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Review of thermal comfort infused with the latest big data and modeling progresses in public health

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Abstract

Thermal environment is important for both occupants' comfort and health. Previously, the impacts of thermal environment were explored in the areas of thermal comfort and public health separately. This paper aims to bridge both disciplines by examining the correlation between comfort temperature and Minimum Mortality Temperature (MMT), which is a key index quantifying the association of health and weather temperature, through literature review and data-driven approach. It was found that the MMT data obtained from the public health area are generally in good agreement with the thermal neutral temperatures from the comfort perspective. The MMT data range from 17.2°C to 30°C, which are similar to the thermal neutral temperatures ranging from 19.5°C to 30°C based on the global field tests. Moreover, the MMT data demonstrate the potential to capture some complex distribution patterns of the field comfort data.

The introduction of the health-temperature data could assist the intensive field experiments and modeling efforts and complement the thermal comfort dataset, which suffers from the problems of limited sample size. Some discrepancies between the two datasets were identified as well. The contextual factors other than the

climate factor which may cause such discrepancies, such as socio-economics, population densities, etc. should be analyzed to enable the potential application of the health-temperature data and modeling to thermal comfort and health studies.

1 Background

Occupants spend the most time in a built environment. How to provide them with a comfortable and satisfactory environment is essential. Thermal comfort in the built environment is defined as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation [1]. The importance of studying thermal comfort has been summarized as following three aspects [2-4]:

- ✓ Provide a satisfactory indoor environment for occupants in terms of controllability, productivity, and health. For example, occupants rate thermal comfort as the most important aspect of indoor environment quality [5], which is closely associated with occupants' overall satisfactory [6]. There are studies revealing the correlations between the thermal condition in a built environment and occupants' productivity [7,8] and health [9,10]
- ✓ Achieve energy efficiency and CO_2 emission reduction. With fast economic development in developing countries, e.g. China,

India, more and more occupants are looking for an improved level of indoor thermal comfort. This may lead to a significant energy consumption increase since 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 [11]. The market penetration for HVAC systems in India was about 3% in 2014, but is expected to grow at the rate of 30% annually [12], which could cause a huge increase in energy consumption.

- ✓ Provide recommendations for improving or updating standards. In building industry, the standards related to thermal comfort have been developed to guide designers and operators to deliver a comfortable indoor environment to occupants [1, 13, 14].

In a built environment, the determination of occupants' perceived thermal comfort is associated with not only local temperature, humidity, and air movement, etc., but also occupants' behavioral, physiological and psychological factors, and thus requiring intensive fieldwork and modeling efforts [15-17]. For example, stringent and extensive field studies have to be designed and performed in order to investigate and differentiate the impacts of local climate, culture, socioeconomics, building types, HVAC systems, demographic factors of the participants studied (e.g. genders and age differences), survey semantics, and measuring device selected, etc. [15, 18, 19]. Kim, et al. [20] designed various subjective rating scales based different objectives and application scenarios; Wang, et al. [21] reviewed the challenges facing to obtain correct subjective evaluations of indoor environments; and Zangheri, et al. [22] presented the costs associated with measurement instrument and labor forces to conduct an accurate and large scale thermal comfort assessment. All of the difficulties have led to limited good quality data available from the fields [23]. From 1995-2016, there were 52 field studies performed at 160 Buildings around the world with about 80,000+ survey samples collected and contributed to the open database supported by ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) [24]. Furthermore, there may exist differences among the results obtained from different field tests and empirical comfort models for the same region, which needs more scientific and practice-based discussions on the correctness of the results [25].

The recent progresses made in public health area may open up a new horizon for the thermal comfort community. Historically, there have been many findings in public health field widely accepted by government authorities and industrial professional associations including ASHRAE to guide public policymaking as well as daily practices by industrial professionals. One successful research fusion from public health to other disciplines is the disclosure of mortality associated with long-term exposure to fine particulate air pollution. In the public health area, the effect of long-term pollution exposure on mortality was not well understood until the 1970s when the original research work was conducted with thousands of subjects from multiple cities for more than a decade [26]. Since then, a series of relevant research programs were designed [27-30] and multiple standards and health guidelines were established by government agencies and health organizations [31, 32]. ASHRAE also adopted the research findings by defining indoor air pollution threshold and associated air cleaning devices, etc. [33].

In recent years, there has been a resurgence of research interest in the public health area regarding the correlation between large population of mortality/morbidity and hot/cold weather temperatures due to several extreme weather accidents and climate change [34, 35]. Many quantifiable findings have been identified because of global cooperation on big data collection and statistical modeling advancement [36-38]. Such study helps policymakers and society to react to the extreme weather impact and climate change strategies, etc.

A similar trend was observed for indoor environment studies. As pointed out by de Dear, et al. [39]: in the 1990s, the majority of the research work presented at the Indoor Air Journal was on indoor air quality (IAQ). Since the beginning of the 21st century, there has been a research drift to thermal comfort partly because of the issue of climate change [40].

The objective of the current study is to review the latest development in the public health area regarding mortality association with ambient temperatures and to identify whether such findings and methodology can assist the thermal comfort study.

2. Method

2.1 Review of the data and models on mortality and ambient temperatures in the public health area

In the public health area, there have been many epidemiologic evidences showing the association between ambient temperatures and mortality/morbidity. Basu and Samet [41] pointed out that the observation on heat and mortality had been reported since the early decades of 20th century. The Eurowinter Group [42] studied the cold exposure and daily deaths due to cardiorespiratory related diseases in the winter in eight different regions of Europe with various climate zones. The results show that the mortality increased in all-cause with fall in temperature. In the 12-U.S. city study [36], both the acute effects and lagged influences of weather on cardiorespiratory deaths were investigated. The association between the mortality and high/low temperatures was observed, though there is no clear pattern for the effect of humidity identified. Anderson and Bell [37] studied the non-linear relationship for the 107 U.S. communities with the dataset of 1987-2000. They found that the heat-related mortality was most associated with a shorter lag and cold-related mortality with a longer lag. They also identified the differences in susceptibility related to age, socioeconomic, urbanity, and central air conditioning.

The historical studies show that ambient temperatures are associated with a wide range of cardiovascular, respiratory, and other causes, and therefore represent a significant risk factor. According to the 2015 Global Burden of Disease Study [43], cardiovascular disease and chronic respiratory disease are among the leading causes of deaths in most countries except for the countries prevailed with wars and hungers, etc. However, quantifying the association between the temperature and mortality is not easy. As stated by Gasparrini et al. [38]:

“First of all, the dose-response association, which is inherently non-linear, is also characterized by different lag periods for heat and cold-ie. Excess risk caused by heat is typically immediate and occurs within a few days. While the effects of cold have been reported to last up to 3 or 4 weeks. Secondly, the association is heterogeneous between populations because of acclimatization, different adaptation responses, and variability in susceptibility factors. Modeling of such complex patterns needs a sophisticated statistical approach.”

To quantify the total mortality burden attributable to non-optimum ambient temperature, a multi-country cooperation was organized to analyze 74 million deaths between 1985 and 2012 from 384 locations in 13 countries [38]. Such study was based on the largest dataset ever collected to assess the temperature-health association with various climates and populations. Furthermore, the advancement in statistical modeling [44] was applied to characterize the temperature-mortality association and pool estimates across locations. In particular, “while previous studies relied on simplification of the exposure-response or lag structure, the new approach can help to estimate and pool non-linear and delayed dependencies and to identify the minimum mortality temperature (MMT)”, which is an optimum weather temperature corresponding to the minimum mortality.

The strong correlation between the MMT and ambient weather temperature may indicate some inherent connections with comfort temperatures (e.g. neutral, preferred, etc.) which are associated with ambient weather temperature as well [22]. Therefore, to investigate the potential connection, both datasets are established first and then compared to each other to identify potential correlations between them. For the MMT dataset, all of the subsequent research papers based on the global collaborative work by Gasparrini et al. [38] were studied and summarized. By May 2019, there are about 300 papers citing Gasparrini’s work (Web of Science). Several criteria have been applied to filter the 300 papers.

- ✓ Cover the health impacts on human beings due to both heat and cold;
- ✓ MMT should be calculated;

- ✓ Based on the existing data analysis rather than future scenario prediction;
- ✓ For each specific region/city, only one paper (the latest one) is included unless the publication includes more cities and/or longer time of period. For example, there are two papers studying Stockholm: Astrom, et al. [45] and Astrom et al. [46], between which the latest one [46] is selected.
- ✓ In English

Table 1 shows that global researchers have studied more than 700 different cities/metropolitan areas/regions (from now on generally referred to as “cities”) with about 100 million deaths data covering six continents with different climates, demographic, socioeconomic, and infrastructure characteristics.

Table 1: Review of the papers quantifying mortality due to heat and cold, and other associated contextual factors (Since 2015).

Region/ No. Countries	**No. Cities/ areas**	**Period**	**Mortality No.**	**Findings**	**References**
Global/ 22	340 cities	1985-2014	49,139,516	Heat- and Cold-related deaths affected by pollution density, PM2.5, GDP, Gini index.	Sera, et al., [47]
Sweden	1 county	1901-2013	1,310,934	Cold-related attributable fraction remained stable over time	Astrom, et al., [46]
Latin American/5	40 cities	1997-2015	9,000,000	Temperature-attributable deaths caused by cold (4.1%) more than heat (0.7%); Most temperature-related mortality mainly observed in dry climates.	Tobias, et al., [48]
India	6 zones	2001-2013	546,360	Moderate cold has higher attributable risk (6.3%); The lowest mortality risk at 30 C.	Fu, et al., [49]
Japan	47	1972-	36,058,4	MMT increased from 23.2 C to 28.7 C over 40 years; Certain climate,	Chung, et al.,

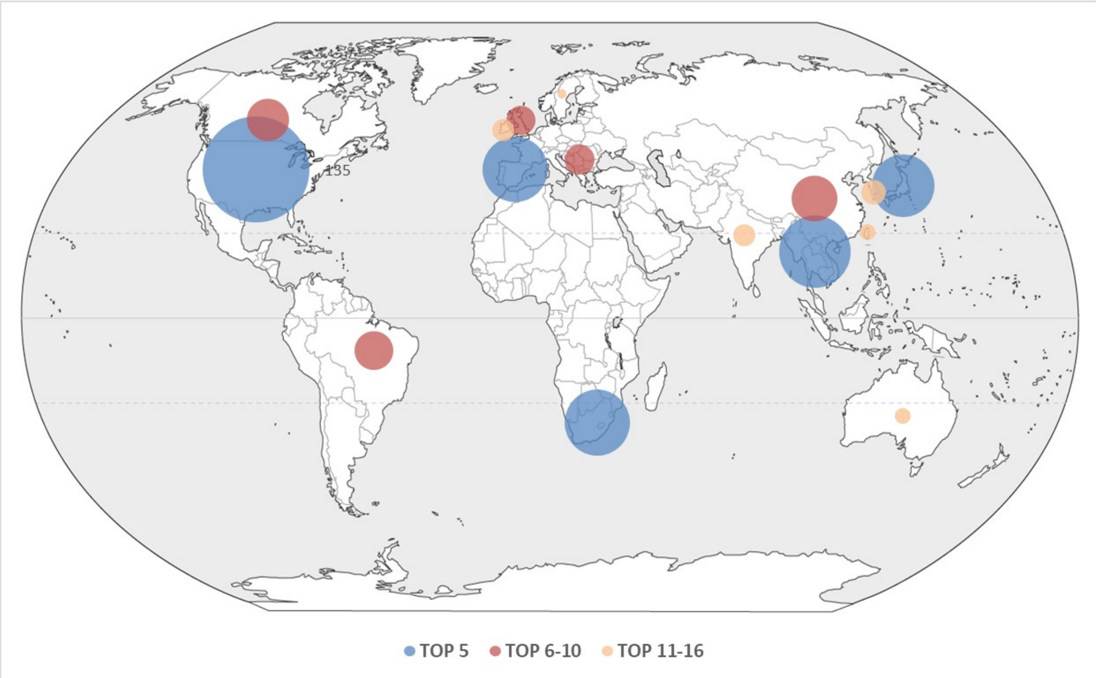
	prefectures	2012	75	demographic, and socioeconomic factors affect susceptibility	[50]
South Africa	52 district	1997-2013	8,800,000	3.4% of deaths attributable to non-optimum temp; The young and elderly vulnerable.	Scovronick, et al.[51]
China	272 cities	2013-2015	1,826,186	14.33% of mortality attributable to non-optimum temperature; Some specific subgroups (female sex, age>75 years, and <9 year spent in edu)	Chen, R., et al., [52]
Global/12	278 cities	1972-2012		Strong evidence shows that most deaths associated in daily analysis with heat and cold are displaced by at least 1-yr	Armstrong, et al., [53]
Spain	52 cities	1990-2010		Presents a method to obtain an estimate, confidence interval (CI), and standard error (SE) for the MMT based on the temperature–mortality shape.	Tobias, et al., [54]
Europe	8 cities	1999-2013	742,526	High temp modify the effects of air pollution (UFP, PM, Ozone) on mortality; High air pollution might enhance the air temperature effect.	Chen, K., et al., [55]
China	16 cities	2007-	114,662	MMT increases from north to south with median of 24.9C; 14.5% of	Yang, et al.,

		2013		stroke mortality attributed to non-optimum temp, with majority to cold	[56]
China	15 cities	2007-2013	936,116	17.1% attributable to ambient temp; Temp deaths caused by cold more than heat	Yang, et al., [57]
Global/12	384 cities	1985-2012	74,225,220	First time quantify heat and cold impacts on deaths; 7.71% mortality attributable to non-optimum temp; More temp-attributable deaths were caused by cold than by heat	Gasparrini, et al., [38]

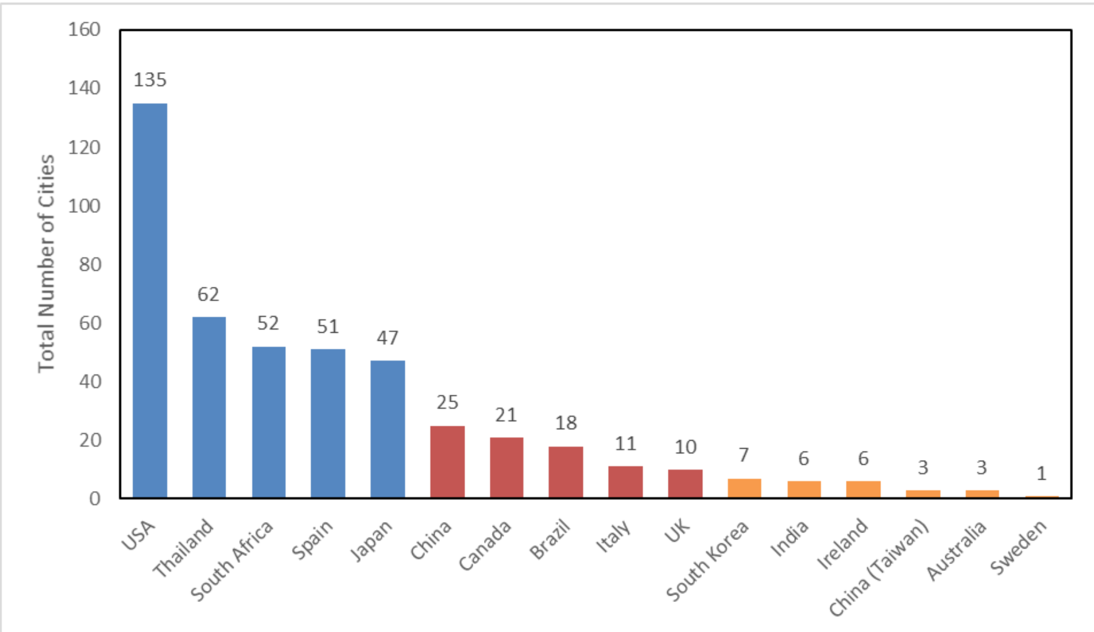
In order to compare the MMT data from the public health area with the thermal comfort data, the "well-presented" results should be collected, which are based on the following two criteria:

- ✓ Presented at peer-reviewed journals;
- ✓ Raw data for each city are provided.

Fig. 1 shows the location of the cities with the MMT data provided. In order to account for the total number of cities, multiple papers with the data for the same city are only accounted for once. For example, in China, there are two sets of data available: one set is from Gasparrini, et al. [38] who studied 15 Chinese cities among the total of 384 cities worldwide; another set is from Yang, et al. [56] who studied 16 cites in China. There were six cities covered by both papers. Therefore, there are total of 25 Chinese cities with the MMT data available. Another two examples are Japan and Sweden, which were originally studied by Gasparrini, et al. [38]. The following studies (Chung, et al., [50]; Astrom, et al., [46]) extended the study periods from the original 28 year and 13 years to 41 years and 113 years respectively. Therefore, the number of cities are still the same as the original paper [38]. There is a total of 458 cities worldwide with the raw data presented in the peer-reviewed journals based on our best knowledge.



(a) The locations in the world with MMT data provided



(b) The total number of cities in each country with the MMT data.

Fig. 1. The location and total number of cities with the MMT

data provided

Fig. 2 further compares the calculated MMT from the two papers for Chinese cities (Gasparrini, et al., [38] and Yang, et al., [56]). There are six Chinese cities studied by both groups. The two sets of data agree well for some cities, such as Beijing, Guangzhou, and Shenyang, which are all within 1°C difference. The largest discrepancy is Shanghai with 3.9°C difference. It is beyond the scope of this paper to investigate which one is more "accurate". Rather, it raises a flag if comparing the MMT data of Shanghai with the thermal comfort data.

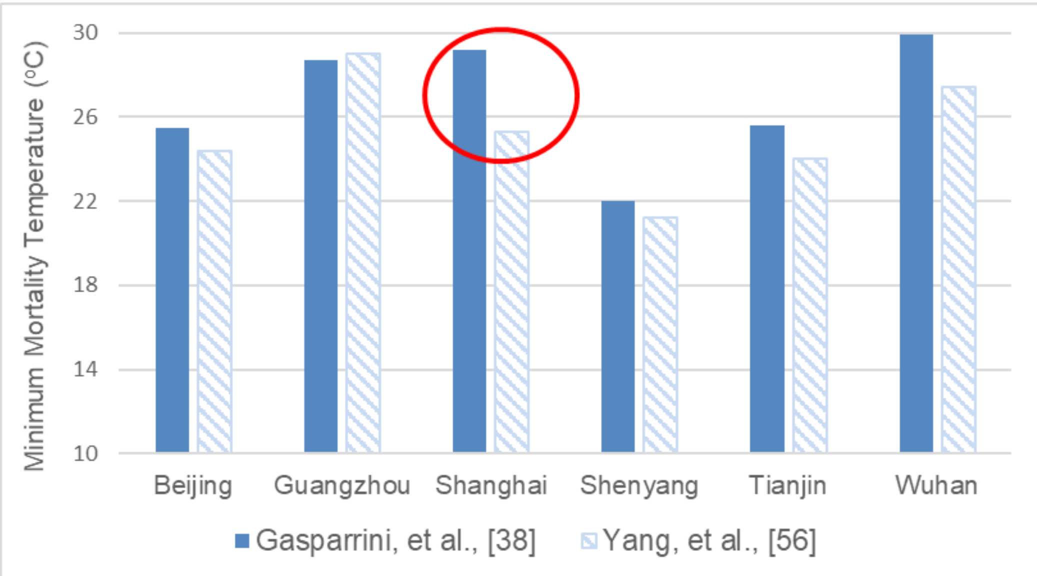


Fig. 2: Comparison of the MMT data for six Chinese cities

2.2 Review of the data and models for thermal comfort in a

built environment

Prediction of the comfortable temperature in a built environment is complicated and depends on not only environmental factors but also human perception factors. Therefore, the research in this area involves various disciplines from building physics, mechanical engineering, physiology, psychology, to socioeconomics, etc.

The original strategy for thermal environment control in an occupied space was to implement industry control philosophy: focusing on environmental settings without considering occupants' perception. There were various versions of Effective Temperatures by integrating multiple environmental parameters e.g. temperature, humidity and airspeed as a set point for an occupied space. Such strategy was adopted by ANSI/ASHRAE standards for more than half a century [58].

In the 1970s, Fanger [59] studied the human perception factor, which was later adopted as a control strategy for an occupied environment. Since then, there has been intensive research work by considering both environmental and human perception factors for environmental control. With several decades of development, most researchers among the thermal comfort community agree that there are two general approaches for determining thermal comfort [39, 60, 61].

PMV-PPD model: Fanger [59] Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD) of human comfort. The PMV/PPD thermal comfort model was then developed based on the steady-state heat balance equation with thermo-physiological data collected from a controlled environment chamber. This model was adopted by various standards, such as ISO 7730 [13] and ANSI/ASHARE 55-1992 [62].

Adaptive model: the original concept was presented by Nicol and Humphreys in the 1970s [63] and illustrated later [17, 64]. Brager and de Dear [15] reviewed the adaptive concept and classified the impactors as physiological (acclimatization), behavioral (use of operable windows, fans, doors, awnings, etc.), and psychological (adjusting comfort expectations toward climatic conditions prevailing indoors and outdoors, etc.). The adaptive model based on global field data [16] was adopted by ASHRAE Standard 55-2010 [1]. The adaptive model based on European field data [65] was adopted by EN15251-2007 [14]. Despite the differences claimed by various versions of adaptive models, the models are inherently similar in terms of the following basic principles/findings [64]:

- ✓ The expression of thermal comfort temperature is as a function of outdoor temperature, i.e. relating acceptable temperatures to the prevailing outdoor temperature [25]

$$T_{comf} = A \times T_{a,out} + B \quad (1)$$

Where T_{comf} = Comfort Temperature (°C); $T_{a,out}$ = Monthly mean outdoor air temperature (°C); and A, B = Constants.

- ✓ Empirical coefficients are statistically calculated based on the field studies;
- ✓ The optimum comfort temperature i.e. neutrality, can be identified with sufficient sample data. The neutral temperature is defined as the temperature at which the majority of the surveyed participants reported their perception of feeling “neutral” with respect to their thermal environment, and no further heating or cooling is needed.
- ✓ Occupants in naturally ventilated buildings accept a wider temperature range of comfort than in centrally controlled HVAC buildings.

After reviewing the literatures of thermal comfort and public health, we propose the hypothesis that there might be some correlations between the calculated minimum mortality temperature (MMT) in the public health area and the neutral temperature in the thermal comfort area. Such hypothesis is mainly based on the two findings:

- ✓ Thermal neutral temperature varies with different climates and regions as the MMT does;
- ✓ Both temperatures are derived based on real-life (field) data of human beings through statistical modeling.

The main objective of this study is to verify the hypothesis we proposed above with large scale widely accepted data that is currently available. In the public health field, we choose MMT dataset, which includes more than 80 million mortality data of 458 cities worldwide (Fig. 1). In the thermal comfort field, the main data source is the ASHRAE Global Thermal Comfort Database II [24] which is recently released and includes 52 field studies conducted in 23 countries with 81,846 data points. In addition, we identified 7 more papers which is consistent and relevant to our research goal but not included in the ASHRAE database [15]. Therefore, a total of 59 studies in the field of thermal comfort has been investigated in this study. We further filtered the 59 papers with the following 3 principles, and finally selected 35 papers as listed in Table 2.

- ✓ The cities with thermal field data are among the 458 cities with MMT data available;
- ✓ The papers are available from scholarly libraries;
- ✓ The papers are presented in English.

Please note that there have been more field experiments than the identified 59 studies [66-68]. The objective of this study is not to make a complete list of the field studies. Rather, the goal is to investigate whether there are some meaningful correlations from both disciplines. After this first step investigation, further studies can be performed to include more field datasets.

Table 2. Thermal comfort field experiments within the regions that have MMT data available for comparison.

Location	Bldg Type	HVAC	Exp period	Sample info	Major Conclusions	References
Europe						
Sweden, Goteborg, Malmo, Halmstad	Office	MM, MV	1997-2000	970	Adaptive control algorithm (ACA) alternative temp setpt control for five individual European countries. Sweden: 0.051*Tout+22.83	McCartney and Nicol, [65]
UK, London	Office	NV, MM, MV	1997-2000	1285	Adaptive control algorithm (ACA) alternative temp setpt control for five individual European countries. London: 0.104*Tout+22.58 (Tout<=10°C); 0.168*Tout+21.63(Tout>10°C)	McCartney and Nicol, [65]
UK,	Multifamil	NV	2015	509	Thermal comfort effect due to air motion	Loveday, etc.,

Loughborough, Yorkshire	y housing				under warmer temp.	[69]
UK, multi-cities (SE, EM, NE, WM)	Office	AC, NV	1995-1996	1,692 people/11,450 votes winter; 1,363 people/9,505 votes summer	NV Comfort range wider than AC; Winter:22.3°C/NV, 23°C/AC; Summer:21.1°C/NV, 22.9°C/AC	Oseland, [70]
UK, South Hampton, Hamshire	Classroom	NV	2011/3-2011/8	260 School children aged 7-11 with 1314 responses	Children are more sensitive to higher temperatures than adults; Actual thermal sensation neutral 20.8°C	Teli, et al. [71]
Asia						
China, Harbin	Multifamily housing	Central heating, NV	2000/12-2001/1	120 occupants mean age 46.4 from 66 households	Male: 20.9°C, Female: 21.9°C	Wang, [72]
China, Harbin	Multifamily housing	Central heating,	2009fall-2010	174 occupants mean age 39.4 from 104	20.4°C	Wang, et al., [73]

		NV		households		
China, Beijing	Classrooms	Space heating; AC	2007-2009	206 college students	Winter: 20.7°C, summer 26.8°C	Cao, et al., [74]
China, Harbin, Beijing, Shanghai	Classrooms	Space heating	Winter (Nov-Mar)	740 college students	Winter comfort comparison: space heating availability affect human behavior impacts	Cao, et al., [75]
China, Shanghai	Classrooms	NV	Sep-following May	105 college students	Thermal comfort perception influenced by previous experience; Adapting to new environment takes years.	Luo, et al., [76]
China, Guangzhou	Classrooms, other	NV	2008/5-2009/5	30 college students	28°C for NV	Zhang, et al., [77]
China, Guangzhou		AC	2009/1-2010/1	30 college students	25.6°C for AC	Zhang, et al., [78]
China, Hong Kong		AC			Summer: 23.5°C; Winter 21.2°C	Chan, et al., [79]

Japan, Tokyo, Yokohama	Classroom	AC, NV	Sep, 2000	74 students mean age 15	Thermal neutral sensation do not correlate with preferred thermal state.	Kwok and Chungyoon, [80]
Japan, Tokyo	Office	AC	2011/7-2011/8	118 subjects	Thermal neutral 26.3°C. Even power saving regulation, increase temp over 27°C cause reduced productivity	Tanabe, et al., [81]
South Korea, Seoul	Senior center	MM	2009/9-2009/10	312 participants	Develop thermal sensation model based on skin temperature for aging people	Bae, et al., [82]
South Korea	Office	MV, MM	2007	262 respondents	More adaptive measures, personal control, help desk help to improve satisfaction	Kwon, et al., [83]
India, Jaipur		AC, NV, MM	2011/4-2013/7	2869 responses	Comfort range in NV is higher than AC; windows, fans, etc. help	Honnekeri, et al., [84]
India, Chennai, Hyderabad	Classroom ,	AC, NV	14 months	2787 occupants - 6048 respondents	These two climate cover 80% of the country; Comfort temp 28.0°C in NV,	Indraganti, et al., [85]

	multifamily, office, etc.				26.4°C in AC	
India, Chennai/ Ahmedabad/Delhi/ Bangalore/Shimla	Office	AC, NV, MM	2012	6330 responses	Develop adaptive comfort models for India and comparison among different models	Manu, et al., [86]
India, Ahmedabad	Multifamily housing	NV	2015/4-2016/1	73 participants, 509 samples	Thermal comfort effect due to air motion under warmer temp.	Loveday, etc., [69]
India, northeast	Multifamily housing	NV	2008 whole year	300 occupants, 150 vernacular dwellings	Perform well during NV season, wide range of comfort	Singh, et al., [87]
Thailand, Bangkok	Office	NV, AC	Hot: 1988/4 Wet: 1988/7	1146 responses	28.5 °C for NV bldgs.; 24.5°C for AC bldgs.	Busch, [88]
Thailand,	Office	NV, AC	Hot: 1988/4	1146 responses	28.5 °C for NV bldgs.; 24.5°C for AC	Busch, [88]

Bangkok			Wet: 1988/7		bldgs.	
North America						
USA, San Francisco	Office	NV	Warm: 2002/9-10 Cool: 2003/2-3	38 warm season, 38 cool season; 2075 responses	Neutral temp: 23°C warm season, 22.1°C cool season; Personal control leads diverse response	Brager, et al., [89]
USA, San Francisco	Office	AC	Cool:1987/1-4, Warm:1987/6-8	304 participants, 2342 visits	Winter: 22°C; Summer 22.6°C	Schiller, et al. [90]
USA, San Francisco	Office	MM	One year	44 participants with 2482	Occupants visual comfort	Konis, [91]
USA, central Texas	Office	AC	2006/9-2011/11	84	Evaluate overall bld performance: energy, water, thermal comfort, IAQ,	Kim, [92]

					lighting, acoustic	
USA, Philadelphia	Office	AC	2012/7-2013/8	24 occupants，2496 sample	Long-term, Multiple behaviors impacts	Langevin, et al, [93]
Canada, Montreal		AC		935 subjects, 1229 datasets	Summer 24°C; Winter 23.1°C	Donnini, et al, [94]
South America						
Brazil, Maceio	Classroom	NV	935 subjects, 1229 sets of data	2075	Subjects' acceptance of higher air vel. increased to compensate elevated temp. and humidity. 26°C~0.4m/s, 30°C ~0.9m/s	Candido, et al., [95]
Oceania						
Australia, Sydney	Office	MM	2009/3-2010/4	60 occupants-1359 comfort questionnaires	Mixed ventilation affect occupants comfort; observed thermal neutral temperature 22.1°C	Deuble and de Dear, [96]
Australia, New	Senior	AC, NV	2015/11-	322 residents, 187	Warm season: 22.9 °C/residents,	Tartarini et al.,

South Wales	center		2016/6	non-residents	22.0 °C/non-residents; Cold season 21.2°C/non-residents	[97]
Australia, Melbourne	Work stations	AC, NV	1982/12-1983/2	211 subjects	NV 21.8°C, AC 22.7°C due to diff outdoor temperature	Auliciems and de Dear, [98]
Australia, Brisbane	Work stations	AC, NV	1983/12-1984/2	186 subjects	NV 25.6°C, AC 23.9°C	Auliciems and de Dear, [98]

In order to extract the meaningful thermal neutral temperatures from Table 2 that can be comparable with the MMT data, the following criteria are further applied:

- ✓ The regional data which provide either the value/range of the thermal neutral temperature or a localized empirical adaptive model can be adopted.
- ✓ The neutral temperatures due to seasonal variations and natural ventilation versus Air Conditioning (AC) modes that have been widely tested and understood are included;
- ✓ The neutral temperatures obtained from a special group, such as special aging groups [71], space heating availability [75], re-adaptation to a different climate zone [76], under an atypical indoor environment [95], which have not been tested to on more generalized scenarios, are excluded from the current study.

Table 3 lists the cities with thermal neutral temperatures processed based on the above criteria. Since for most cities/regions, there are multiple neutral temperature values due to different field tests, various seasons, and/or natural ventilation versus air conditioning, etc., the neutral temperature range with upper and lower bounds is used rather than a single value.

Table 3: The list of cities with the thermal neutral temperatures to be compared with the MMT data.

Location	Neutral Temp (℃)		Data Processing Explanations	References
	Lower	Upper		
Sweden, Stockholm	23.2	23.2	Only Stockholm has MMT, whose annual mean 6.6 C*, similar as the cities with thermal field data and adaptive model. So use 0.051*T+22.83 to predict Stockholm thermal neutral temp.	McCartney and Nicol, [65]
UK, London	23.4	23.4	London annual mean temp 10.4C*. So use 0.168xTout+21.63(Tout>10C)	McCartney and Nicol, [65]
UK, multi-cities (SE, EM, NE, WM)	21.1	23.0		Oseland, [70]
China, Harbin	20.4	21.9	Neutral temp range from multiple papers	Wang Z., [72]; Wang, Z., et al., [73]
China, Beijing	20.7	26.8	Lower and upper neutral temp from winter & summer	Cao, et al., [74]
China,	25.6	28.0	Lower and upper neutral	Zhang, et al.,

Guangzhou			temp from AC & NV	[77]
China, Hong Kong	21.2	23.5	Lower and upper neutral temp from winter & summer	Chan, et al., [79]
Japan, Tokyo	26.3	26.3		Tanabe, et al., [81]
India, Chennai, Hyderabad	26.4	28.0	Lower and upper neutral temp from AC & NV	Indraganti, et al., [85]
Thailand, Bangkok	24.5	28.5	Lower and upper neutral temp from AC & NV	Busch, [88]
USA, San Francisco	22.1	23.0	Neutral temp range from multiple papers & multiple modes	Brager, et al., [89]; Schiller, et al. [90]
Canada, Montreal	23.1	24.0	Lower and upper neutral temp from winter & summer	Donnini, et al, [94]
Australia, Sydney	21.2	22.9	Neutral temp range from multiple papers & multiple modes	Deuble,de Dear, [96]; Tartarini et al., [97]
Australia, Melbourne	21.8	22.7	Lower and upper neutral temp from AC & NV	Auliciems and de Dear, [98]
Australia, Brisbane	23.9	25.6	Lower and upper neutral temp from AC & NV	Auliciems and de Dear, [98]

*: www.climatemps.com (Several global climate datasets were compared. Difference is generally below 3% except for extreme cold zone).

2.3 Comparison between health-temperature and thermal comfort temperature

The hypothesis of the current research is that the latest progress made in public health area based on the developed statistical model and big data analysis [38 and 44] may help to provide macro-scale guidance for the thermal comfort study.

Based on the review work conducted in Sections 2.1 and 2.2, Table 4 compares the data sets, model types, and study period of the two different disciplines. In the public health field, in order to quantify the cold and heat impacts on mortality, there have been more than 700 cities worldwide with about 100 million human mortality data investigated. On the other side, in thermal comfort field, there have been several hundred buildings tested worldwide, and about 10,000+ subjects surveyed, with approximately 100,000+ sample data accumulated in the last half-century. Table 4 compares the differences in terms of spatial, temporal, and number of subjects between the two areas. Although each serves for different purposes, now it is time to identify whether the results based on the large datasets and models from public health field can enlighten the thermal comfort study.

Table 4: Comparison of the data sets, model types, and study periods.

	Thermal Comfort	Public Health
Published Cases	1980s-Now, adaptive concepts initiated, standards adopted	2015-Now, DNLM statistical model, multi-country data
No. Cities/areas	<100	700+
Data collection period	1980s-2015: several days to 2-year measurement	Majority 1980s-2013 except for Sweden, Japan with long period study: 109 yrs, 40 yrs
No. Samples	~100,000 sample responses	~100 million mortality data
Model	Multi-variate linear model	Multi-variate, lag, non-linear model

3 Results

In the current study, there are 15 cities worldwide with both the MMT and thermal neutral temperature datasets. Table 5 presents the comparison between the two datasets. The cities are arranged based on the annual mean temperatures from low to high. The basis for such arrangement is that the current study is from a macro-scale level to identify similar patterns, but not to consider all possible impact factors e.g. humidity, geographic locations, for detailed classified comparisons. Moreover, previous studies show that temperature is the key element determining thermal sensation and mortality in many situations [36, 99].

Table 5 shows that the MMT data agree well in general with the field neutral temperatures. The overall correlation coefficient between the median field neutral temperatures (average of the upper and lower values) and the MMT is 0.72. The large discrepancies of the five cities are Montreal, Stockholm, UK multi-cities, London, and Hong Kong. The differences between the MMT and the range of the thermal neutral temperatures for the five cities are from 3.9-5.1°C, while the differences for the other 10 cities are within 2°C.

Table 5: Comparison between MMT and thermal neutral

temperatures

City/Area	Annual Mean Temp* (ºC)	Field Neutral Temp		MMT (ºC)	MMT & Field Neutral Range Temp Diff (ºC)
		Lower	Upper		
China, Harbin	4.0	20.4	21.9	20.3	0.1
Canada, Montreal	5.9	23.1	24.0	18.9	4.2
Sweden, Stockholm	6.6	23.2	23.2	18.9	4.3
UK, multi-cities (SE, EM, NE, WM)	9.0	21.1	23.0	17.1	4.0
UK, London	10.0	23.4	23.4	19.5	3.9
China, Beijing	11.8	20.7	26.8	25.0	0.0
USA, San Francisco	14.0	22.1	23.0	20.8	1.3
Australia, Melbourne	14.5	21.8	22.7	22.4	0.0
Japan, Tokyo	15.6	26.3	26.3	26.5	0.2
Australia, Sydney	17.7	21.2	22.9	22.6	0.0
Australia, Brisbane	20.6	23.9	25.6	22.8	1.1
China, Guangzhou	21.8	25.6	28.0	28.9	0.9
China, Hong Kong	23.2	21.2	23.5	28.6	5.1

India, Chennai, Hyderabad	28.0	26.4	28.0	30.0	2.0
Thailand, Bangkok	28.0	24.5	28.5	29.9	1.4

*: www.climatemps.com

Fig 3 further compares the temperature distributions with the increase of ambient temperatures (annual mean temperature) for the 15 cities. Fig. 3 shows that when the cities are in the cool zones (high latitude areas with annual mean temperature below 10°C, Table 5), there are large discrepancies between the MMT and neutral temperatures for the four European/Canadian cities, while good agreement for the Chinese city, Harbin. For the rest warm/subtropical/tropical regions, there are generally good agreements between the two datasets, though Hong Kong has a large discrepancy of 5.1°C. If further reviewing the distribution patterns, the MMT data catch some special patterns of the thermal neutral temperatures which do not simply increase with weather temperatures. For example, MMT decreases in San Francisco, Melbourne, and Sydney as the thermal neutral temperatures do.

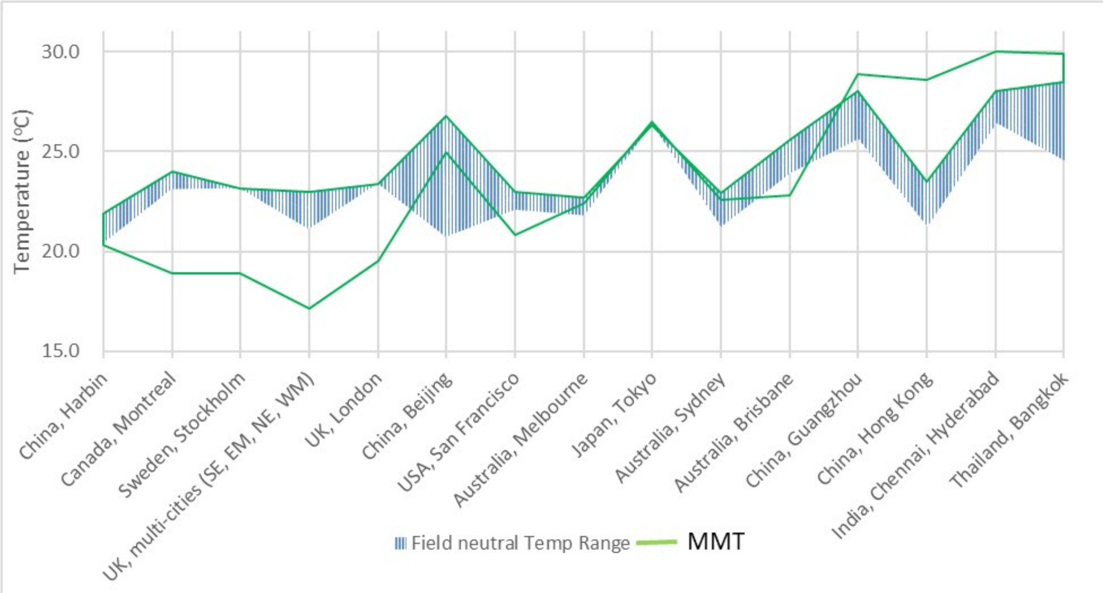


Fig 3: Comparison between the thermal neutral temperatures and the minimum mortality temperatures (MMT) of the 15 cities.

4 Discussions and Conclusions

This study focuses on the health effects of thermal environment by bridging the gap between the field of thermal comfort studies and public health studies through a data-driven approach. In both the thermal comfort and public health areas, the recent progress of large scale data collection enables statistical modeling and quantitative association between the health/comfort temperature and contextual factors e.g. local climate. In this study, we used the neutral temperature to reflect people's thermal comfort demands, and use the minimum mortality temperature (MMT) to reflect health requirements. The comparison results show that the MMT data are generally in good agreement with the measured thermal comfort temperatures. The correlations coefficients between the field thermal neutral temperatures (median value) and the MMT data is 0.72.

In the current study, 15 cities worldwide are selected to compare both the MMT and thermal neutral temperature. With an increase of the mean annual temperature, both thermal neutral temperatures and MMT increase in general. Basically, occupants are adapted to a wide range of thermal comfort, and human bodies are physiologically acclimated to the local weather. As claimed by the thermal comfort community: people are heavily influenced by the weather he is exposed to. So from similar climatic zones, there would be more similarities than differences [99]. As pointed out by Zhang, et al. [100], the comfort range can be from 19.5°C to 30°C, which echoes the MMT range worldwide from 17.2°C to 30°C [33].

If further reviewing the distribution patterns, the MMT data show better potential to catch some special patterns of the thermal neutral temperatures which do not simply increase with ambient weather temperatures as the linear adaptive model does. For example, the MMT data decrease in San Francisco, Melbourne, and Sydney as the thermal neutral temperatures do, which cannot be captured by the adaptive model. This indicates that there may exist possibility of applying the public health data to assist thermal comfort studies. Such efforts will help not only to reduce the intensive field experiments and modeling work but also to analyze some impact factors on thermal comfort which normally require large demographic data over a long time of period, and are almost impossible to obtain any conclusive results from the existing small-scale field studies.

Before applying the large-scale heath data and modeling for comfort study, there are still some significant discrepancies between the two datasets for some cities. For example, in cold regions, there are four cities with higher perceived neutral temperatures than the MMT data: Montreal, Stockholm, London, and UK multiple cities. In warm/hot regions, Hong Kong has a lower perceived neutral thermal temperature than the MMT. One common feature of these five cities/areas is that they are all economically developed cities. This indicates that thermal comfort temperatures are not simply a physiology index as the MMT does. Rather it is inherently subjective based in addition to the association with the ambient weather environment. Brager and de Dear [13] investigated the factors affecting thermal comfort. Both thermal and non-thermal factors are covered for a heat balance model and corresponding behavior adjustment, physiology feedback and psychological feedback, many of which are associated with regional and/or generic impacts, i.e. demographic, socioeconomics, etc. For example, mild climates afford greater adaptive opportunities, but harsh or extreme climates need an exclusive barrier with affordable economic measures. In the public health area, the researchers investigate the health-temperature association with not only the MMT index but also the attributable faction (AF) which reflects the degree of relevance due to heat or cold. It is found that some city indicators could modify the health-temperature association. Example are city population density, Gross Domestic Product (GDP), Gini Index (a measure of income inequality), and fine particles (PM2.5), etc. [47]. Therefore, in order to apply the health-temperature model and dataset to the thermal comfort study, a systematic investigation should be performed first, which is beyond the scope of this paper and will be discussed in greater details in the future [101].

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