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Abstract: Recognizing the value of open-source research databases in advancing the art and science of HVAC, in 2014 the ASHRAE Global Thermal Comfort Database II project was launched under the leadership of University of California at Berkeley's Center for the Built Environment and The University of Sydney's Indoor Environmental Quality (IEQ) Laboratory. The exercise began with a systematic collection and harmonization of raw data from the last two decades of thermal comfort field studies around the world. The ASHRAE Global Thermal Comfort Database II (Comfort Database), now an online, open-source database, includes approximately 81,846 complete sets of objective indoor climatic observations with accompanying "right-here-right-now" subjective evaluations by the building occupants who were exposed to them. The database is intended to support diverse inquiries about thermal comfort in field settings. A simple web-based interface to the database enables filtering on multiple criteria, including building typology, occupancy type, subjects' demographic variables, subjective thermal comfort states, indoor thermal environmental criteria, calculated comfort indices, environmental control criteria and outdoor meteorological information. Furthermore, a web-based interactive thermal comfort visualization tool has been developed that allows end-users to quickly and interactively explore the data.

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Highlights:

- The scope, development, contents, and accessibility of the Comfort Database is documented
- The Comfort Database II includes approximately 76,000 complete sets of thermal comfort data
- The Comfort Database provides access to the collected raw data
- Web-based interactive visualization tool was developed that allows end-users to interactively explore the data

Development of the ASHRAE Global Thermal Comfort Database II

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Abstract

Recognizing the value of open-source research databases in advancing the art and science of HVAC, in 2014 the ASHRAE Global Thermal Comfort Database II project was launched under the leadership of University of California at Berkeley's Center for the Built Environment and The University of Sydney's Indoor Environmental Quality (IEQ) Laboratory. The exercise began with a systematic collection and harmonization of raw data from the last two decades of thermal comfort field studies around the world. The ASHRAE Global Thermal Comfort Database II (Comfort Database), now an online, open-source database, includes approximately 81,846 complete sets of objective indoor climatic observations with accompanying "*right-here-right-now*" subjective evaluations by the building occupants who were exposed to them. The database is intended to support diverse inquiries about thermal comfort in field settings. A simple web-based interface to the database enables filtering on multiple criteria, including building typology, occupancy type, subjects' demographic variables, subjective thermal comfort states, indoor thermal environmental criteria, calculated comfort indices, environmental control criteria and outdoor meteorological information. Furthermore, a web-based interactive thermal comfort visualization tool has been developed that allows end-users to quickly and interactively explore the data.

Key words: Thermal comfort, Field study, Data repository, Visualization tool

1. Introduction

The ASHRAE Thermal Comfort Database I (de Dear, 1998) was compiled in the late 1990s with the simple purpose of testing the adaptive thermal comfort hypothesis and developing a model (de Dear and Brager, 1998), and in 2004 the resulting model went on to form the empirical basis of ASHRAE's adaptive thermal comfort standard for occupant-controlled, naturally conditioned spaces (ASHRAE 2017). That project collated high-quality instrumental measurements of indoor thermal environments and their simultaneous subjective thermal comfort evaluations from 52 field studies conducted in 160 buildings worldwide, mostly commercial offices, between 1982 and 1997. The database assembled almost all of the scientifically rigorous field study datasets available at that time (circa 22,000 questionnaire responses with accompanying instrumental measurements) into a single repository. Upon completion of the original ASHRAE research project, the research team made the database accessible to the global thermal comfort research community via the internet.

An inductive strategy that begins with extant data and works "backwards" towards a research question now complements the more conventional deductive model of science based on hypotheses drawn from theory and testable with experimental data. Even the research niche of thermal comfort has benefited from data mining research methods (Han et al., 2011). In the two decades since its inception, the ASHRAE Thermal Comfort Database I has been mined for diverse research questions well beyond the scope of its original purpose, resulting in many papers in the peer-reviewed literature (e.g. Fanger and Toftum, 2002; Langevin et al. 2015; Zimmerman, 2008; Djamila, 2013, Arens et al. 2010) and higher degree research projects (e.g. Law, 2013). Furthermore, ASHRAE Thermal Comfort Database I has become the first port of call when a question regarding thermal comfort and HVAC practice arises. For example, the current provisions for elevated airspeed in ASHRAE Standard 55 (ASHRAE, 2017) were based exclusively on the analysis of Database I (Arens et al., 2009), as was the dynamic clothing model implemented in the current ASHRAE Standard 55 to estimate indoor clothing insulation levels from 6:00 am outdoor meteorological observations (Schiavon and Lee, 2013). Given the strong connections of thermal comfort with the issues of energy consumption in the built environment (e.g. Nazaroff, 2008), along with building occupant wellbeing and productivity, it is understandable that there has been a resurgence of research activity in the topic over the last two decades (de Dear et al., 2013). New thermal comfort research containing original field data has grown dramatically since the Database I was launched twenty years ago, and so it seems timely that we consolidate those new data into an even larger repository. With a larger body of data to work on, comfort researchers will be able to drill down even deeper while still retaining enough power to deliver statistically significant findings. It should be possible to identify trends of thermal comfort preference over longer time periods as air-conditioning becomes the pervasive building control strategy. The aim of this paper is to document the origins, scope, development, contents, and accessibility of ASHRAE Global Thermal Comfort Database II (short name: Comfort Database).

2. Methods

In order to ensure that the quality of the database would permit end-users to conduct robust hypothesis testing, the team built the data collection methodology on specific requirements, as follows:

- Data needed to come from field experiments rather than climate chamber research, so that it represented research conducted in "real" buildings occupied by "real" people doing their normal day-to-day activities, rather than paid college students sitting in a controlled indoor environment of a climate chamber.
- Both instrumental (indoor climatic) and subjective (questionnaire) data were required, such that they were recorded in the same space at the same time.
- The database needed to be built up from the raw data files generated by the original researchers, instead of their processed or published findings.
- The raw data needed to come with a supporting codebook explaining the coding conventions used by the data contributor, to allow harmonization with the standardized data formatting within the database.
- Data must have been published either in a peer-reviewed journal or conference paper.

All data submissions were subjected to a rigorous quality assurance process. Field data were organised into separate folders according to their origins, including contributor's name, country, and sample size. A detailed list of contributors and the sample size of each submission are summarized in section 3. Each folder contained the raw data files, supplementary codebook, and publication(s) providing details about the field study such as geographic location, building type, cooling strategy, season and climate information. These references are listed in the Comfort Database online Query Builder interface and the visualization online tool (more details below). The research team built a meta-file which allowed easy filtering, such as describing the origin and characteristics of the data, and included the following information:

- *Name* of contributor.
- *Publications* (Authors, Title, Journal/Conference information).
- *Year* of the measurement.
- *Country*.
- *City*.
- *Season* when the measurement was conducted.
- *Climate zone*: data were classified into various climate zones using the Köppen climate classification. A detailed description of the sample sizes grouped in various climate categories is presented in the Results section.
- *Building type*: data were classified into five categories, as follows: Multifamily housing, Office, Classroom, Senior Center and others.
- *Cooling strategy*: data were assigned characteristics of the building's cooling strategy, describing what system type was used while the study was conducted, using the following categories: air-conditioning, natural ventilation, mechanically controlled ventilation, and mixed-mode system (i.e., a combination of natural ventilation and mechanical cooling).
- *Sample size* of each contribution.
- *Directory*: The file path where the raw data, codebook, and publication(s) were saved.

- List of objective and subjective thermal comfort variables that each field study investigated.

The research team created the database file itself using a standardized spreadsheet format. The main header contained the unique identifier for each column of data (i.e., variable names). The information was categorized into the following groups:

- *Basic identifiers*, such as building code, geographical location, year of the measurements, and heating/cooling strategy.
- *Personal information* about the subjects participating in the field studies, such as sex, age, height, and weight.
- *Subjective* thermal comfort questionnaire, such as sensation, acceptability, and preference, as well as self-assessed metabolic rate (met) and clothing intrinsic thermal insulation level (clo).
- *Instrumental* measurements indoor climate, including various types of temperatures, air velocity, relative humidity.
- *Comfort indices*, including Predicted Mean Vote (PMV), Predicted Percentage Dissatisfied (PPD), and Standard Effective Temperature (SET) calculated uniformly throughout the entire database using a calculator that was fully compliant with the ISO Standard 7730 (2005) sourcecode in the case of PMV and PPD calculations, and ASHRAE/ANSI Standard 55 (2017) sourcecode in the case of the 2-node SET index. Compliance of the calculator was checked by applying it to the validation datasets supplied in appendices to the two standards.
- *Indoor environmental controls* available (blinds, fan, operable window, door, heater).
- *Outdoor meteorological* information, such as monthly average temperatures. Some original data submissions contained relevant meteorological data. For cases without those data, fields meteorological data were updated based on archival weather data sourced from weather station websites based on the available information about location and the time of the measurements.

All datasets from individual studies were subject to a stringent quality assurance process (Figure 1) before being assimilated into the database. The research team conducted a final validation by first comparing each raw dataset with its related publication provided by the data contributor to prevent transmission errors. Systematic quality control of each study was performed to ensure that records within the database were reasonable. Firstly, distributions of each variable were visualized to identify aberrant values. Then, cross-plots between two variables (e.g. thermal sensation and thermal comfort) were used to check for incorrectly coded data. Finally, a few rows from each study were randomly selected to verify consistency between the original dataset and the standardized database. Since the data came from multiple independent studies, every record did not necessarily include all of the thermal comfort variables. Where data were missing, that particular range of cells was filled with a null value. The thermal comfort visualization tool (described later) was used to help remove anomalies in the data. The detailed list of project identifiers and thermal comfort variables is presented in the Results section.

The database is structured so that rows (i.e., "records") represent an individual's questionnaire responses, and the columns include the associated instrumental measurements, thermal index values, and outdoor meteorological observations. Table 1 summarizes the full listing of variables in the database file and their coding conventions. There is a total of 49 possible thermal comfort variables for each record. There are 65 columns so that quantities can be expressed in both imperial and metric units, and any post-processed variables can be flagged. The "offline" spreadsheet version of the database includes the codebook for each parameter. The full citation for the original publication associated with each dataset is also stored in the database. Users can download the latest database version through the University of California's DASH repository (Foldvary et al. 2018)

Table 1. Variable coding conventions.

Variable	Description
Basic Identifiers	
Publication (Citation)	Published paper describing the project from where the data was collected
Data contributor	Principal Investigator of the study
Year	Year when the field study was conducted
Season	Spring, Summer, Autumn, Winter
Climate	Köppen climate classification
City	City where the study was done
Country	Country where the study was done
Building type	Classroom, Multifamily housing, Office, Senior Center, others
Cooling strategy	Air Conditioned, Mechanically Ventilated, Mixed Mode, Naturally Ventilated
Subjects' Personal Information	
Age	Age of the participants
Sex	Male, Female, Undefined
Subject's Weight	Participating subject's weight (kg)
Subject's Height	Participating subject's height (cm
Subjective Thermal Comfort Information	
Thermal sensation	ASHRAE thermal sensation vote, from -3 (cold) to +3 (hot)
Thermal acceptability	0-unacceptable, 1-acceptable
Thermal preference	cooler, no changes, warmer
Air movement acceptability	0-unacceptable, 1-acceptable
Air movement preference	less, no change, more
Thermal comfort	From 1-very uncomfortable to 6-very comfortable
Clo	Intrinsic clothing ensemble insulation of the subject (clo)
Met	Average metabolic rate of the subject (Met)
activity_10	Metabolic activity in the last 10 minutes (Met)
activity_20	Metabolic activity between 20 and 10 minutes ago (Met)
activity_30	Metabolic activity between 30 and 20 minutes ago (Met)
activity_60	Metabolic activity between 60 and 30 minutes ago (Met)
Humidity sensation	3-very dry, 2-dry, 1-slightly dry, 0-just right, -1slightly humid, -2-humid, -3-very humid
Instrumental Thermal Comfort Measurements	
Air temperature	Air temperature measured in the occupied zone (°C, °F)
Ta_h	Air temperature at 1.1 m above the floor (°C, °F)
Ta_m	Air temperature at 0.6 m above the floor (°C, °F)
Ta_l	Air temperature at 0.1 m above the floor (°C, °F)
Operative temperature	Calculated operative temperature in the occupied zone (°C, °F)
Radiant temperature	Radiant temperature measured in the occupied zone (°C, °F)
Globe temperature	Globe temperature measured in the occupied zone (°C, °F)
Tg_h	Globe temperature at 1.1 m above the floor (°C, °F)
Tg_m	Globe temperature at 0.6 m above the floor (°C, °F)

Tg_l	Globe temperature at 0.1 m above the floor (°C, °F)
Relative humidity	Relative humidity (%)
Air velocity	Air speed (m/s, fpm)
Velocity_h	Air speed at 1.1 m above the floor (m/s, fpm)
Velocity_m	Air speed at 0.6 m above the floor (m/s, fpm)
Velocity_l	Air speed at 0.1 m above the floor (m/s, fpm)
Calculated Indices	
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
SET	Standard Effective Temperature (°C, °F)
Environmental Control	
Blind (curtain)	State of blinds or curtains if known (0-open, 1-closed); otherwise NA-non applicable
Fan	Fan mode if known (0-off, 1-on); otherwise NA-non applicable
Window	State of window if known (0-open, 1-closed); otherwise NA-non applicable
Door	State of doors if known (0-open, 1-closed); otherwise NA-non applicable
Heater	Heater mode if known (0-off, 1-on); otherwise NA-non applicable
Outdoor monthly air temperature	Outdoor monthly average temperature when the field study was done (°C, °F)

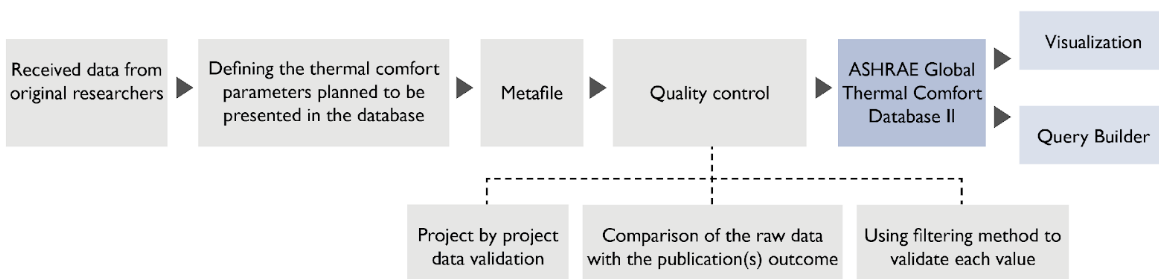

Figure 1. Flowchart of the data collection and quality assurance processes.

3. ASHRAE Global Thermal Comfort Database II

3.1 Database description

The final Comfort Database is comprised of field studies conducted between 1995 and 2016 from around the world, with contributors releasing their raw data to the project for wider dissemination to the thermal comfort research community. After the quality-assurance process, there was a total of 81,846 rows of raw data of paired subjective comfort votes and objective instrumental measurements of thermal environmental parameters[2].Standardized data files from the ASHRAE RP-884 Adaptive model project (de Dear, 1998) were transformed and assimilated into the new database structure with appropriate coding conventions. Thermal comfort indices were recalculated using the same validated code used throughout this project to ensure

[2] this paper is based on data contributions received by February 2018. Researchers can contribute new data to the ASHRAE Global Thermal Comfort Database II by contacting the corresponding author.

consistency. A total of 25,617 records from the RP-884 database were added to Database II, bringing the total to 107,463. The following sections will describe the new datasets only; more information on the field studies from the RP-884 database can be found in the final report (de Dear et al, 1997).

3.1.2 Data distribution by geographical location

The field studies from which this database draws were conducted in five continents, with a broad spectrum of geographical locations (countries) represented. Figure 2 shows the distribution of records within the database by continent. The largest portion is from European (n = 31,392) and Asian field studies (n = 29,064). South America (n = 7,390) and North America (n = 9,969) have a similar number of records. Africa is represented by 2,163 rows of data, and Australian studies accounted for 1,868 rows. Overall, the Comfort Database includes field study data from 23 countries, including Australia, Belgium, Brazil, China, Denmark, France, Germany, Greece, India, Iran, Italy, Japan, Malaysia, Mexico, Nigeria, Philippines, Portugal, Slovakia, South Korea, Sweden, Tunisia, the United Kingdom and the United States of America (Figure 3).

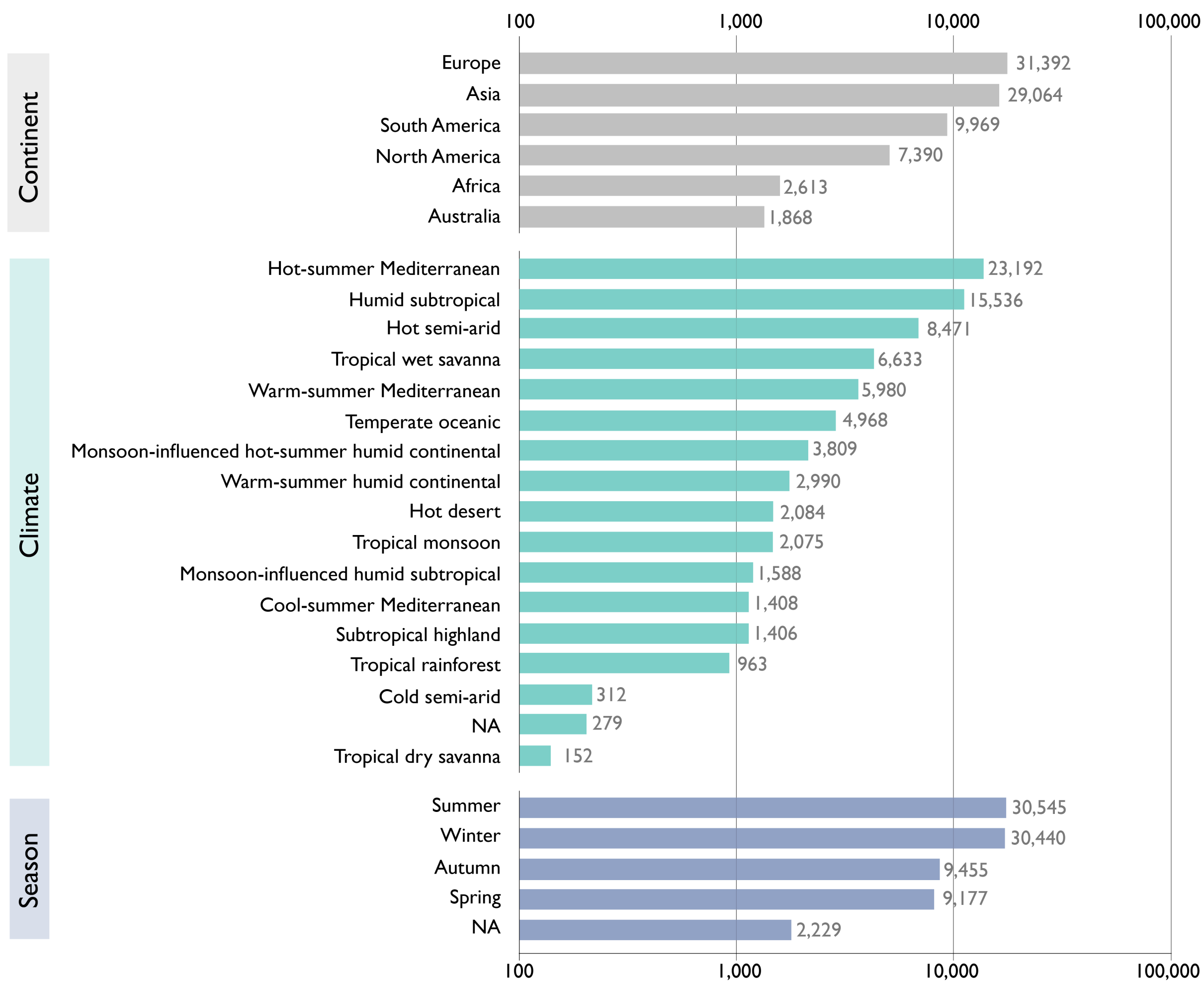

Figure 2. Distribution of thermal comfort data by continent.

Table 2 lists the associated publications and important metadata for each dataset e.g. location, season, building type, etc. The largest dataset is from Oseland's (1998) study based in the United Kingdom, which took measurements in all four seasons (spring, summer, autumn and winter), characterizing thermal environments in naturally ventilated multifamily houses (Loveday et al, 2016) as well as office buildings using various cooling strategies such as natural ventilation, mixed-mode, mechanical ventilation (Oseland, 1998; Stoops, 2001; McCartney and Nicol, 2002) and air-conditioning (Oseland, 1998). The second highest number of observations comes from the Indian thermal comfort research community (Honnekeri et al, 2014 a; Honnekeri et al, 2014 b; Indraganti et al, 2014; Manu et al, 2016; Singh et al, 2010), which is similar to the British contributions, originated from all four seasons representing thermal environments in air-conditioned classrooms, naturally ventilated multifamily houses, offices and other building types using various type of cooling strategies.

Figure 3. Location of the field studies contained in the ASHRAE Global Thermal Comfort Database II.

Table 2. Basic metadata for contributions to the ASHRAE Global Thermal Comfort Database II.

Publications	**Experiment location**	**Building type**	**Cooling strategy**	**Sample size**
Andamon, 2006	Philippines	Office	AC	277
Bae et al., 2016	South Korea	Senior center	MM	312
Kwon et al., 2011	South Korea	Office	MV, MM	262
Bouden et al, 2005	Tunisia	Multifamily housing, Office	NV, MV	1 651
Brager et al, 2004	USA	Office	NV	2 075
Cândido et al., 2010	Brazil	Classroom	NV	2 075
Cao et al, 2011 and 2016	China	Classroom, Office	AC, NV	1 735
De Vecchi et al, 2012	Brazil	Classroom, Office	AC, MM	5 036

De Vecchi et al, 2017				
Deuble et al, 2012	Australia	Office	MM	1 359
Djamila et al, 2013	Malaysia	Multifamily housing, Office	AC, Undefined	989
Földváry et al, 2017, Pustayová, 2013	Slovakia	Multifamily housing	NV	648
Hawighorst et al. 2016	Germany	Office	MM, NV	628
Heidari et al, 2002	Iran	Multifamily housing, Office	NV	1 971
Honnekeri et al, 2014 a	India	Classroom, Multifamily housing, Office, Others	AC, NV	2 859
Honnekeri et al, 2014 b	USA	Office	NV	1 408
Indraganti et al, 2014	India	Office	AC, NV, MM	6 048
Jin et al, 2013	China	Others	NV	376
Kim, 2012	USA	Office	AC	84
Konis, 2013	USA	Office	MM	2 482
Kwok and Chun, 2003	Japan	Classroom	AC	74
Langevin et al, 2015	USA	Office	AC	2 497
Liu et al, 2013	China	Multifamily housing, Others	AC, NV	610
Loveday et al, 2016	United Kingdom	Multifamily housing	NV	509
Luo et al, 2016	China	Classroom	NV	1 810
Nakamura et al, 2008	Japan	Multifamily housing	MM	715
Oluwafemi and Adebamowo, 2010	Nigeria	Multifamily housing	NV	512
Oseland,1998	United Kingdom	Office	AC, NV	20 997
Pedersen, 2012	Denmark	Classroom	MV	170
Romero et al, 2013	Mexico	Multifamily housing	NV	1 423
Manu et al, 2014	India	Office	AC, NV	6 330
Loveday et al, 2016 (based on India data from Rawal et al, CEPT University, India)	India	Multifamily housing	NV	573
Sekhar et al, 2003	Singapore	Office	AC	217
Singh et al, 2010	India	Multifamily housing	NV	300
Singh et al, 2014	Belgium	Multifamily housing	NV	85
Stoops, 2001 McCartney and Nicol, 2002	France	Office	NV, MM, MV	516
	Greece	Office	NV, MM, MV	325
	Portugal	Office	NV, MM	1 559
	Sweden	Office	MM, MV	970
	United Kingdom	Office	NV, MM, MV	1 285
Tanabe et al, 2013	Japan	Office	AC	118
Tartarini, 2018	Australia	Others	AC, NV	509
Teli et al, 2012	UK	Classroom	NV	2 990
Wagner et al, 2007	Germany	Office	NV	427
Wang, 2006 Wang et al, 2011 Wang et al, 2014	China	Office, Classroom, Multifamily housing	NV, MV	1 380
Xavier, 2000	Brazil	Undefined	Undefined	279
Zangheri et al, 2010 and 2011	Italy	Classroom, Office	AC, NV	283
Zhang et al, 2010 and 2013	China	Classroom. Other	AC, NV	2 324
			Total	**81,846**

Note: AC-Air Conditioned, NV-Naturally Ventilated, MM-Mixed Mode, MV-Mechanically Ventilated

3.1.3 Data distribution by climate zones and seasons

Seasonal variations as well as prevailing weather can impact physiological acclimatization, behavioural adjustment and indoor comfort expectations (Brager and de Dear 1998). This section presents the distribution of thermal comfort data according to the Köppen climate classification.

The Comfort Database contains thermal comfort field measurements from 16 distinct Köppen climate classes (Figure 2). Climate zones with the highest numbers of thermal comfort data include hot-summer Mediterranean (n = 23,192), humid subtropical (n = 15,536), hot semi-arid (n = 8,471), and tropical wet savanna (n = 6,633). Other samples were classified as warm-summer Mediterranean (n = 5,980), temperate oceanic (n = 4,968), Monsoon-influenced hot-summer humid continental (n = 3,809),warm-summer humid continental (n = 2,990), hot desert (n = 2,084), tropical monsoon (n = 2,075), monsoon-influenced humid subtropical (n = 1,588) and cool-summer Mediterranean (n = 1,408) regions. Relatively small volumes of data came from the subtropical highland (n = 1,406), tropical rainforest (n = 963), cold semi-arid (n = 312), and tropical dry savanna (n = 152) climate zones. Due to missing information, some samples (n = 279) could not be classified into any climate group and were assigned a null value.

Figure 2 summarises the seasonal distribution of data points. The highest number of observations were collected in summer (n = 30,545). There was a slightly lower sample size for winter (n = 30,440), and fair representation of the shoulder seasons of spring (n = 9,455) and autumn (n = 9,177). Some datasets did not contain the requisite information to classify season (n = 2,229), and these entries were left undefined.

3.1.4 Data distribution by building type and cooling strategy

The research team classified the thermal comfort data into five main building categories, including offices (n = 55,238), classrooms (n = 12,755), multifamily houses (n = 10,120), senior centers (n = 312) and a building category defined by the contributor as “others” (any other building type than the defined ones) (n = 3,421).

The team also collected information on cooling strategy used in each building, with the largest proportion of measurements being from buildings using natural ventilation (n = 38,584), followed by air-conditioned buildings (n = 28,544). A significant number of thermal comfort data came from environments using mixed-mode cooling (n = 11,745), while a smaller sample was collected from mechanically ventilated spaces (n = 1,804). As with other descriptors, data that could not be confidently classified into any of the defined cooling strategies were grouped as undefined (n = 1,169).

Table 3 shows the distribution of records by continent, building type, and cooling strategy. Most of the field measurements from European studies were collected from offices (n = 26,929) that were either naturally ventilated or air-conditioned. Similarly, most of the data sourced from Asian countries were from office buildings (n = 14,839), with the majority using mixed mode ventilation. Data from South America, however, are mostly measurements made in classrooms (n = 4,366) that were naturally ventilated or with mixed-mode cooling. The residential context is well-represented in the African dataset. Both the North American and Australian datasets were wholly comprised of offices.

Table 3. Sample size distribution according to the data´s experimental location.

		Cooling Strategy				
		Air-conditioning	Mixed Mode	Mechanically Ventilated	Natural Ventilation	Undefined
Europe (n = 31,392)	**Classroom**	8	0	170	3,034	0
	Multifamily housing	0	0	0	1,242	0
	Office	11,408	2,191	1,386	11,944	0
Asia (n = 29,064)	**Classroom**	2,190	0	0	2,978	0
	Multifamily housing	618	715	0	3,889	890
	Office	7,925	2,283	191	4,440	0
	Others	1,404	0	0	1,229	0
	Senior Centre	0	312	0	0	0
South America (n = 7,390)	**Classroom**	0	2,291	0	2,075	0
	Office	1,274	1,471	0	0	0
	Others	0	0	0	0	279
North America (n = 9,969)	**Multifamily housing**	0	0	0	1423	0
	Office	2,581	2,482	0	3,483	0
Africa (n = 2,163)	**Multifamily housing**	0	0	26	1,317	0
	Office	0	0	31	789	0
Australia (n = 1,868)	**Office**	1065	0	0	294	0
	Others	71	0	0	438	0

3.2 Interactive thermal comfort data visualization tool

The aim of developing an interactive visualization tool (see Figure 4) was to provide a user-friendly interface for researchers and practitioners to explore and navigate their way around the large volume of data in ASHRAE Global Thermal Comfort Database II.[4] The tool is built with R version 3.2.3, using “ggplot2”, “ordinal” and “shiny” packages for graphic visualization, percentage of dissatisfied probit curve analysis and web-based interaction respectively. One key feature of the visualization tool is the ability for users to customize their selected dataset over the entire database for specific data comparisons. Some major filters are cooling strategy, building type, meteorological context, indoor climatic physical parameter ranges, along with various human factors. This tool was originally developed by Pigman (2014), and modified by research team members from the Center for the Built Environment (CBE) to reflect the newly updated database. On top of the original features, the current version includes some new graphic types to assist data visualization and analysis, including two boxplots and a bar chart for data statistics, a

[4] https://cbe-berkeley.shinyapps.io/comfortdatabase/

scatter plot of raw data on the elevated air speed comfort zone in ASHRAE Standard 55 (ASHRAE, 2017), and two local relationship plots available for user-customized parameters in the x and y axis.

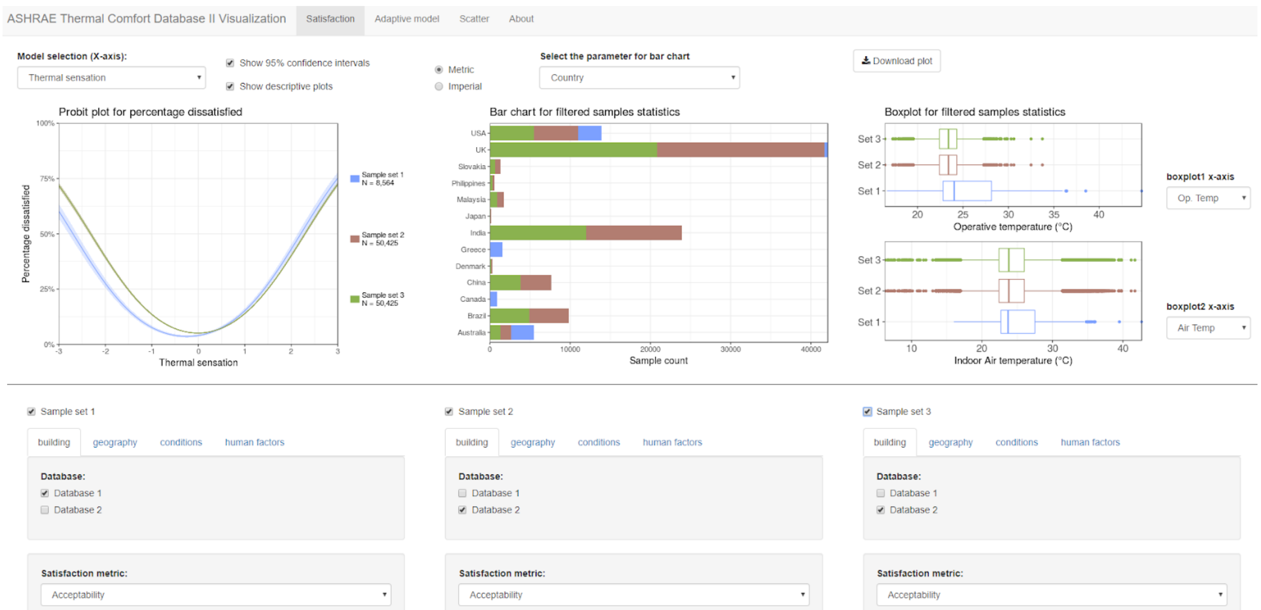

Figure 4. A screen shot showing an example of the thermal comfort visualization tool's "Satisfaction" page. The tool is freely available at https://cbe-berkeley.shinyapps.io/comfortdatabase/

3.2.1 Data filters

The graphic interface is divided into three pages to examine satisfaction scores, adaptive comfort, and scatter plots of selected variables. Below the graphs are four categories, or tabs, to filter the data and create different subsets:

(1) The "building" tab allows the selection of a satisfaction metric to use (acceptability or comfort), conditioning type, and building type.

(2) The "geography" tab allows filtering of selected data by seasons, climate classifications, countries, and cities.

(3) The "conditions" tab allows for the creation of a subset of data where bounded ranges of selected physical parameters are specified, such as prevailing mean outdoor, indoor, radiant and operative temperature, indoor relative humidity, and indoor air speed.

(4) The "human factors" tab allows filtering by characteristics of subjects, including sex, age, clothing insulation and metabolic rate; or by the availability of indoor environmental controls (if provided), such as operable windows, doors, thermostats, blinds, heaters, and fans.

3.2.2 Graphic output

Above the graphs are three different pages for exploring the data and generating different types of graphs:

<u>"Satisfaction" page</u>

ASHRAE Standard 55 defines thermal comfort as the “condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (ASHRAE, 2017). Since most field studies do not ask directly about satisfaction with the thermal environment, researchers use questions about thermal sensation, acceptability and comfort to infer occupant thermal satisfaction. The “Satisfaction” page explores the relationship between thermal sensation and these other two metrics (thermal acceptability and thermal comfort) using multinomial probits. The probit plot displays curves of percent dissatisfied (based on thermal acceptability and comfort votes in field surveys) against either the subjects’ thermal sensation vote or PMV (i.e., similar to the PPD vs. PMV graph). Furthermore, the graphic output on this page displays basic statistical distributions from the selected subsets of the filtered database. In addition to the filters previously mentioned, one can choose from a variety of parameters to summarize as counts in a bar chart (e.g., basic identifiers), or as boxplot distributions (e.g., instrumental, or measured, parameters).

“Adaptive model” page

This graphic output is used for comparing the measured percentage satisfied (using acceptability, comfort, or sensation votes) with predicted ranges of comfortable indoor temperatures based on adaptive comfort standards in ASHRAE Standard 55 (ASHRAE, 2017) and EN 15251 (Standard EN 15251, 2007). These adaptive models establish a range of comfortable indoor temperatures based on prevailing outdoor temperatures. The “Adaptive model” page analyses the database within the adaptive framework by binning thermal comfort votes according to the prevailing outdoor temperature and the indoor temperature the subjects were experiencing at the time (shown on the x- and y-axis, respectively). The percentage of satisfied votes is calculated within each two-dimensional bin and visualized with a color scale, with 80% or higher satisfaction being shown in green. For example, Figure 5 shows that the bin with an outdoor and indoor temperature each of 20 °C has 100 acceptability votes of which 90 are acceptable. This bin (20 °C, 20 °C) is colored green to indicate it has >80% satisfaction. Conversely, there are 50 votes in the bin of 20 °C outdoor and 30 °C indoor temperature, and 10 of them are “acceptable,” so that bin (20 °C, 30 °C) is colored red to mark it as having only 20% satisfaction. An accumulation of the green bins delineates an observed comfort zone, and one can compare it with the adaptive comfort zones predicted by the ASHRAE 55 and EN 15251 standards.

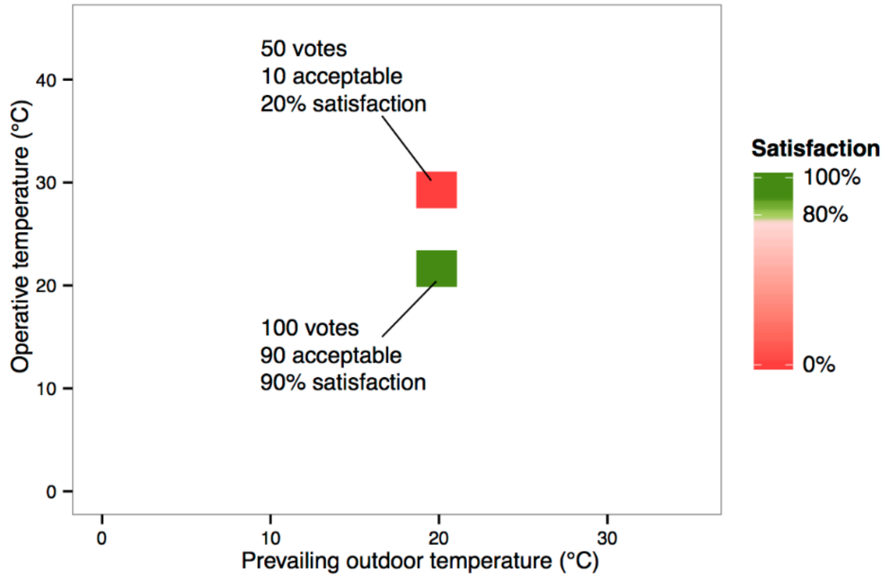

Figure 5. An example of binning thermal comfort votes according to the coincident indoor and outdoor temperature conditions

<u>"Scatter" page:</u>

The three graphs on this page are used for evaluating a filtered subset of the database using scatter plots. The first graph is specifically designed to display the air speed (y-axis) against different types of temperature (x-axis) and compares that distribution with the elevated velocity comfort zone in ASHRAE Standard 55 (ASHRAE, 2017). The elevated air speed comfort zone in ASHRAE Standard 55 (ASHRAE, 2017) is adopted when the average air speed exceeds 0.2m/s, subject's metabolic rate is 1 to 2 met, and clothing insulation is between 0 and 1.5 clo. It is permissible to determine the operative temperature range by linear interpolation between the limits found in corresponding comfort zones. The first graph on this page considers the data in this aspect and overlays onto the raw data scatter plot two comfort zones criteria (for clothing insulation = 0.5 and 1 clo) at 1.1 met. One can also generate two additional scatter plots with selectable x-axis and y-axis for a wide variety of variables, with an overlay identifying local regressions.

3.3 ASHRAE Global Thermal Comfort Database II Query Builder

The ability to explore the Comfort Database using the interactive thermal comfort visualization tool provides convenient access for many users. However, most end-users of these comfort databases have proficiencies in common statistical software packages and very specific queries in mind when they use such a data repository. It is therefore likely that they will prefer performing analyses using their own suite of software. To accommodate such end-users, the Query Builder tool is accompanied by a simple web-based Graphical User Interface (GUI).[5] This tool allows users to filter the database according to a set of selection criteria, and then download the results of that query in a generic comma-separated-values (.csv) file format for importing into

[5] ASHRAE Global Thermal Comfort Database II Query Builder can be found at www.comfortdatabase.com

their software package of choice. In this way, the Comfort Database may be accessed by users with differing analytical skills.

The Query Builder tool uses a combination of Javascript for the interface, and PHP and MySQL for the backend. There are 49 parameters upon which the database can be filtered, with descriptions of each parameter displayed in the sidebar (Figure 6). Less common parameters (defined as those contained in less than 30% of all database records) are indicated by an asterisk character to alert users that queries that include these may not return any meaningful results. Parameters are organized into 7 groups for easier navigation (which are similar, but slightly different than the groups defined in Table 1 for organizing the database):

- *Study*: the origins of the data (e.g., study, year).
- *Climate*: locational context (e.g., season, climate etc.).
- *Building*: building typology and use (e.g. building type, HVAC type etc.).
- *Demographic*: respondent anthropometrics (e.g., age, sex, height weight).
- *Subjective*: common survey measures (e.g., thermals sensation, thermal acceptability, thermal preference).
- *Comfort*: indices relevant to thermal comfort (e.g., PMV/PPD, clothing, activity).
- *Measurements*: instrumental measurements of the thermal environment (e.g., air temperature, globe temperature, relative humidity, air velocity). The system of units is user-selectable but defaults to SI.

Filters are based on radio buttons, checkboxes, or sliders, depending on the level of measurement for the parameter in question. For example, categorical variables like thermal acceptability or building type use checkbox selection, whilst interval or ratio variables like air temperature or air velocity use slider selection. Filters are only applied to queries upon user selection. Queries containing multiple filters are executed using Boolean 'AND' statements, meaning all selection criteria are to be met for results to be returned. Any resulting output from the query contains the entire record or row from the database. Finally, new data can be easily added to the Comfort Database without requiring any modification to the Query Builder code; the only requirement is for new data to be organized in the same structure and parameters coded in the same convention as the existing database.

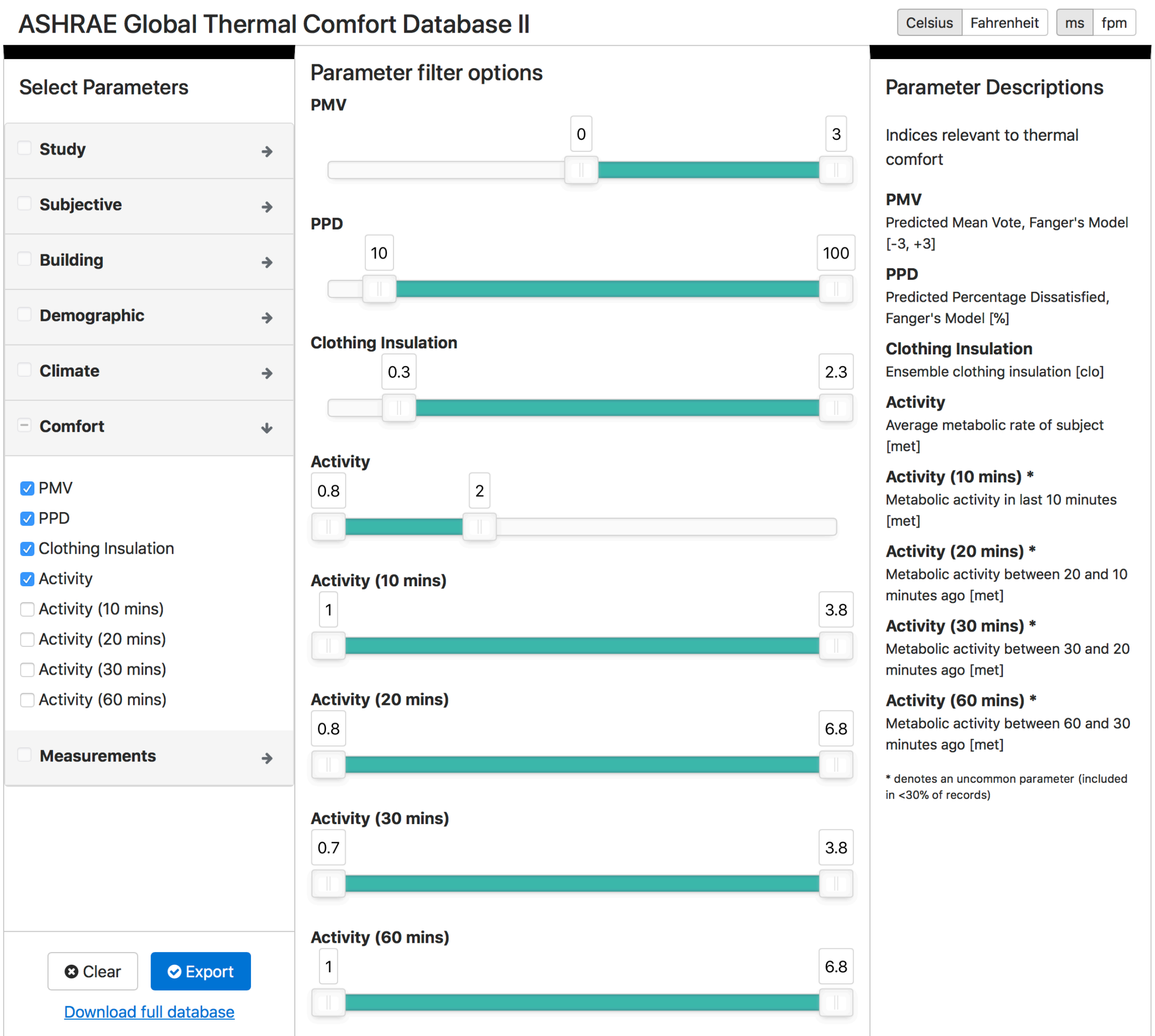

Figure 6. A screenshot of the Query Builder tool. The accordion menu to the left organizes variables by their categories, the central section presents the filtering capabilities, and the right sidebar gives descriptions of the selection parameters.

4. Conclusion

The purpose of this paper is to describe the methods behind the development of the ASHRAE Global Thermal Comfort Database II ("Comfort Database") and its accompanying analysis tools, to provide attribution to all of the contributors of the raw data, and to inspire researchers and practitioners who might want to use this open resource. The Comfort Database is made available under the Open Database License (Open Data Commons, 2017). This means that end-users are free to share (i.e., duplicate, disseminate and use the database), to produce new works from the database, and to transform the Comfort Database, providing they comply with the following rules:

- *Attribute:* End-users must attribute any publicly visible application of the Comfort Database, or works derived from it, in the manner specified in the ODbL (Open Data Commons, 2017). Dissemination of the database or any products or services derived from it, must make clear the license of the Comfort Database and keep intact any notices on the original database. Research papers derived from the Comfort Database must cite the current paper (full citation given on both web tools).
- *Share-Alike:* If end-users publicly use any modified version of the Comfort Database you must also offer that modified database version under the same Open Database License.
- *Keep open:* If end-users redistribute the Comfort Database, or a modified version thereof, then they may restrict accessibility to the work as long as they also make publicly available a version without such access restrictions in place.

It is hoped that Comfort Database will support diverse inquiries about thermal comfort in the built environment and be used as a resource to support numerous subsequent publications by varied authors.

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