral temperature and minimum mortality temperature (MMT) with the correlation coefficient increased to 0.91 from original 0.72.

Cross-disciplinary study could benefit the current study through improving data efficiency. For instance, by introducing the large spatial and longitudinal scale of health-temperature datasets, the intensive field experiments and modeling works in the thermal comfort area could be reduced. Furthermore, the impacts of some factors, such as variations with time, gender, and age, on thermal comfort have never reached any conclusive results due to lack of mega demographic data. The recent findings from the public health area may enlighten the thermal comfort community: there is an observable variation of health-temperature (MMT) in response to climate temperature changes; there is no significant health-temperature difference between genders, though female is more inclined to use resources for better environment management. Other factors, such as age and prevalence of air conditioners, are also studied.

1. Background

In a built environment, thermal comfort is defined as "condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" [1]. The determination of occupants' perceived thermal comfort is associated with not only air and radiant temperature, humidity, air movement, clothing, and activity levels, but also occupants' behavioral, physiological and psychological factors, and thus requiring intensive field measurements and modeling development. However, there exist large uncertainties with the results due to limited testing data and multiple variables, many of which are not well controlled and/or understood [2,3].

In the public health area, the recent progresses made on statistical modeling and multinational big data collection enable the quantifiable correlation between mortality/morbidity and ambient weather temperature [4]. Furthermore, a series of studies are conducted to understand the relevant impact factors. Anderson and Bell [5] study the non-linear relationship for 107 US communities with the dataset from 1987-2000. They identify the differences in susceptibility related to age, socioeconomic, urbanity, and the prevalence of central air conditioning. Other researchers [6-8] study the roles of gender, age, and temporal changes with the minimum mortality temperature (MMT) and relative risks.

Jiang, et al. [2] investigate whether the MMT obtained from public health have any correlations with the thermal comfort neutral temperatures. The datasets of 15 global cities with both the MMT and thermal comfort temperatures are compared. The comparison results show that the MMT data are in general good agreement with the measured thermal comfort temperatures. The health-temperature dataset/modeling from the public health area show promising potential for thermal comfort study. However, there are significant discrepancies for some cities, and therefore requiring systematic modifications before the health-temperature dataset could be applied to the thermal comfort study.

There are three research goals for the current study:

- ✓ The previous study on the dataset of 15 global cities demonstrates the benefits of combining health and thermal comfort data for a big data analysis. The power of the big data analysis comes from the mega sample size. Therefore, the first goal of this study is to expand the data size by including more field tests on thermal comfort;
- ✓ In the previous study, though the neutral comfort and minimum mortality temperatures agree well in general, marked discrepancies are observed in some cities. Therefore, this study is to identify the parameters that may lead to such discrepancies, and more importantly, propose a modified model to explain those discrepancies between the two datasets.
- ✓ In this study, we aim to better understand the individual level, i.e. to investigate the impacts of some influential factors, such as age. In the thermal comfort field, there have been many studies on whether demographic differences (e.g. age, gender) would lead to different thermal perceptions. However no consensuses have been reached so far [2, 9]. A main reason is the lack of large amount of subjects to participate over a period of time sufficiently long (e.g. decade basis). The recent

findings through the mega demographic data analysis in the public health area may enlighten some specific thermal comfort studies.

This paper is organized as follows. Section 2 presents the big data analysis on health-thermal comfort combining data with a larger thermal comfort dataset. The modified model to explain those discrepancies between the existing health and thermal comfort datasets is introduced in Section 3. Section 4 discusses the influential factors that might lead to different thermal comfort neutral and minimum mortality temperatures between individuals or sub-groups. Discussions and conclusions are drawn in Section 5.

2. Analysis on the combined health-thermal comfort datasets

2.1 Data

In the previous health-thermal comfort study, the ASHRAE Global dataset II [10] is adopted as the main data resource of thermal neutral temperatures to be compared with the MMT from the public health field [2]. The goal is to investigate whether there are any meaningful correlations between the two disciplines. The 15-city data comparison shows that the MMT data are generally in good agreement with the thermal neutral temperatures. Moreover, the MMT data demonstrate the potential to capture some complex distribution patterns of the thermal comfort data obtained from field tests.

Built upon previous efforts, the first objective of this paper is to include more thermal comfort field data which could be further compared and analyzed with the MMT data. The relevant review papers over the last ten years are studied. The search keywords are: thermal comfort/human comfort, review/overview, indoor, field work, general buildings (e.g. offices, residence, and school buildings), mechanical cooling and heating, and/or natural ventilation. Each review paper refers to at least 100 papers to allow broader coverage. There is a total of 7 review papers meeting above criteria and covering several hundreds of field works, though many of which are overlapped [3, 9-14].

By filtering the field studies from the review papers, some criteria are applied:

- ✓ Field studies that are not included in the previous comparison study by Jiang, et al. [2];
- ✓ In English;
- ✓ Provide either the value/range of the thermal neutral temperature or a localized empirical adaptive model;
- ✓ Represent a specific climate zone and/or a region. For example, both of the review papers by Karjalainen [9] and Wang, et al. [3] list the field study of Nakano, et al. [15], who investigate thermal comfort for both Japanese and non-Japanese workers. The thermal comfort result for such study may not represent local genuine occupants' sensation, and is therefore excluded from the current study;
- ✓ Only field studies are included to reflect "real" buildings occupied by "real" people

doing their normal day-to-day activities. Such selection criterion is adopted by the ASHRAE Global Thermal Comfort Database II [10].

- ✓ For one set of the field data which are presented by multiple papers, only one paper is selected. For example, there is a field study conducted in Kalgoorlie, Australia, presented by two papers: Cena and de Dear [16] and Erlandson, et al. [17]. The current study adopts the paper by Cena and de Dear [16] which is published earlier with complete data presented. The objective of this paper is not to provide a full list of papers rather to cover global field works as many as possible.
- ✓ Remove unique building types, such as theaters, hospitals that are not representative as normal people's daily living environment, and are therefore removed. The special groups, such as young children or elder groups, are also excluded from the current work. As pointed out by Mishra and Ramgopal [13], children have different levels of thermal sensation, metabolic rates, clothing restrictions, sensitivities to temperature changes, and activities compared to adults. There are similar claims for the aging group [18, 19]. The neutral temperatures obtained under special scenarios, such as space heating availability [20], re-adaptation to a different climate zone [21], under an atypical indoor environment [22] that have not been tested widely, are excluded from the current study.
- ✓ There are multiple thermal comfort filed studies for some Chinese cities. However, multiple impact factors are coupled, such as average data of multiple cities [23], and various extreme weather impacts in the city of Chongqing [24]. Therefore, the neutral temperatures obtained can be quite different even for the same city and similar group of subjects. To avoid any "preference selection", the current study only keeps the Chinese cities with the impact factors of seasonal variations, and natural ventilation versus Air Conditioning (AC) modes that have been widely tested and understood. It is expected that with the newly developed big-data model, many of the previous studies for China and other countries could be re-evaluated to identify more findings.

With the above selection criteria implemented, there is a total of 31 field studies included, which are listed in Table 1. Note from now on, cities/metropolitan areas are generally referred to as "cities". For many cities/regions, there could be multiple neutral temperature values due to different testing settings, such as subject difference, season variation, and natural ventilation versus air conditioning system. Therefore, the neutral temperature range with upper and lower bounds is used rather than a single value.

Table 1 Review of the field tests with thermal comfort data in the cities that are not included by Jiang, et al. (2019).

Location	Bldg Type	HVAC	Exp period	Sample info	Major Conclusions	Neutral Temp (ºC)		References
						Lower	**Upper**	
Europe								
France, Lyon	Office	NV, MM, MV	1997-2000	516	Adaptive ctrl algorithm (ACA) alternative temp setpt ctrl for 5 individual Euro countries. Lyon:0.049*Tout+22.58 (Tout<= 10°C); 0.206*Tout+21.42(Tout>10°C)	23.8	23.8	McCartney and Nicol [25]
Greece, Athens	Office	NV, MM, MV	1997-2000	325	Adaptive ctrl algorithm (ACA) alternative temp setpt ctrl for 5 individual Euro countries. Athens: 0.205*Tout+21.69	25.3	25.3	McCartney and Nicol [25]
Portugal, Porto, Afragida	Office	NV, MM	1997-2000	1559	Adaptive ctrl algorithm (ACA) alternative temp setpt ctrl for 5 individual Euro countries. Portugal: 0.381*Tout+18.12	24.2	24.2	McCartney and Nicol [25]
Italy, Bari	Office	NV, AC	Winter and summer	1165 males, 675 females, Ages 17-50 yrs.	Males: winter 20.3°C in AC, 19.8°C in NV; summer 22.8°C in AC, 26.2°C in NV Female: winter 21.3°C in AC, 21.4°C in NV; summer 24.8°C in AC, 26.4°C in NV	19.8	26.4	Fato, et al. [26]
Italy, Bari	Classrooms	NV	Spring	126 college students	21.8°C			Nico, et al. [27]

Italy, Campania	Classroom	NV, heating	2004-2008	4000 subjects, 11-18 years	20°C	20.0	20.0	Alfano, et al. [28]
Germany, multi-cities	Office	NV, AC,MV	Winter	173 males, 148 females	22.7°C	22.7	22.7	Kuchen, et al. [29]
Denmark	Office	AC	July-October	94 males, 133 females	22.2°C	22.2	22.2	Melikov, et al. [30]
Asia								
China, Lhasa	Multifamily housing, others				18.9°C winter, 23.3°C summer	18.9	23.3	Yang, et al. [31]
China, Hainan	Multifamily			991 males, 953 females, Ages 18-52 yrs.	25.8°C for males, 26.3°C for females	25.8	26.3	Lu, et al. [32]
China, Taiwan: Centr, South	Classroom	NV, AC	2003-2004	944 college students, 1294 data sets	26.3°C	26.3	26.3	Hwang, et al. [33]
Singapore	Classroom	NV	Summer	493 subjects	28.8°C for NV classrooms	24.2	28.8	Wong and Khoo [34]
Singapore	Apartment, office				28.5°C NV bldgs; 24.2°C for AC bldgs			de Dear, et al. [35]
India, Kharagpur	Classroom	NV	Whole year	67 college students	29°C	29.0	29.0	Mishra and Ramgopal [36]
Indonesia, Jakarta	Office		12 months	345 males, 227 females, Ages 19-53 yrs.	26.7°C for males, 26.6°C for females	26.6	26.7	Karyono [37]

Indonesia, Jogjakarta	House	NV			29.2°C	29.2	29.2	Feriadi, et al. [38]
Thailand, multi-cities	Office	AC	Eighteen months	620 males, 900 females, Ages 17-60 yrs.	25.7°C for males, 26.2°C for females	25.7	26.2	Yamtraipat, et al. [39]
Thailand, Bangkok	Office and residences	NV			28.0°C	28.0	28.0	Rangsiraksa, 2006
Malaysia, Johor Bahru	Clinic waiting, classroom	NV, AC	January	375 subjects	24.4°C for AC, 28.4°C for NV	28.4	28.4	Hussein and Rahman [40]
Kuwait	Middle school lecture		Fall	167 males, 169 females, Ages 11-17 yrs.	21°C for males, 22°C for females	21.0	22.0	Al-Rashidi, et al. [41]
Israel, Haifa	dwellings	HVAC, Free-running	Summer and winter	189 dwellings in winter, 205 dwellings in summer	HVAC: winter 21.5°C, summer 23°C; Free running: winter 19.5°C, summer 26°C	19.5	26.0	Becker and Paciuk [42]
North America								
USA, Hawaii	Classroom	AC, NV	Winter, summer	2181 NV, 1363 AC	27.4 °C AC bldgs; 26.8 °C NV bldgs	26.8	27.4	Kwok [43]
South America								
Brazil, Florianopolis	Classroom, office	AC, MM	2015/3-2015/10	617 occupants-2688 questionnaires	24°C NV, 25°C AC	22.9	25.0	De Vecchi, et al., 2017
Brazil, Florianopolis	Classroom	NV	1997	28	22.9°C			Xavier and Lamberg [45]

Brazil, Florianopolis	Office	AC, MM	Fall and winter, 2014	796 males, 479 females	23.1°C for males, 24.3°C for females			Maykot, et al. [46]
Brazil, Florianopolis	Office	AC, MM	2014-2016	4158 males, 3406 females	23.4°C for males, 24.2°C for females			Rupp, et al. [47]
Oceania								
Australia, Darwin		AC			AC dry 24.2, AC wet 23.9	23.9	24.2	de Dear and Auliciems [48]
Australia, Townsville	Office	AC	Dry and wet seasons	515 males, 719 females, 17-64 yrs.	Dry: 24.2 C; Wet 24.6 C	24.2	24.6	de Dear and Fountain [49]
Australia, Kalgoorlie	Office		Winter, summer	641 males, 585 females, 16-67 yrs.	Winter 20.3 C; Summer 23.3 C	20.3	23.3	Cena and de Dear [16]
Africa								
Zambia	Old and contemp houses		cool season: June/July	21 subjects, total of 1974 data sets	Thermal comfort temperature 22.2°C	22.2	22.2	Sharples and Malama [50]
Nigeria, Jos	Classroom	NV	summer	200 subjects	26.3°C	26.3	26.3	Ogbonna and Harris [51]

2.2 Results

In Table 1, there are 31 field tests performed in 25 cities with thermal neutral temperatures provided. By comparing the cities in Table 1 with the cities having MMT data available [2], there are two more city/region which can be added to the comparison study of MMT and thermal neutral temperatures, which are Bari of Italy and Taiwan. Even though many cities with thermal comfort data currently don't have the corresponding MMT data available for comparison, it is expected that more MMT data might be available in future for comparison. By adding the two cities to the comparison pool, there is a total of 17 cities worldwide to compare the MMT with the thermal neutral temperatures.

Figure 1 compares the temperature distributions with the increase of ambient temperatures (annual mean temperature) for the 17 cities. For the two new added city/region, Bari and Taiwan, the MMT data are within the thermal neutral temperature ranges. The MMT data catch up some special patterns of the thermal neutral temperatures which do not simply increase with weather temperatures. For example, MMT decreases in San Francisco, Melbourne, Sydney, and the newly added Bari city, as the thermal neutral temperatures do. As observed by Jiang, et al. [2], there are marked discrepancies for five cities: Montreal, Stockholm, London, UK multiple cities, and Hong Kong. The correlation coefficient between the MMT and the median value of thermal comfort for the 17 cities is 0.72.

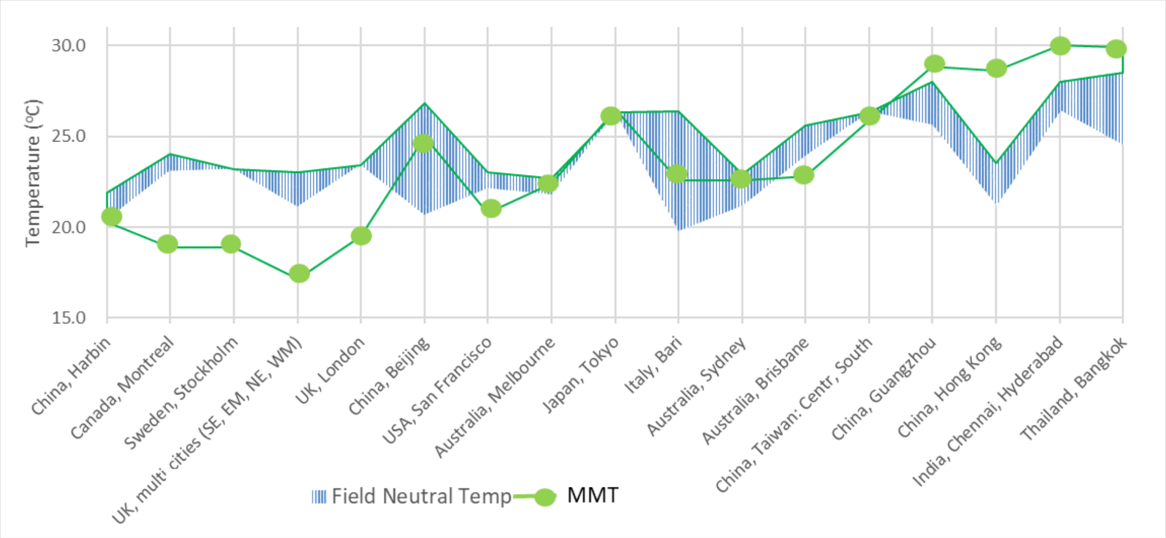


Figure 1. Comparison between the thermal neutral temperature range and the minimum mortality temperatures (MMT) of the 17 global cities.

3. Modeling the discrepancy of health-thermal comfort datasets

3.1 Parameters identification

As shown in Figure 1, there are some significant discrepancies between the two datasets for some cities. The current work is to investigate whether there are some systematic reasons causing such discrepancies, and the health-temperature dataset can therefore be modified for thermal comfort study.

To investigate the systematic reasons, the influencing factors in both disciplines are reviewed first. Since the quantifiable, mega-data study of health burden associated with temperature by Gasparrini, et al. [4], there have been over 600 papers (via Google Scholar) citing the original work with research interests in MMT. To our best knowledge, there are five research papers [6-8, 52, 53] directly addressing the factors with the effects on health-temperature. Since such study is quite new, it is expected that there will be more relevant work presented in the future. Table 2 provides a summary of the relevant factors from the five research papers.

Table 2: The factors that may affect the health-temperature association.

Categories	Corresponding Elements
Climate	Temperature, humidity, pollution
Temporal scale	Longitudinal development
Demographic	Gender, age; Life expectancy at birth.
Socio-economic	GDP, labor productivity, education level, unemployment rate, Gini index, poverty gap, economic power index, savings, consumer power index, AC prevalence.
Health systems	Hospital-bed rates
Urban characteristics	Type of surrounding region (rural/urban), urbanized area share, green area, concentration of population in the core, sprawl.

In order to understand which factors in Table 2 are associated with thermal comfort, the factors affecting occupants' thermal sensation are reviewed as well. In the thermal comfort field, the association between the perceived comfort and ambient environment has been studied for almost half century since the PMV/PPD thermal comfort model proposed by Fanger in the 1970s [54]. The PMV/PPD model, which is based on steady-state heat balance equation, together with the adaptive model [55, 56] developed in the late 1990s are the two mostly accepted comfort models among thermal comfort community, and have been adopted by various global standards [57, 58]. Brager and de Dear [59] compare the two models, and review the relevant factors affecting thermal comfort, which are listed in Table 3 and compared with the factors affecting health-temperature association in Table 2.

Table 3: Factors affecting thermal comfort and corresponding temperature related risk factors in public health.

The Heat Balance Model		**Corresponding factors of the Thermal Adaptive Model**	**Connection with the public health factors (Table 2)**
Categories	**Detailed Description**		
Thermal related factors			
Insulation	Clothing, chair	Behavior: personal	None
Met	Activity patterns, mental stress, transient effects of earlier activities, vigor of a given activity.	Behavior: personal	None
Environment	Air temp, humidity, velocity, radiant; Transient or spatial non-uniformities	Behavior: environment/ tech control; Physiology: genetic adaptation	Climate; Urban characteristics; Temporal scale
Other non-thermal factors			
Demographics	Gender, age, weight.	None	Demographic
	Organizational and social customs, working type; dressing code; environment/ energy regulations	Behavior: culture; Physiology: response to environment stressors	Socioeconomics
	Economics status: capital and operating costs of thermal environmental control systems.	Behavior: culture; physiology: response to env. stressors; psychological feedback.	Socioeconomics
Context	Building design and function: envelope, interior layout, control types.	Behavior: environment/tech control case-by-case	None
	Climate/season: mild climates afford adaptive opportunities; extreme climates need exclusive barrier.	Behavior: environment/tech control	Climate
	Semantics	Behavior: personal	None
Environmental interaction	Lighting, acoustic, and IAQ	Behavior: environment/tech control case-by-case	None
Cognition	Attitude, preference and expectation: one's perception of warmth, control.	Behavior: culture; psychological. Case-by-case	None

In Table 3, some parameters in the thermal comfort area are individualized, case-by-case type, such as personal activity level and clothing type, which have little association with the public health; some parameters are inherently associated with regional and/or generic variations, such as climate and socioeconomics, which also affect the health-temperature association. Therefore, when applying the health-temperature dataset/modeling for thermal comforts studies, the common characteristics between the two areas should be identified and analyzed. Based on the comparison, there are five categories with connections between the thermal comfort and health-temperature areas, which are: climate, temporal scale, demographic, socioeconomics, and urban characteristics.

Among the five categories, both the temporal scale and the demographic (e.g. gender and age) will be investigated in Section 4 with the findings mainly from the public health area. This is because those factors require large spatial and temporal scale studies which are hard to execute, and therefore haven't reached any conclusive results in the thermal comfort field [3, 9, 13].

The parameters of the remaining three categories (i.e. climate, socioeconomics, and urban characteristics) are investigated in this section with the findings from both public health and thermal comfort areas. Though it is beyond the scope of this paper to consider all parameters of the three categories listed in Table 3 for two reasons. Firstly, in the public health area, the impacts of some parameters on health-temperature are still not well understood, and the results are either insignificant or contradictory [5, 7, 53]. Secondly, it is expected that some parameters may play key roles; some are insignificant; and some are coupled together. Therefore, the current objective is to choose one parameter from each category that has been proved significant impacts in the past, and can therefore be applied to modify the current health-temperature dataset/model to verify the effectiveness. Further modifications with other parameters would require more comprehensive data, modeling efforts, and field works.

Parameter 1: Climate - Annual mean temperature

Jiang, et al. [2] find that people chose to look for optimum ambient environment not only for thermal comfort needs but also for better survival chance unless under extreme cold and hot conditions where immediate air conditioning management is needed to remove heat or cold.

In the building science area, to evaluate the heating capability of a building system, the balance point temperature is used as a quick rule-of-thumb. The balance point temperature is the outdoor air temperature when the heat gains of the building are equal to the heat losses. The internal heat sources due to electric lighting, mechanical equipment, body heat, and solar radiation may offset the need for additional heating although the outdoor temperature is well below the thermostat set-point temperature [60, 61]. In a typical building (e.g. offices, residences), when the outdoor mean temperature is below the building balance point temperature, it means that additional heating energy is needed to keep the building space warm. The building balance point temperatures normally range from 10 °C for large open plan office buildings with low surface-area-to-volume ratio and large internal heat gains to 15 °C for small residence buildings with high surface-area-to-volume ratio and less internal heat gains [61]. Normally, the places under better economic situation would be able to spend more resources to live in a warm environment under cold weather [21]. On the other side, from cooling perspective, since indoor air temperature is normally higher than outdoor due to internal heat gains, active cooling measures are needed to reduce indoor temperature even though outdoor temperature is within the thermal comfort range. Givoni [62] lists the experiments conducted to monitor indoor temperature ranging from 2 °C to 10 °C above outdoor temperature under various natural ventilation and other passive cooling conditions.

The research from thermal comfort field shows that thermal comfort is strongly correlated with ambient weather condition which echoes the same claim from health perspective [4]. There is a certain range of ambient temperature (roughly between 10-20°C), within which occupants feel comfortable inside a typical building with any system assistance. However, heating and cooling measures are needed when ambient weather temperature is beyond this “thermal comfort range”.

Parameter 2: Socioeconomic - Two levels of development (advanced economy and developing economy)

There are many indices to evaluate the economic status of a region and citizens. The current study adopts two-level of economic development, advanced and developing, based on the national GDP per capita and the average GDP of the world, which is $11,298/person in 2018, according the World Bank records [63]. Basically, removal of thermal discomfort requires two different actions based on resource availability: act to remove immediately or adapt with wider thermal tolerance. Social economics plays an important role in human perceived thermal comfort. The better economic situation, occupants have a narrower temperature comfort range and willing to achieve thermal comfort at the cost of energy consumption [13].

Parameter 3: Urban characteristic – Floor Area per Person

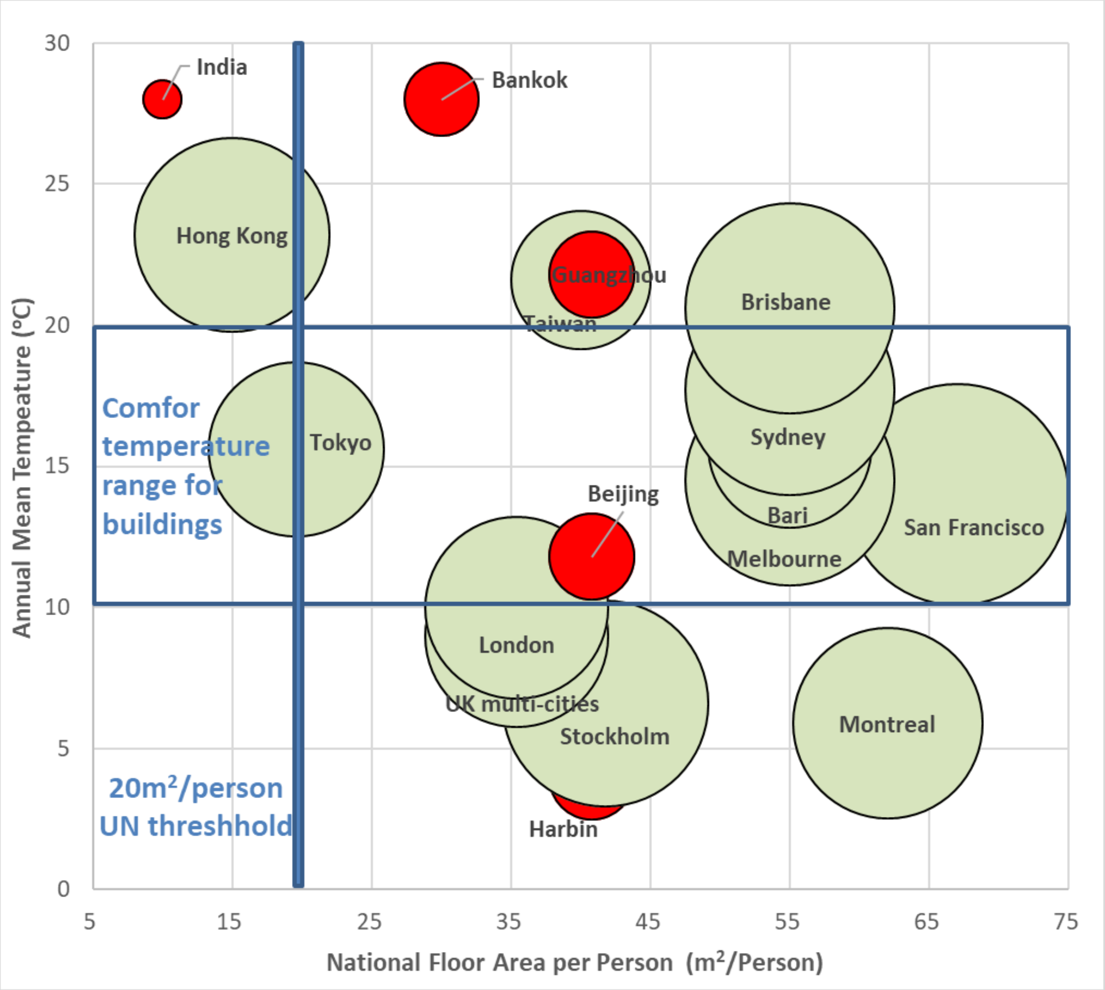
In an occupied environment, if internal heat gains cannot be effectively removed, occupants would feel too warm or hot, and actions are taken to leverage such uncomfortable environment. This normally occur during a hot season, and in a concentrated urban area with limited air movement and high population density.

For the urban characteristic category, there are various indices adopted by different entities. The current study adopts the “Floor Area per Person” as an indicator, which is defined as “the median floor area (in square meters) of a housing unit divided by the average household size” by the United Nations [64]. Such indicator measures the adequacy of living space in dwellings. A low value for the indicator is a sign of overcrowding, which can be associated with certain health risks in low-income settlements [64]. To further investigate the potential health risks due to low floor area per person, the research and professional practices in heating, ventilation and air conditioning (HVAC) area are introduced. Firstly, in an occupied environment, among the sources contributing to internal heat gains, human body is one of the important factors, especially within the core spaces of heavily populated regions. Secondly, concentrated building space prevents the effective ventilation to introduce air movement for cooling and freshness. Therefore, if a living space is too dense, occupants at advanced economy level would use mechanical cooling and ventilation at the cost of energy consumption to remove heat and odors to obtain thermal comfort and freshness immediately. The study by the United Nations [64] shows that floor area per person is more than 20 m^2/person for 60% of the advanced developed countries and only 10% of the developing countries.

Figure 2 presents the distributions of the 17 global cities with the above three systematic parameters and relevant threshold considered. The five cities with large discrepancies between thermal neutral temperatures and MMT might be explained as follows.

Four of the five cities, Stockholm, Montreal, UK multiple cities, and London are located in the right-bottom area, which corresponds to a cold climate zone with average annual temperatures below the balance point of 10°C and relatively spacious living area per capita. As summarized by Mishra and Ramgopal [13]: when money is not a concern, people will prefer to “indulge” in using the ease and effectiveness of gadgets like coolers and conditioners. In a long term, such use makes them less dependent on other adaptive actions. In the current study, the four cities at “advanced economy” level have higher neutral temperatures than the MMT. While in the same cold climate zone, the city of Harbin at “developing economy” level is more adapted to local weather with the thermal neutral temperature similar as the MMT, and is much lower than the other four “advanced economy” cities.

There are two cities, Hong Kong and India, located in the upper-left area, which corresponds to the hot climate zone and crowed living space. The thermal neutral temperature of Hong Kong is significantly lower than the MMT (28% difference compared to the other cities which are all below 10% differences between the two datasets). Hong Kong only has Floor Area per Person of 15 m^2/person, which is less than most of the other “advanced economy” cities in the world with living spaces normally above 20 m^2/person [64]. By comparison, Taiwan is similar to Hong Kong in terms of hot climate, advanced economy, culture, average body dimensions of citizens, and geography. But the floor area per person in Taiwan is over 30 m^2/capita, and the field thermal neutral temperature is 26.3 °C [33] well above Hong Kong’s neutral temperature of 23.5 °C. Another city to compare is Tokyo, whose floor area per person is 20 m^2/person. However, the average annual temperature in Tokyo is 15.6 °C which is within the thermal comfort range and much cooler than Hong Kong (23.2 °C). The occupants in Hong Kong live in an extremely crowded space without effective ways to remove both high-density internal and external heat gains. Therefore, they may prefer to have a cool environment to ease such situation at the cost of energy consumption for mechanical cooling. Another city even worse than Hong Kong in terms of ambient heat and floor area per person is India (Figure 2). However, the low GDP/capita doesn't allow most occupants in India to perceive such cool environment. Though nowadays, with fast economic development in India, there is a vast development of AC market [65]. It is expected that future India may choose to increase floor area and/or reduce thermal temperature at the cost of higher energy consumption.



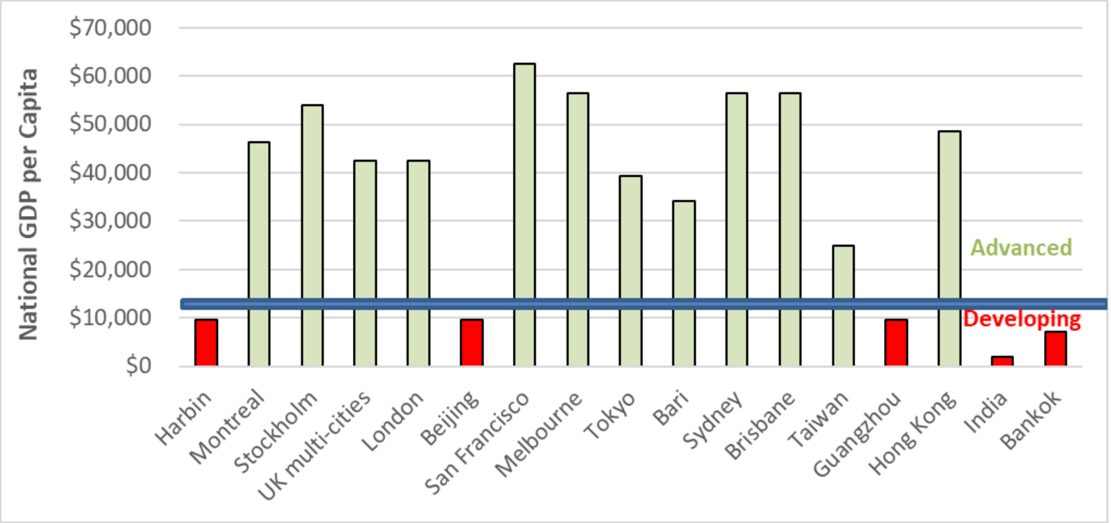


Fig. 2: The distributions of the 17 global cities with three parameters and related thresholds: annual mean temperature, floor area per person, and GDP per capita.
Annual meant temperature: www.climatemps.com
National floor area per person: From various sources, e.g. national/regional statistical bureau, which serves the current analysis for relative magnitude comparison;
National GDP per Capita (The World Bank, 2018);

3.2 Model development

With the three parameters identified, the MMT dataset is modified based on the following three rules:

1. The global thermal comfort neutral temperature is set as the mean value of 23.5°C base on the thermal comfort temperature range provided by ASHRAE Standard 55 [66].
2. In a cold climate, where the outdoor mean annual temperature is below building balance point temperature, the cities with “Advanced economy” prefer warm and comfortable environment at higher heating energy consumption, and thus leading to higher thermal comfort neutral temperatures compared to the MMT. The outdoor temperature threshold for heating is set up as 10°C.
3. In a warm climate, where the outdoor mean temperature is above 20°C, and the averaging floor area per person is below 20 m^2 /person, the cities with “Advanced economy” prefer cool and comfortable environment at higher cooling energy consumption.

The current selection of the thermal comfort neutral temperature, and the temperature thresholds for heating and cooling are based on field experiments and common practices. Further solid and comprehensive research should be conducted to provide data-driven and/or theoretical-based evidence.

Figure 3 shows the modified MMT values considering socioeconomic development, living density, and climate temperature. With the newly developed modeling dataset compared against thermal comfort neutral temperatures, the correlation coefficient is increased from 0.72 to 0.91. To differentiate from the MMT, the newly developed model/dataset is called big-data thermal comfort model since it applies the big-data results from the public health field modified with the systematic health-thermal comfort related parameters.

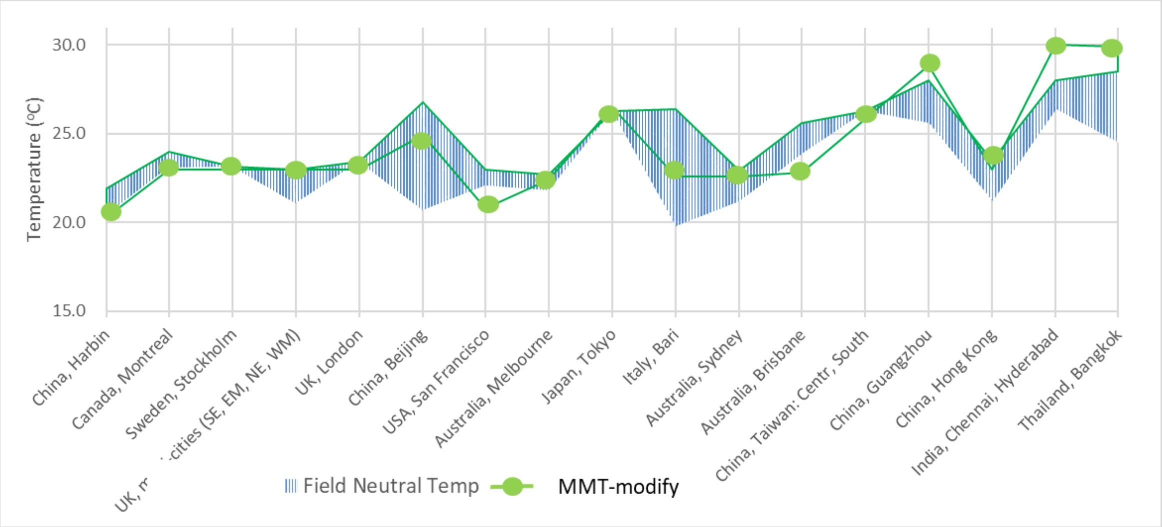


Figure 3: Comparison of thermal neutral temperatures with the modified MMT with systematic health-temperature related parameters.

4. Influencing Factors: Time, Gender, and Age

In this section, we will discuss how occupants' thermal environment demand might involve over time, gender, and age. Such study requires mega temporal and spatial scale datasets, which are hard to obtain from any existing thermal field measurements. As a benefit of integrating comfort and health datasets, these factors could be investigated in the current paper. To our best knowledge, there are seven papers covering nine different countries based on large demographic data and associated mortality/morbidity available to assist current study [6-8, 52, 67-69].

4.1 Longitudinal Studies

Few studies have been conducted to understand how thermal comfort changes over time even though it could provide valuable insight into the adaptive behavior and acclimatization of certain populations change over the years [13]. Table 4 summarizes the temperature changes over years in both thermal comfort and public health areas. Such comparison shows the unparalleled advantage of the big data obtained from the public health area. Such data cover millions of subjects over several decades to one hundred years long compared to the small scale thermal comfort data with several hundred subjects and several years duration except for the UK south tests.

Table 4 shows that the MMT progressively increases for all eight regions covering hot/warm and cold climates except in South Korea without any changes observed probably due to the shortest study period of 15 years. As pointed out by Achebak, et al. [6] and Todd and Valleron [67]: the increase of MMT might be due to human adaptation to the increase of climate temperature. Yin, et al. [70] provides the similar conclusion after investigating six papers with the MMT values of 62 locations from eight countries. In addition to the climate temperature changes, there might be some other reasons causing the MMT variation in terms of trends and magnitudes. For example, the Spanish study only covers the temperature-mortality due to cardiovascular diseases [6]. While the Japanese study indicates that respiration diseases may cause more MMT variation than the cardiovascular disease [7]. Some other factors, such as culture and economic development status, may also contribute to the magnitude of the temperature variations.

In the thermal comfort field, limited cases are available and no significant trends have been observed except for the UK south which also shows an increase of thermal comfort neutral temperature [76, 77]. By comparing the two sets of data, it is clear that a "significant" trend of temperature variations could be observed on several decades basis together with millions of subject data. As pointed out by Brager and de Dear [59], physiological adaptation normally develops at time scales beyond that of an individual's life-time. Current comparisons show that a 30-year and longer period of study might be able to show the adaptation characteristics both from health and thermal comfort perspectives (Table 4).

Table 4: Health and thermal comfort temperatures change over years.

	Region	Time period	Years Difference	Temperature Change (ºC)	No. Subjects	Ref
Health: MMT	Spain	1980-2016	36 years	0.7	4.6 million	Achebak, et al. [6]
	Sweden	1901-2013	103 years	10.5	1.3 million	Astrom, et al. [52]
	Japan	1972-2012	40 years	4.8	30 million	Chung, et al. [7]
	France	1968-2009	41 years	0.7	16 million	Todd and Valleron [67]
	South Korea	1998-2013	15 years	No change	0.66 million	Kim, et al. [8]
	USA	1971-1997	28 years	3.6	~ 1 million	Donaldson, et al. [68]
	Finland	1971-1997	28 years	1.3	~ 1 million	

	UK	1971-1997	28 years	2.7	4.4 million	
	Netherlands	1855-2006	150 years	2+	0.54 million	Ekamper, et al. [69]
Thermal comfort: Neutral temperature	Bangkok	1988/ 2002-03	15 years	-0.7	1377	Busch [71]; Rangsirak [72]
	Singapore	1986-87/ 2000-01	15 years	0.1	818/ 493	de Dear, et al. [35]; Feriadi, et al. [73]
	Harbin	2000-01/ 2009-10	10 years	-1.1	120/174	Wang [74]; Wang, et al. [75]
	UK South	1967/ 2011	44 years	3.7	624/ 230	Auliciem [76]; Teli, et al. [77]

4.2 Gender

When thermal comfort sensation voting is introduced, the differences between male and female subjects in terms of thermal comfort requirements are considered to be small and insignificant [54, 78]. However, the later studies find some differences between the genders [79-81]. Karjalainen [9] provides an overall review of thermal comfort and gender difference. The basic conclusion is that female express more dissatisfaction than males under the same thermal environment, but there are no differences on thermal neutral temperatures identified. The possible reasons behind such dissatisfaction difference are also explored: such as clothing levels, physiological gender differences, and psychological and cultural factors. But there have been no convincing reasons identified mainly due to limited number of tests and participants (less than 50 tests and 1,000 subjects of the same gender for each test) [9].

If we turn to the public health data covering sufficient longitudinal and spatial scope, the findings may provide some in depth insights about the impacts of gender differences on thermal comfort [6, 7]. Figure 4 shows the variations of MMT with years for both male and female in the two countries. In Japan, the MMT of female is lower than male about 0.5 ºC in 1972; the discrepancy is larger in 1990 as 1.5 ºC; and then both are almost the same by 2012. Such longitudinal results show that the MMT and corresponding thermal neutral temperatures can be different or the same depending on the studied periods, and there is no clear trend of MMT differences between genders.

The similar findings are also obtained in Spain. Figure 4 shows that although the MMT of overall males are higher than females, the MMT of males aging from 60-74 years are either equal or lower than the females of the same age.

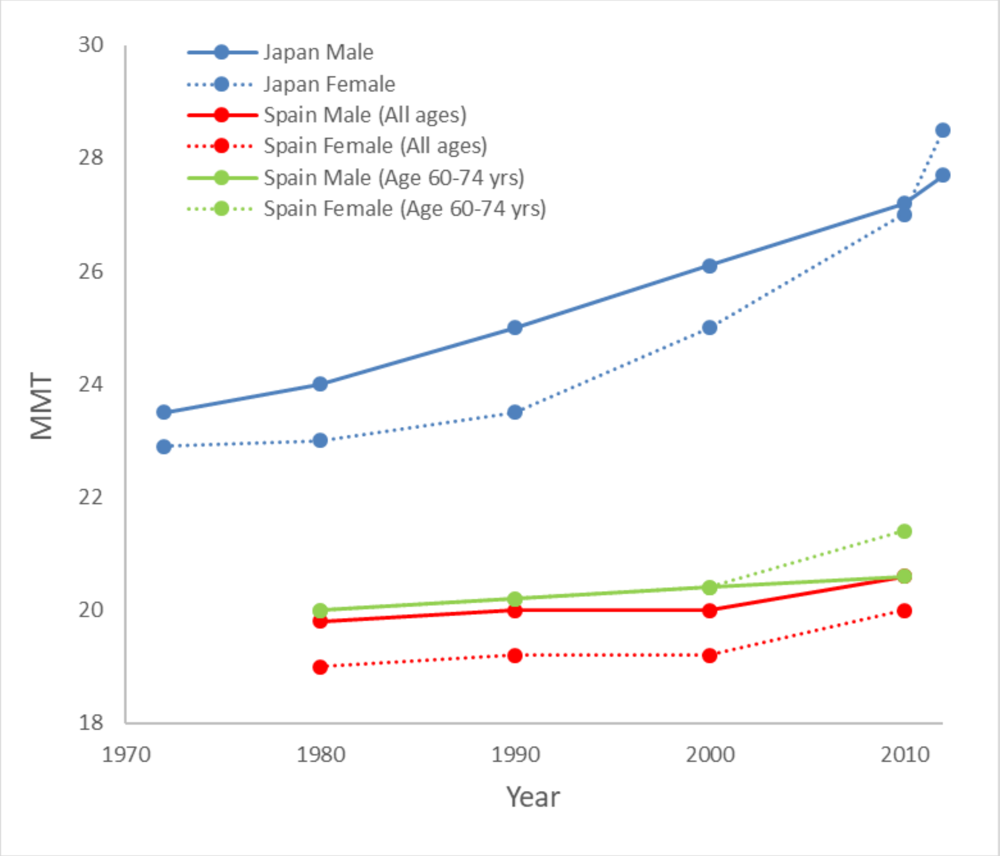


Figure 4: MMT variation with year for males and females Spain [6] and in Japan [7]. Data are extracted from the figures of the reference papers for illustration purpose only.

As for the gender difference, the health-temperature studies show that with the increase of annual savings and socioeconomic status, there is a decrease of cold risks only for females, but not for males [7]. As suggested by Chung, et al. [7], females are more likely than males to utilize their economic resources when applicable to reduce health risks. In the thermal comfort field, it is found that females express more dissatisfaction than males under the same thermal environment even though there is no clear neutral/preferred temperature difference identified between the genders [9]. When comparing the findings in both fields, one hypothesis to explain that females “complain” more than males about ambient thermal environment might be because females are more likely trying to reduce health risks, though more research studies are needed to make any solid conclusions.

Some other findings in the health-temperature area show that females are more in health related risk when exposed to high temperatures and men are more in risk at low temperatures [6]. This seems to be contradictory with the findings in thermal comfort area: females express more dissatisfaction in cooler conditions [3, 9]. There might be two reasons for such contradiction: firstly, the health-temperature research is more focusing on the impacts of extreme temperatures on mortalities while thermal comfort research the studies the comfortable temperature range which is much narrower than extreme temperatures. Secondly, previous health-temperature study shows that cold causes most temperature-related mortalities than heat [4]. Females, who are more likely trying to reduce health risks as stated above, therefore "complain" more about coldness. More thorough analysis should be conducted before making any conclusive claims.

4.3 Age

Few studies provide clear conclusions about the thermal comfort difference due to age. Wang, et al. [3] overviewed four environmental chamber and ten field studies carried out since the earlies chamber experiment conducted by Fanger in the 1970s [82]. No conclusive results have been drawn regarding the significance of age-related difference in the preferred/neutral temperature. Wang, et al. [9], Mishra and Ramgopal [13] show that from physiological point of view, all three major cold defenses get compromised with aging; and it has been generally acknowledged that elderly people are less able to maintain core temperature in cold exposure than the young people.

In the health-temperature field:

- ✓ Chung, et al. [7] finds that demographic variables are strongly associated with MMT at both heat-related and cold-related risks, and elderly people are associated with a higher cold risk.
- ✓ Achebak, et al. [6] compares the MMT for cardiovascular diseases by both age and gender. They find that the MMT in general decreases with ages. There is an exception, for the men of the 60-74 age group, the MMT is the highest among other senior age groups. Though there are two constraints of this study: temperature related mortality is only due to cardiovascular diseases; and most subject data represent senior sub-groups over 60-year old.

For the changes over age, only limited number of thermal comfort and health-temperature studies have been conducted which show that elderly people are associated with a higher cold risk, but no significant temperature differences due to various age sub-groups have been observed. With the introduction of the new model and big dataset, it is expected that more relevant findings could be obtained in future.

5. Discussions and Conclusions

This study focuses on the development of a data-driven thermal comfort model by integrating the public health and thermal comfort dataset. The recent research effort has identified that there is a close correlation between the health and thermal comfort temperatures, corresponding to the minimum mortality temperature (MMT) and thermal comfort neutral temperature respectively [2]. However, there are still some significant discrepancies between the two datasets for some cities, which indicates that unlike MMT, thermal comfort is not simply a physiology based index.

There have been some research efforts conducted to correlate the MMT with indoor health and thermal comfort. Thai et al. [83] presents an indirect epidemiological approach to evaluate the impact of high indoor temperatures on mortality, and recognize the importance of human adaptability to a local climate, which echoes the concept of thermal adaptive model [55, 56]. In this paper, the parameters affecting both occupants' thermal sensation, health-temperature, and three relevant parameters have been identified: GDP per capita associated with socioeconomic status, floor area per person associated with urban characteristics, and climate temperature.

There are two constraints for the data-driven thermal comfort modeling.

1. There are many more influential parameters that require further research to correlate them with health-thermal comfort temperatures, and better understand key drivers in the data-driven thermal comfort modeling. For example, in the public health area, researchers try to understand the mortality impacts of AC prevalence, which is associated with socioeconomic status [7, 8]. But no association is identified between the heat risk and AC prevalence. One possible reason is that those studies are conducted in the countries at advanced economy level, such as South Korea and Japan. As pointed out by Anderson and Bell [5], earlier work found that heat-related mortality decreased significantly in the southeastern US as AC prevalence increased. Over time, such trend disappeared in the cities where AC has reached almost universal prevalence. Therefore, further studies covering more geographic and economic variations should be conducted to understand the parameters' impacts.

2. For the three identified parameter, the determination of corresponding threshold levels require intensive data-driven and/or theoretical-based research efforts and evidence. The current study applies some rule-of-thumb principles and common practices to explore the effects of those parameters. More specifically,
   - ✓ The threshold to differentiate advanced economy and developing economy of a country/region is the average GDP of the world which is \$11,298/capita based on the World Bank record;
   - ✓ The climate temperature range for thermal comfort in a building is 10ºC-20 ºC based on some field experiments and practices in HVAC industry;
   - ✓ The threshold of floor area per person is 20 m^2 /person based on some studies by the United Nations.

   The purpose of the current study is not aiming to ensure accuracy, rather to demonstrate that the data-driven modeling from integrated public health and thermal comfort dataset could open a new horizon and provide benefits to both areas.

By modifying the MMT dataset with the identified parameters and adding more thermal field data for comparison, the observed thermal neutral temperatures could be better explained with the correlation coefficient increased from 0.72 to 0.91. This newly developed data-driven thermal comfort model could shed light on the setup of thermal comfort temperatures in regions where no previous field study has been undertaken. Furthermore, the association studies of occupants' thermal comfort with time, gender, and age require mega temporal and spatial scale datasets, which are hard to obtain from any existing thermal field measurements. The relevant big-data analysis from the public health field is investigated.

- ✓ Longitudinal scale: there are clear adaptation characteristics both from health and thermal comfort perspectives with decades of weather temperature changes;
- ✓ Gender: there is no clear temperature differences between males and females. Though females are more likely trying to utilize available resources to reduce health-related risks when ambient temperature is deviated from the optimal value;
- ✓ Age: Elderly people are associated with a higher cold risk, but no significant temperature differences due to various age sub-groups are observed.

In addition to benefit the thermal comfort and HVAC community, the associations identified among the climate temperature change, occupants' thermal sensation, and health may have multiple impacts on energy and economy planning and development. As illustrated in Figure 5, the climate change causes the variations on weather temperature and thus on both the thermal comfort temperatures and MMT over years. Such changes would lead to the re-evaluation of building temperature setpoint strategies (i.e. wide vs narrow range) and associated HVAC systems as well as energy power systems, which are strongly correlated with overall urban and energy planning and infrastructure. This is because buildings are responsible for about 20%-40% of total energy consumption, and the mechanical and electrical systems (e.g. HVAC, lighting, etc.) of commercial buildings consume about 70% of final energy consumption [84]. Furthermore, such change is not simply a one-way impact. With the vast economy development in some countries currently at a "developing economy" level, such as India, the needs to achieve cooler thermal comfort environment in the summer at the cost of energy consumption increase significantly in recent years. To understand the multi-coupled associations of these crucial elements, more careful, comprehensive, and interdisciplinary studies among building science, public health, design, and policy making on energy and economic development are needed.

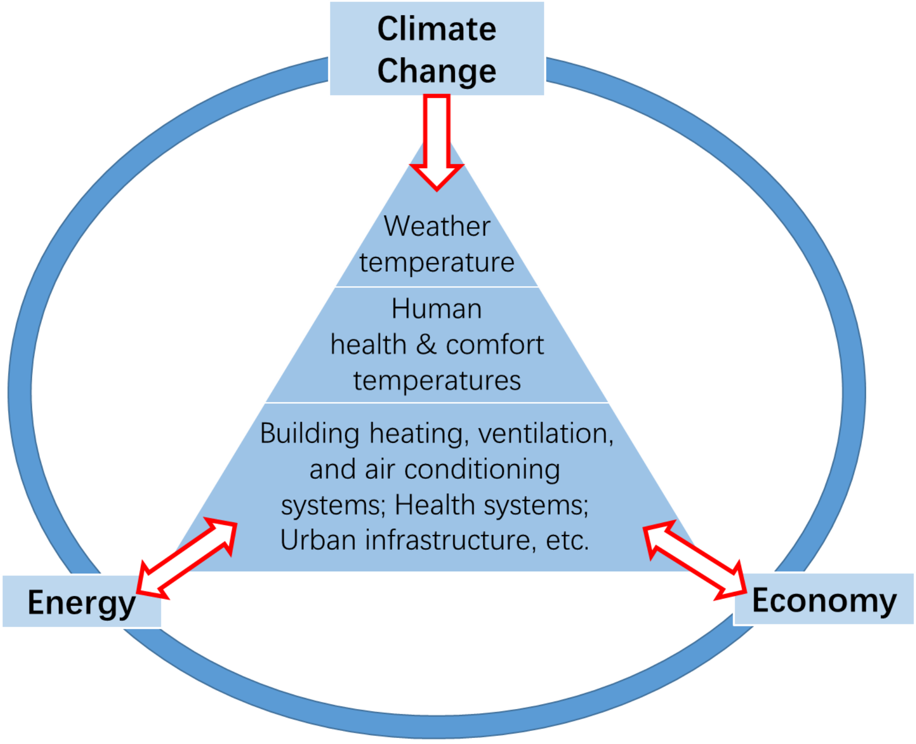


Figure 5. The associations among climate change, energy, and economy due to temperature variation impacts on health and thermal comfort sensation.

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