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Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC)

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ABSTRACT

India is witnessing unprecedented growth trends in building construction, particularly office spaces. Indian offices are designed to operate at 22.5 ± 1 °C all year round to meet the stringent "Class A" specifications outlined by international standards in the absence of an India-specific comfort standard. This paper proposes an India Model for Adaptive Comfort – IMAC – based on the field surveys administered in 16 buildings in three seasons and five cities, representative of five Indian climate zones. A total of 6330 responses were gathered from naturally ventilated, mixed mode and air-conditioned office buildings using instantaneous thermal comfort surveys.

Occupants in naturally ventilated Indian offices were found to be more adaptive than the prevailing ASHRAE and EN models would suggest. According to the IMAC model, neutral temperature in naturally ventilated buildings varies from 19.6 to 28.5 °C for 30-day outdoor running mean air temperatures ranging from 12.5 to 31 °C. This is the first instance where a study proposes a single adaptive model for mixed mode buildings asserting its validity for both naturally ventilated and air-conditioned modes of operation in the building, with neutral temperature varying from 21.5 to 28.7 °C for 13–38.5 °C range of outdoor temperatures. For air-conditioned buildings, Fanger's static PMV model was found to consistently over-predict the sensation on the warmer side of the 7-point sensation scale.

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1. Introduction

India is a rapidly growing economy with a population of more than 1.2 billion which marks a 17.6% increase in 10 years. According to the City Census of 2011, the country has about 46 cities with population of over 1 million [1] and many more cities will join this list in a matter of a few years. People need buildings to live and work. The growth in population, therefore, is linked to the rapid increase in building construction and infrastructure demand [2]. According to the estimates developed by the USAID ECO-III Project, the total projected commercial floor space in Indian in 2014–15 is ~840 million m^2 [3]. Based on the effective compounded annual growth rate (CAGR) of 5%, the commercial floor area growth in India would be 450% by 2050, or five times the current floor area estimate. In other words, more than 80% of the buildings that will exist in 2050 are yet to be constructed at the time of writing.

The market value for Indian construction sector is projected to expand up to 180 billion US$ by 2017 from 117 billion US$ in 2012–13. Urbanization is expected to increase to 51% by 2050 with more than 40 million m^2 of real estate development planned in the office space across 10 major cities of India in 2013–15 [4].

According to the projections by the Planning Commission, to deliver a sustained GDP growth rate of 9%, India's per capita energy consumption will be marginally above China's current per capita consumption (1100–1200 Million Tonnes of Oil Equivalent) in 2031–32, even after substantial reduction in energy intensity [5]. The production of electricity from utilities registered an annual growth rate of about 6.1% from 2012 to 13 while electricity consumption growth rate during the same period was 7.1%, indicating a deficit [6].

Buildings are responsible for around 35% of India's total energy consumption, and this is increasing by 8% annually [7]. HVAC (Heating, Ventilation and Air Conditioning) systems account for 31% of the energy used by commercial buildings. The current market penetration of HVAC systems is 3% but is expected to grow at the rate of 30% per annum over the next five years [8]. Room air-

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conditioner purchases in India are currently growing at 20% per year, with about half of these purchases attributed to the non-residential sector [9].

Average energy use per unit area due to operation of HVAC systems in conditioned buildings in India currently lies in the range of 120–290 kW h/m^2/year. If not improved, total energy usage for providing AC in buildings is expected to grow to 1547 TW h in 2030 [8]. A study showed recently that the energy used for space heating and cooling can be expected to increase in India by 850% from 2005 levels to 2050 if the buildings continue to be operated and built as they are done today [10]. A simulation study for Indian climate zones indicated an EPI (Energy Performance Index – kwhr/m^2/year) savings of 5–6% per degree increase in thermostat set-point temperature can be accomplished, with greater savings accruing on the lower set-point temperature side [11].

Fossil fuels play a major role in powering India's economic development, making it the world's fourth-largest source of energy-related CO_2 emissions. In a business as usual scenario, India's CO_2 emissions from space heating and cooling are projected to increase by 860%, as compared to global increase of 62% [10]. The large and growing population in India, its increasing levels of per capita energy consumption and the high rates of projected economic growth are set to commit India to a high-carbon development path [12].

To achieve an energy efficient building regime, governments, businesses and individuals must transform the way buildings are designed, built and operated. Energy consumption in new and existing buildings can be reduced through design interventions, low-energy systems and behavioural changes.

India boasts a rich tradition of naturally ventilated buildings with context-specific passive design strategies. Since the subcontinent covers a large geographical area, it encompasses diverse climatic contexts. Consequently, unique climate-responsive design features are relevant to each of India's numerous climate zones. Until about 10 years back, naturally ventilated buildings represented the norm for most building typologies, but with deeper market penetration of air-conditioning systems, higher household income levels driving higher comfort expectations and the rapid increase in built-up floor space, the number of air-conditioned buildings increased in the last decade. Most of the new buildings are air-conditioned and much of the existing building stock is being retrofitted with AC systems. This has resulted in a wide array of mixed mode buildings and begs a closer look at mixed mode operation.

In India, the National Building Code (NBC) [13] specifies that the indoor comfort conditions for air-conditioned offices lie between 25 °C and 30 °C with optimum condition at 27.5 °C, expressed in terms of a Tropical Summer Index (TSI) [14], regardless of their climatic location [15]. The Energy Conservation Building Code (ECBC), introduced in 2007, cross references the NBC for its ventilation guidelines in naturally ventilated buildings, and in its accompanying user guide [16] recommends the de Dear and Brager adaptive comfort model [17] as “additional information” for its users. The Code, however, remains silent on specific comfort conditions for office buildings.

A set of comfort field studies [18–20] was conducted recently in Jaipur by a team of Indian researchers in 6 air-conditioned (subject sample size, N = 642), 13 mixed mode (N = 809) and 17 naturally ventilated (N = 1418) buildings. Based on this dataset, one study proposed an adaptive comfort model for hostels (N = 426), which may be categorised as residential building type with day and night-time occupancy leading to a neutral temperature of 30.15 °C. The surveys were administered between August–November which is not representative of peak summer conditions for the location. The proposed model, therefore, was based on the data that does not include responses from extreme conditions that are characteristic of composite climate [20]. From the larger dataset, the researchers proposed an adaptive model for naturally ventilated buildings [18] from 1811 samples. These samples were a mix of responses from residential and office buildings. Residential buildings have 24-h occupancy and different thermal expectations from day-time use buildings which also means that the comfort adaptation in such buildings would differ from office buildings and may not be best expressed in a combined equation. A third study [19], stemming from the same dataset, focused on adaptation in spatial mixed mode buildings (N = 604) but used the climate zone categorization for Jaipur as hot-dry although the city is characterized as composite as per ECBC [19]. This study mentions that “mixed mode observations were available only during summer” and other seasons were not included.

Comfort field studies in Chennai (warm and humid) and Hyderabad (composite), both located in the southern part of the country, proposed adaptive models for naturally ventilated and air-conditioned buildings for the southern region of the country [21,22]. This research did not include mixed mode buildings in the dataset used to derive the adaptive equation for warm and humid climate zone. The authors also recognized the need to gather data from hot-dry, moderate and cold climate zones in order to derive a holistic model for India.

It is evident that thermal comfort field studies undertaken in India until now have either been limited to a specific building type, such as residential modern [20,23], classrooms [24], vernacular/traditional [25–27] and railway stations [28], laboratories [29,30]; a geographical region [31] or a climate zone – composite [18–20], warm and humid [21–23,27,32]. These studies are indicative of a substantial effort by researchers to articulate a more Indian context-specific understanding of thermal comfort and adaptation, but do not offer a comprehensive and integrated solution to inform policy-makers, building and system designers and facility managers about comfort.

In the absence of a pan-India thermal comfort standard specifically focused on India's climatic and cultural context, the predominant trend in India is to design air-conditioned office buildings that operate at 22.5 ± 1 °C [15] all year round to meet the stringent “Class A” specifications outlined in ISO Standard 7730 [33] and ASHRAE Standard 55–2010 [17], which are climatically inappropriate for buildings in India. More importantly, there are no local or international thermal comfort standards for mixed mode buildings which are increasingly becoming the norm in India.

An Adaptive Thermal Comfort standard can play a major role in reducing energy use and greenhouse gas emissions whilst maintaining the comfort, productivity and well-being of occupants. It recognizes that people's thermal comfort needs depend on their past and present context and that these needs vary with the outdoor environmental conditions of their location. In order to address the lack of thermal comfort guidelines that recognize the climatic, cultural and workplace context of Indian offices, the IMAC study was initiated in December 2011. A thermal comfort standard based on an India-specific model would provide design and operation guidance for mixed mode and naturally ventilated typologies prevalent across the subcontinent and allow buildings to operate within broader indoor temperature bands compared to current international practices. The specification of adaptive comfort temperatures suited to the Indian context will reduce the energy consumed by space cooling for India's building stock, which will translate into significant greenhouse gas abatement from the Indian building sector.

2. Methodology

The research design, field methods and data analyses adopted in the IMAC 2014 were based on the ASHRAE RP-884 precedent [34]. This paper is based on the data collected over four survey campaigns in office buildings across India, spanning a period of one year. These surveys were administered in five Indian cities selected to represent the five main climate zones of the subcontinent (given in the Indian Energy Conservation Building Code [35]) – warm & humid (Chennai), hot & dry (Ahmedabad), composite (Delhi), moderate (Bangalore) and cold (Shimla). In order to document a wide range of indoor environmental conditions, surveys were administered in three groups of buildings – naturally ventilated (NV), mixed mode (MM) and air-conditioned (AC) buildings in these five cities. All buildings classified as MM in this study were operated to switch from natural ventilation to air conditioning in summer and in monsoon. In other words occupants surveyed in MM buildings experienced natural ventilation for a part of the year and air conditioning at other times. On the other hand, buildings classified as NV and AC were always operated in their respective modes all year round. “Right-here-right-now” thermal comfort surveys (TCS), were administered to occupants to gather responses relating to thermal sensation, temperature preference and thermal acceptability, air movement preference, clothing insulation level and metabolic activity. The surveys were administered during office hours in each building for a period of 1–2 days during each of the three seasons - summer winter and monsoon seasons, with dates identified based on the outdoor climatic conditions for that location [36]. The questionnaire was also translated in Gujarati for Ahmedabad campaign. The TCS surveys were accompanied by simultaneous measurement of the indoor climatic parameters of the questionnaire respondent's occupied zone – air temperature, globe temperature, relative humidity and air velocity [37]. Long-term post-occupancy surveys were also administered once in each building to characterise the workspace environment across the year [38]. The post-occupancy questionnaire covered aspects of work area satisfaction, general thermal comfort, ventilation, lighting, noise, indoor air quality, personal control, productivity, health and mode of travel to work.

A total of 16 buildings across five cities were selected for this study. The primary criterion for selection was to ensure a wide range of indoor operating conditions for all climate zones. This was achieved by selecting buildings operated in three modes in each city – NV (7 buildings, $N = 2005$), MM (6 buildings, $N = 2476$) and AC (3 buildings, $N = 1849$). A total of 6330 TCS and 2002 long-term responses were gathered from 16 buildings. Of the 6330 responses, 4353 were gathered from male respondents and 1977 from female respondents. Table 1 gives a distribution of the survey responses across seasons, cities and buildings.

Based on the categorization of field studies proposed in ASHRAE RP-884 [39], the present IMAC study was a Class II investigation. Indoor climate measurements were recorded using hand-held equipment at each subject's workstation at 0.6 m height while the survey response was taken, meaning that each set of measurements was spatially and temporally coincident with the occupant's location. All instruments were calibrated before each campaign by a National Accreditation Board for Testing and Calibration Laboratories accredited lab.

Extech HT30 Heat Stress WBGT Meter (globe temperature 0–80 °C with an accuracy of ±2 °C; air temperature 0–50 °C, ±2 °C; relative humidity 0–100%, ±3%) and TSI VelociCalc 9565 with 964 thermoanemometer probe (air temperature −10 to 60 °C, ±0.3 °C; air velocity 0–50 m/s, ±3%) were used to measure air and globe temperature, relative humidity and indoor air velocity. For most survey campaigns, four teams of two researchers each accompanied the field investigator. Prior to the research team arriving in the building the employer announced the presence of the study and encouraged participation. The team randomly approached occupants and asked if the time was convenient for the survey. One of the researchers interviewed the respondent on the instantaneous and background surveys while the other took environmental measurements as close to the position of the respondent as feasible. Additional information about operation of fans, HVAC, windows, and chair types etc. was also recorded and the respondent's location was marked on the floor plan.

Table 2 presents a statistical summary of the indoor environmental measurements of air temperature, relative humidity and air velocity for each season. It also includes mean radiant temperature calculated from the globe temperature measurements. The maximum recorded indoor air temperature was 39.8 °C in summer and the lowest was 13.4 °C in winter. The average mean radiant temperature was very close to the average air temperature, indicating a general absence of sources of radiation across all buildings surveyed. The maximum relative humidity was recorded in the monsoon season (88.8%) and the minimum in winter (14.5%). The maximum indoor air velocity was recorded in monsoon (2.4 m/s) owing to the ceiling fans. ASHRAE Standard 55–2010 [17] methodology was used for operative temperature calculations. A building and season-wise statistical summary of indoor air temperature is presented in Table 3.

Meteorological data for air temperature, relative humidity and air speed, was obtained from World Weather Online (http://www.worldweatheronline.com) for the days of each of the IMAC surveys. Table 4 presents a statistical summary of the outdoor air temperature data.

The clothing garment checklist was revised to add Indian garments for women and men, such as *sari*, *kurta*, *pajama*, etc. *CLO* values were assigned to each garment based on the lists published in ASHRAE Standard 55–2010. For garments not listed in the standard, *CLO* values were interpolated from those of the existing garments. The clothing checklist was filled by the field researchers based on their observation of the respondents and confirmed with the respondents in winter campaigns where they were likely to wear multiple hidden layers. A checklist of office activities was provided in the TCS form to document the respondents' activities in the hour preceding the survey, divided into four time brackets: 60 → 30 min, 30 → 20 min, 20 → 10 min and 10 min before the interview. The activities were translated into metabolic rates based on the detailed tables published in ASHRAE Standard 55–2010.

The raw data went through a rigorous quality assurance before starting with the analysis. The purpose was to check for potential errors that may have occurred at the time of data entry when the paper forms were digitized. Protocols were designed for survey as well as indoor environmental data. These protocols were applied using MS Excel's ‘conditional formatting’ function to flag potential errors. The range of error for each field was also determined. The erroneous fields were then addressed by correcting them, ignoring them or removing them altogether from the database.

After the raw data progressed through several stages of quality checks, the survey responses and the physical data entries were merged using the time stamp to create a single row of datasets corresponding to each respondent. This led to 6330 sets (rows) of results in the final data matrix which were used for the IMAC analysis. Thermal comfort indices for each survey entry were calculated using the ASHRAE Thermal Comfort Tool developed by UC Berkeley [40].

Table 1
Number of survey responses.

Bldg code	Bldg mode	City (climate zone)	"Right-here-right-now" thermal comfort questionnaire			Long-term post-occupancy questionnaire responses (Month)
			Summer responses (Month)	Monsoon responses (Month)	Winter responses (Month)	
A1	NV	Ahmedabad (hot and dry)	137 (May, 2012)	121 (Jul, 2012)	167 (Jan, 2012)	123 (Jul, 2012)
A2	MM		194 (May 2012)	170 (Aug 2012)	186 (Jan 2012)	180 (May, 2012)
A3	MM		180 (May 2012)	183 (Jul 2012)	169 (Jan 2012)	158 (May, 2012)
B1	NV	Bangalore (moderate)	38 (May, 2012)	48 (Aug, 2012)	33 (Jan, 2012)	46 (Aug, 2012)
B2	AC		194 (May, 2012)	230 (Aug, 2012)	200 (Jan, 2012)	204 (Aug, 2012)
B3	NV		132 (May, 2012)	149 (Aug, 2012)	127 (Jan, 2013)	138 (Aug, 2012)
C1	NV	Chennai (warm and humid)	90 (Jun, 2012)	85 (Oct, 2012)	104 (Jan, 2013)	98 (Oct, 2012)
C2	AC		200 (Jun, 2012)	199 (Oct, 2012)	200 (Jan, 2013)	198 (Oct, 2012)
D1	MM	Delhi (composite)	66 (Jun, 2012)	55 (Aug, 2012)	52 (Dec, 2012)	44 (Aug, 2012)
D2	MM		55 (Jun, 2012)	64 (Aug, 2012)	64 (Feb, 2012)	58 (Jun, 2012)
D3	AC		200 (Jun, 2012)	230 (Aug, 2012)	196 (Jan, 2012)	173 (Jun, 2012)
D4	MM		138 (Jun, 2012)	147 (Aug, 2012)	121 (Dec, 2012)	122 (Dec, 2012)
S1	MM	Shimla (cold)	212 (Jun, 2012)	213 (Aug, 2012)	207 (Dec, 2012)	213 (Aug, 2012)
S2	NV		64 (Jun, 2012)	68 (Aug, 2012)	69 (Dec, 2012)	68 (Aug, 2012)
S3	NV		120 (Jun, 2012)	126 (Aug, 2012)	111 (Dec, 2012)	108 (Aug, 2012)
S4	NV		83 (Jun, 2012)	72 (Aug, 2012)	61 (Dec, 2012)	71 (Aug, 2012)
Total			2103	2160	2067	2002
				6330		

Table 2
Statistical summary of indoor measurements.

Sample size	Summer	Monsoon	Winter	Summer	Monsoon	Winter
	2103	2160	2067	2103	2160	2067
	Air temperature (°C)			Relative humidity (%)		
Mean	28.4	25.6	23.5	49	69	44
Standard Deviation	4.7	3.0	3.5	9	10	14
Median	26.4	25.0	24.4	48	70	44
Maximum	39.8	32.4	30.0	70	89	73
Minimum	20.7	19.5	13.4	21	42	15
	Air velocity (m/s)			Mean Radiant temperature (°C)		
Mean	0.3	0.2	0.1	28.6	25.7	23.4
Standard Deviation	0.3	0.3	0.1	4.6	3.0	3.6
Median	0.2	0.1	0.1	26.7	25.3	24.3
Maximum	2.2	2.4	1.3	40.4	32.6	29.4
Minimum	0.0	0.0	0.0	21.2	18.7	13.0

Table 3
Statistical summary of indoor air temperature measurements for each building.

Bldg. code	Bldg. mode	City (climate zone)	Summer			Monsoon			Winter		
			Max.	Min.	Mean	Max.	Min.	Mean	Max.	Mean	Min.
A1	NV	Ahmedabad (hot and dry)	39.8	34.0	36.4	31.4	27.6	29.6	26.0	23.8	21.0
A2	MM		37.2	28.0	33.5	31.0	25.6	29.8	30.0	24.4	23.3
A3	MM		28.7	22.4	25.3	29.6	20.7	24.6	28.3	25.5	22.7
B1	NV	Bangalore (moderate)	29.2	26.5	28.3	28.2	24.0	26.6	28.2	27.2	25.1
B2	AC		29.8	22.1	24.6	26.5	23.1	25.0	28.5	26.1	24.1
B3	NV		31.2	27.9	29.2	27.5	24.3	25.9	29.0	26.7	25.0
C1	NV	Chennai (warm and humid)	35.9	31.5	34.5	30.3	27.5	29.3	28.9	27.9	26.6
C2	AC		28.8	22.3	25.8	28.2	23.7	25.5	28.9	26.1	24.7
D1	MM	Delhi (composite)	37.4	33.9	36.2	30.4	25.4	27.5	19.6	17.9	15.4
D2	MM		31.1	23.3	26.1	27.6	20.0	25.2	26.6	24.1	18.8
D3	AC		25.3	22.5	23.7	25.4	22.8	24.1	26.5	24.3	21.4
D4	MM		38.5	27.7	35.1	32.4	26.0	30.5	20.7	18.2	16.0
S1	MM	Shimla (cold)	27.7	20.7	24.7	25.0	20.0	21.9	29.2	20.6	16.2
S2	NV		28.3	24.5	26.2	23.3	19.9	21.8	20.5	16.3	13.4
S3	NV		27.6	23.9	25.5	23.8	19.5	21.7	22.2	19.0	15.6
S4	NV		29.0	24.0	27.2	24.9	20.4	22.8	23.1	18.5	14.6
All			39.8	20.7	28.4	32.4	19.5	25.6	30.0	23.5	13.4

2.1. Analytical approach towards the development of the adaptive model

A two-stage analytical approach was taken to derive the adaptive models. Stage1 involved the derivation of thermal neutrality through an analysis of the interaction of thermal sensation with indoor climate while Stage 2 sought to find the relationship between thermal neutrality and outdoor climate that

Table 4
Statistical summary of outdoor air temperature.

City	Summer			Monsoon			Winter		
	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean
Ahmedabad	43.0	29.0	35.9	31.0	26.0	28.3	28.0	13.0	20.6
Bangalore	34.0	22.0	28.2	28.0	19.0	23.3	32.0	18.0	24.7
Chennai	35.0	30.0	32.3	32.0	27.0	29.1	29.0	24.0	26.5
Delhi	44.0	32.0	38.5	39.0	26.0	31.6	24.0	10.0	16.8
Shimla	35.0	22.0	28.4	24.0	17.0	20.4	20.0	5.0	12.6
All	44.0	22.0	33.3	39.0	17.0	25.7	32.0	5.0	19.1

can be posited as a model of adaptive thermal comfort. In a second part of this exercise, thermal acceptability was used to set acceptability limits for the adaptive model. Fig. 1 shows an overview of the analysis steps that will be detailed in this paper.

This paper focuses on two levels of data aggregates which form the primary units of data analysis for the study.

- Building Mode: Here all the data is pooled at the level of the 3 modes of building operation –NV, MM, and AC
- Building + Season: Here the data is pooled at the level of each building, each of the three seasons, and mode of operation (whether NV, MM or AC) of the building across the year

The 'Building + Season' formed the smallest aggregate that was found to be relevant for further analysis. The IMAC dataset yielded 54 'Building + Season' aggregates. Outputs from the 54 'Building + Season' aggregates were grouped for meta-analysis based on the type of building they originate from namely - NV, MM or AC. It is important to note here that all survey responses from MM buildings were grouped under MM; and there are no common data points between the NV, MM and AC groupings.

A number of methods are used to derive thermal neutrality. In the ASHRAE RP-884 [34] Linear Regression (LR) and Probit Regression (PR) were adopted while the Griffiths Method (GF) was used in the EN15251 studies [41]. In the above studies indoor climate is characterised in two ways: Operative temperature (*TOP*) and New effective temperature (*ET**). Outdoor conditions can be characterised as the 30-day running mean of outdoor ambient air temperature in RP-884 or as the 7-day weighted mean of outdoor *ET** as adopted for the EN15251.

As part of the IMAC study, several of the myriad possibilities were explored at both Stage 1 and Stage 2. For brevity and clarity the authors present only the key elements of what contributed to the development of the adaptive model.

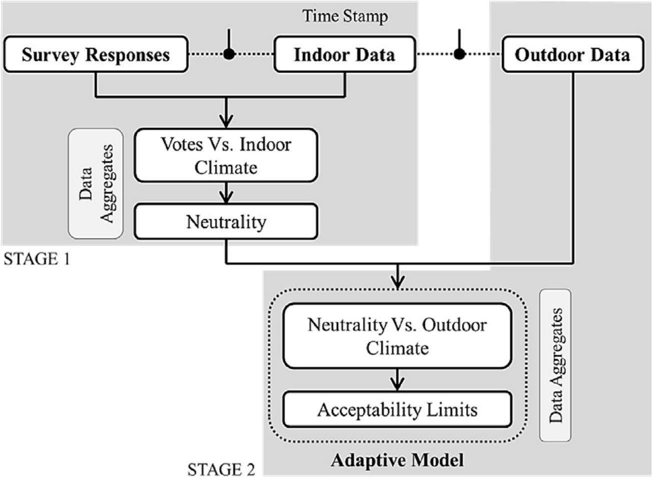

Fig. 1. IMAC analysis steps.

3. Results

3.1. Comparing observed and predicted sensation

Indoor operative temperature (*TOP*) observations were binned into 0.5 K increments and the bin's mean vote (observed and predicted sensation) was used for further analysis, instead of individual subjects' thermal votes.

A linear regression model was fitted between the votes and the x-axis index (*TOP*). The regression models weighted each point according to the number of observations within each x-axis bin to minimize the impact of outlying data points that were based on relatively small number of observations.

Fig. 2 shows the regression models for the building modes aggregates (NV, MM and AC) as well as the entire IMAC dataset (ALL). The solid points are the mean observed sensation votes (*m_ASH*) for the respective *TOP* bins and the open points are the mean predicted sensation (*m_PMV*). For all building types, and more importantly for the AC buildings, the *m_PMV* gradient was higher than that of *m_ASH*, which shows that the PMV model predicted higher sensitivity of the occupants to indoor *TOP* as compared to what was observed in the field. The gap between the regression lines shows that at any given indoor *TOP*, PMV model predicted the sensation to be warmer than was observed on the right-here-right-now seven point thermal sensation scale. A Z-statistical test was run to compare the regression coefficients of the *m_PMV* and *m_ASH* regression models for every building mode aggregate and the coefficients were found to be significantly different ($p < 0.05$) in all cases.

The difference between predicted sensation derived from Fanger's PMV model and observed thermal sensation derived from occupant responses on the questionnaire, showed significant variations ranging from 0.5 unit sensation vote at 21.5 °C indoor *TOP*, to 1 full unit at 29 °C for AC dataset, with the predicted sensation was always warmer than the observed. The results clearly demonstrate a preference for warmer temperatures and suggest a high level of adaptation in Indian buildings.

Of particular interest is the finding that in the NV and MM buildings occupants registered close to neutral (thermal sensation = 0) votes for temperatures ranging from approximately 22 °C up to 31 °C, suggesting that they were very effectively adapting to any indoor temperature up to about 31 °C before indoor temperature had an effect. To pursue this further a detailed analysis on the highest resolution aggregate of data – 'Building + Season' was undertaken.

3.2. Stage 1: derivation of thermal neutrality

Both Linear Regression (LR) and the Griffiths (GF) methods were used to derive thermal neutrality. Significant neutralities were identified using the following procedure:

- By removing aggregates that had less than 30 votes; the threshold of 30 votes was based on the number of votes available in each aggregate.
- By removing models where neutralities exceeded one degree of extrapolation from the indoor operative temperature range; extrapolation was limited to two additional steps in each direction (towards the lower and higher temperatures)
- By removing models that had p-value greater than 0.10 (only for LR models)

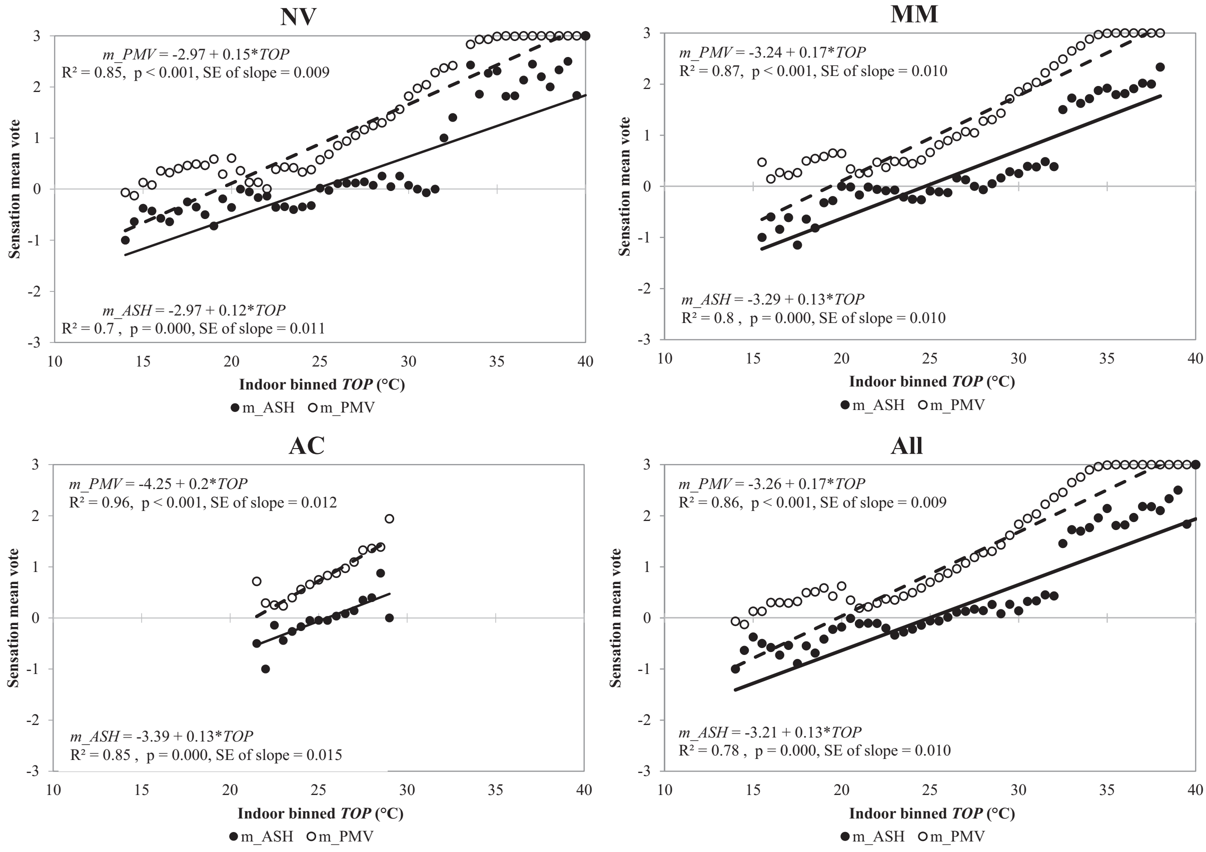

Fig. 2. Dependence of observed and predicted sensation on indoor operative temperature.

3.2.1. Linear regression

This approach was based on the ASHRAE RP-884 [34] document wherein the neutral temperature (*TOP*) was calculated for each ‘Building + Season’ aggregate by solving the regression model for the ‘mean observed vote’ = 0. Of the 54 aggregates only 23 achieved statistical significance. The relatively small number of NV and MM buildings producing valid regression models was primarily due to the neutral temperatures falling more than a degree outside of the indoor temperature observations for that aggregate, and then due to the variability in votes at a given indoor temperature as shown in Table 5. Given the loss of a large number of aggregates in this approach, the authors pursued the calculation of thermal neutrality using the GF method.

Table 5
Statistical summary of the weighted linear regression of mean observed sensation on indoor binned operative temperature (°C).

	NV	MM	AC
No. of ‘Building + Season’ aggregates	21	24	9
No. of aggregates $\geq$30 votes	21	22	9
No. of aggregates $\leq$ 1 K extrapolation	15	17	8
No. of aggregates achieving 90% significance	9	13	5
Total no. of aggregates*	6	12	5
% of aggregates	28.6%	50.0%	55.6%
Mean (±stdev) model constant (y-intercept)*	−4.82 (±2.83)	−4.02 (±2.3)	−5.94 (±1.54)
Mean (±stdev) model gradient*	0.19 (±0.11)	0.15 (±0.08)	0.24 (±0.06)

*Based on the models (y = a + b*TOP) achieving $\geq$ 90% significance, and $\leq$ 1 K extrapolation.

3.2.2. Griffiths method

The GF method uses the average sensitivity of the dataset, known as Griffiths' constant, to predict neutrality of occupants. In this approach, neutral temperature is calculated using the following equation:

Neutral Temperature = Measured Globe or Operative temperature − (Observed Sensation Votes/Griffiths' constant)

GF method has been used by Nicol and Humphreys [41] and has also been used to derive the European adaptive thermal comfort model (EN15251). The methodology used by Humphreys et al. [42] formed the basis for calculating the average sensitivity of the IMAC study respondents. To do this, mean of sensation votes (*avg_ASH*) and mean operative temperature (*avg_TOP*) was calculated for each ‘Building + Season’ aggregate. For each individual vote falling in a given aggregate, the following variables were calculated:

$$\text{deltaASH} = \text{ASH} - \text{avg\_ASH} \tag{1}$$

$$\text{deltaTOP} = \text{TOP} - \text{avg\_TOP} \tag{2}$$

This was done for all 6330 votes in the IMAC dataset. *deltaASH* was plotted against *deltaTOP* for four aggregates – NV. MM, AC and All. Fig. 3 plots the binned *avg_deltaASH* against *avg_deltaTOP* and a weighted linear regression trend line.

The regression coefficients (b) from the equations in Fig. 3 were adjusted to account for field measurement errors and variance in *TOP*. *TOP* error variance (σ^2_{err}) was taken as 0.158 from a study by Humphreys et al. [42]. Adjusted regression coefficients were calculated as follows:

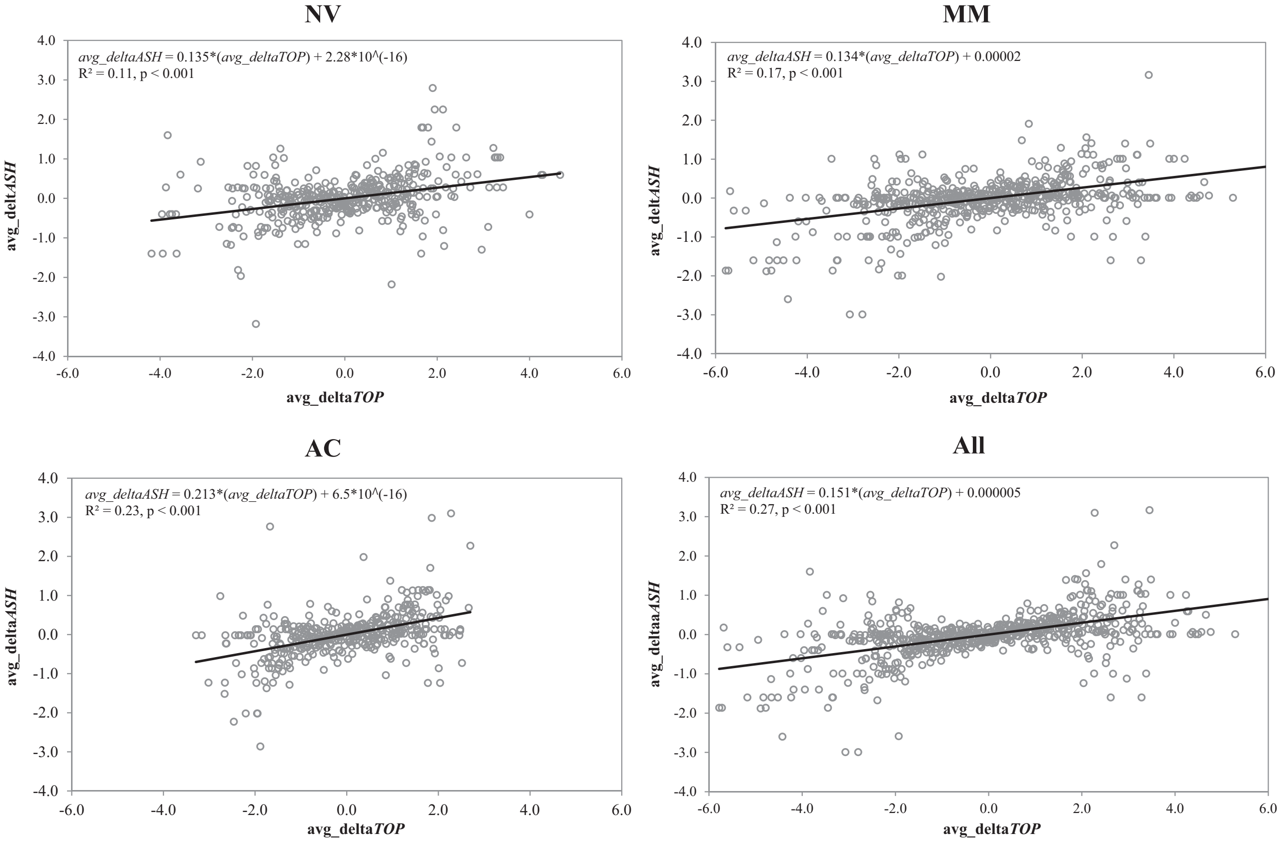

Fig. 3. DeltaASH vs. deltaTOP plotted for each survey response.

$$b_{adj} = b\cdot(\sigma^2{}_{TOP})/(\sigma^2{}_{TOP} - \sigma^2{}_{err}) \tag{3}$$

where,

b_{adj} = adjusted regression coefficient
$\sigma^2{}_{TOP}$ = variance of operative temperature
$\sigma^2{}_{err}$ = error variance of operative temperature

Table 6 lists the adjusted regression coefficients indicating average thermal sensitivity of NV, MM, and AC occupants in IMAC database. Higher the value, greater the change in sensation per unit change in temperature, indicating higher sensitivity. For ease of further analysis, it was decided to use the value of 0.16/K for NV and MM buildings and 0.25/K for AC as these were more conservative values. In their study, however, Humphreys et al. [42] have used 0.5/K as the value for the regression coefficient based on Nicol and Humphreys analysis of SCATs database [43]. It is important to note here that the aforementioned studies used globe temperature (*TG*) as the metric for indoor warmth. Since the IMAC study consistently used *TOP*, the GF method calculations were done for *TOP*, and not *TG*. These values for regression coefficients were then used to calculate the neutral temperature for each 'Building + Season' aggregate using the following equation:

$$GFneut\_TOP = avg\_TOP - (avg\_ASH/b_{adj}) \tag{4}$$

where,

GFneut_TOP = neutral *TOP* for a 'Building + Season' aggregate using different b_{adj} values (0.16/0.25/0.5)
avg_TOP = average *TOP* for a 'Building + Season' aggregate
avg_ASH = average *ASH* for a 'Building + Season' aggregate
b_{adj} = adjusted regression coefficient (0.16 for NV, 0.25 for AC and 0.5)

Table 7 summarizes the neutralities obtained from the GF method analysis by using the regression coefficients derived from the IMAC database, 0.16/K for NV and MM buildings and 0.25/K for AC buildings. Neutral temperatures falling more than a degree outside of the range of observed indoor temperatures for a given

Table 6
Regression coefficients (Griffiths constants) calculated from IMAC database.

	NV	MM	AC	All
No. of Observations	2005	2470	1849	6324
Regression Coefficient (*b*)	0.13	0.13	0.21	0.15
Standard error of coefficient	0.02	0.01	0.02	0.01
Variance of *deltaTOP*	0.87	1.51	0.82	1.11
Assumed error variance in *deltaTOP* ($\sigma^2{}_{err}$)	0.158	0.158	0.158	0.158
Adjusted Regression Coefficient (b_{adj})	**0.16**	**0.15**	**0.25**	**0.18**

'Building + Season' aggregate were removed and were not considered statistically significant.

As seen in Table 7, thermal neutrality was observed across the summer experiments at an average *TOP* of about 25.7 °C, regardless of whether the buildings were NV or MM, which was about half a degree lower than the summer neutrality for AC buildings. In the monsoon field experiments the average neutrality for MM buildings was a degree higher than of NV buildings but the standard deviation (SD) in NV monsoon neutralities was about twice that of MM.

In Fig. 4, the significant *GFneut_TOP* observations for all three Griffiths' constant values were regressed against the mean indoor *TOP* to result in significant models in all cases (NV, MM and AC). There was a significant relationship ($p < 0.05$) between neutrality and mean indoor *TOP* for NV, MM and AC buildings. Indoor neutrality increased by about 2 K for every 2.5 K degrees increase in indoor *TOP* for NV buildings. The model gradient for NV buildings was higher than MM buildings but same as that of AC buildings.

Using the Griffiths constant of 0.5 allowed more 'Building + Season' aggregates to remain in the analysis, and the gradient of the regression line for 0.5/K based neutralities was marginally higher than the 0.16/K based neutralities with slightly higher correlation coefficients for NV and MM. However, further analysis was done using the 0.16/K and 0.25/K constants derived from the IMAC database as being specific to Indian conditions. Moreover the conservative values ensured that the adaptation to indoor conditions was not overestimated.

3.3. *Stage 2: deriving the relationship between thermal neutrality and outdoor climate*

Linear regression models were constructed for the relationship between indoor thermal neutrality derived using the GF method and mean outdoor warmth for NV, MM AC and ALL buildings aggregates. The former was assessed in terms of the operative temperature while outdoor warmth was parameterized in terms of both 7-day outdoor running mean weighted ET^* and 30 day running mean *TA*. The results are shown in Table 8.

As can be seen from Table 8, NV and MM models demonstrate a significant relationship between thermal neutrality and outdoor conditions in these buildings. The models with 30-day running mean *TA* as the independent variable performed best in terms of explained variance (R^2) which was as high as 80% and were selected as most suitable to be put forward as the IMAC models. The AC dataset did not yield a significant model.

3.4. *Stage 2b: deriving thermal acceptability limits using sensitivity slope*

Acceptability bands are calculated to derive comfort limits around the neutrality line and represent upper and lower temperature values that can be considered for maintaining comfortable temperature conditions.

In the linear regression equations ($ASH = m \cdot TOP + c$), the slope (m) represents the sensitivity of the occupants in that data set. The slopes were identified for 'Building + Season' aggregates that provided statistically significant neutralities. For the aggregates falling in the NV group, a weighted average of the slopes was calculated (weighted by the number of votes in the aggregate). The same was done for MM and AC aggregates. This gave the average sensitivities for NV, AC and MM datasets in Table 9.

The average sensitivities or slopes were then used to calculate the *TOP* acceptability limits for NV, MM, and AC using the following relationship:

$$\Delta ASH = (\text{weighted average slope}) \cdot \Delta TOP \tag{5}$$

For each group, the values from Table 9 were used to calculate ΔTOP from Equation (5). The values for ΔASH of 0.85, 0.7 and 0.5 sensation vote correspond with 80, 85 and 90% acceptability limits according to Fanger's PMV-PPD model [44]. The resultant ΔTOP values are given in Table 10 and indicate the range of acceptability. Consequently, their equal distribution on either side of the neutrality line lends the upper and lower limits of 80, 85 and 90% acceptability.

4. Behavioural adjustments

4.1. *Clothing insulation adjustments*

Clothing decisions and behaviour is expected to be influenced by outdoor weather conditions as well as the thermal conditions experienced indoors. Clothing insulation and also the incremental insulation of the chairs upon which the occupants were sitting at the time of the survey were converted into clo units according to the ASHRAE Standard 55–2010 methods. Table 11 indicates significant seasonal differences in thermal insulation, with average summer *INSUL* values of 0.8 clo for NV buildings and 0.9 clo for MM and AC, average winter values exceeding 1.6 clo for NV and MM buildings and 1.3 clo for AC. Average monsoon *INSUL* values were very close to the summer *INSUL* values for NV and MM buildings. Building mean insulation values showed slightly greater variability in MM buildings in summer and monsoon as compared to the NV and AC sample.

Fig. 5 presents weighted linear and exponential trend lines plotted between the mean level of thermal insulation worn inside a building and its mean indoor temperatures. For indoor temperatures over 30 °C, there seemed to be no recognizable trends in clothing insulation so the data for which the regressions were run was truncated beyond 30 °C. The graphs indicate a statistically significant relationship between thermal insulation and mean indoor *TOP* for NV and MM buildings. For these building types, the exponential model provided a better fit than the straight line. The model for AC buildings failed to achieve significance possibly due to the narrow range of indoor temperatures recorded in these buildings as compared to the NV and MM datasets.

Table 7
Summary of the operative temperature neutralities derived from the Griffiths method (°C).

	NV *(b = 0.16)*	MM *(b = 0.16)*	AC *(b = 0.25)*
No. of 'Building + Season' aggregates results in summer*	3 out of 7	3 out of 7	3 out of 3
Mean *GFneut_TOP* (±SD) in summer °C	25.7 (±1.45)	25.7 (±1.61)	25.3 (±0.61)
No. of 'Building + Season' aggregates results in monsoon*	7 out of 7	8 out of 10	3 out of 3
Mean *GFneut_TOP* (±SD) in monsoon °C	26.1 (±3.44)	27.0 (±1.97)	25.5 (±1.04)
No. of 'Building + Season' aggregates results in winter*	6 out of 7	4 out of 7	3 out of 3
Mean *GFneut_TOP* (±SD) in winter °C	23.7 (±9.71)	23.9 (±12.91)	25.1 (±1.63)

b = Griffiths constant.

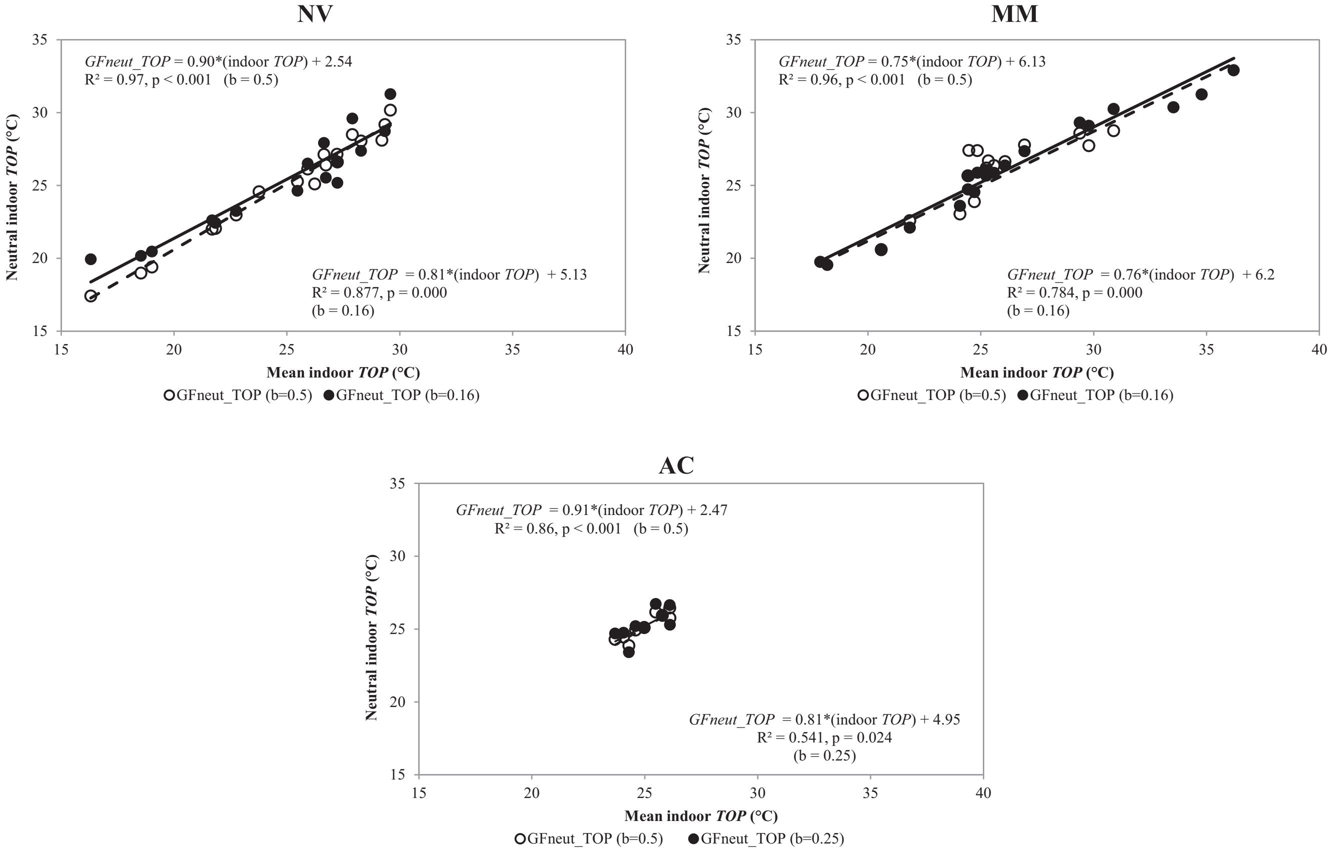

Fig. 4. Dependence of neutral operative temperatures from Griffiths method on mean indoor operative temperature.

Table 8
IMAC models based on the Griffiths Method.

Dependent variable	Independent variable	Slope	*y*-intercept	R2	*p*	*f*-value
NV Models *(b = 0.16)*						
Neutral indoor *TOP*	7-day outdoor weighted mean *ET**	0.53	13.4	0.77	<0.001	46.96
Neutral indoor *TOP*	30-day outdoor running mean *TA*	0.54	12.83	0.81	<0.001	57.87
MM Models *(b = 0.16)*						
Neutral indoor *TOP*	7-day outdoor weighted mean *ET**	0.29	18.1	0.69	<0.001	28.47
Neutral indoor *TOP*	30-day outdoor running mean *TA*	0.28	17.87	0.72	<0.001	33.48
AC Models *(b = 0.25)*						
Neutral indoor *TOP*	7-day outdoor weighted mean *ET**	0.08	23.2	0.19	0.237	1.67
Neutral indoor *TOP*	30-day outdoor running mean *TA*	0.05	23.96	0.11	0.394	0.83

* 7-day weighted running mean calculated using the EN15251 formula.

Table 9
Values of weighted average slope (sensitivity).

NV	MM	AC
0.21	0.14	0.24

Table 10
Operative temperature acceptability ranges (°C).

	NV	MM	AC
80% Acceptability	4.1	5.9	3.6
85% Acceptability	3.3	4.8	2.9
90% Acceptability	2.4	3.5	2.1

The error bars on either side of the plotted points in the figure represent ± one SD around the within-building mean. The SD bars indicate the variability of clothing insulation which decreased as the indoor temperature increased. This probably shows the diminished freedom to adjust clothing as the number of garments in the ensemble reduced to the socially acceptable minimum dress standards.

Fig. 6 presents weighted linear and exponential trend lines plotted between the mean levels of thermal insulation for each 'Building + Season' aggregate against 30-day outdoor running mean air temperatures. The graphs indicate a statistically significant relationship between thermal insulation and outdoor temperature for NV buildings, with the exponential model providing a better fit than the straight line and explaining 90% of the variance in *INSUL* values by variations in outdoor temperature. Thermal insulation was also found to decay exponentially with outdoor temperature in MM buildings where the regression model accounted

Table 11
Statistical summary of the thermal insulation variable INSUL (clothing + chair*) (clo).

	NV	MM	AC
No. of 'Building + Season' aggregates results in summer	7	7	3
Mean *INSUL* (±SD) in summer °C	0.77	0.87	0.86
	(±0.11)	(±0.13)	(±0.1)
No. of 'Building + Season' aggregates results in monsoon	7	10	3
Mean *INSUL* (±SD) in monsoon °C	0.89	0.92	0.94
	(±0.14)	(±0.17)	(±0.13)
No. of 'Building + Season' aggregates results in winter	7	7	3
Mean *INSUL* (±SD) in winter °C	1.65	1.61	1.29
	(±0.67)	(±0.58)	(±0.19)

*clo value of 0.15 was added to clothing insulation for chairs with cushions from ASHRAE 55-2010.

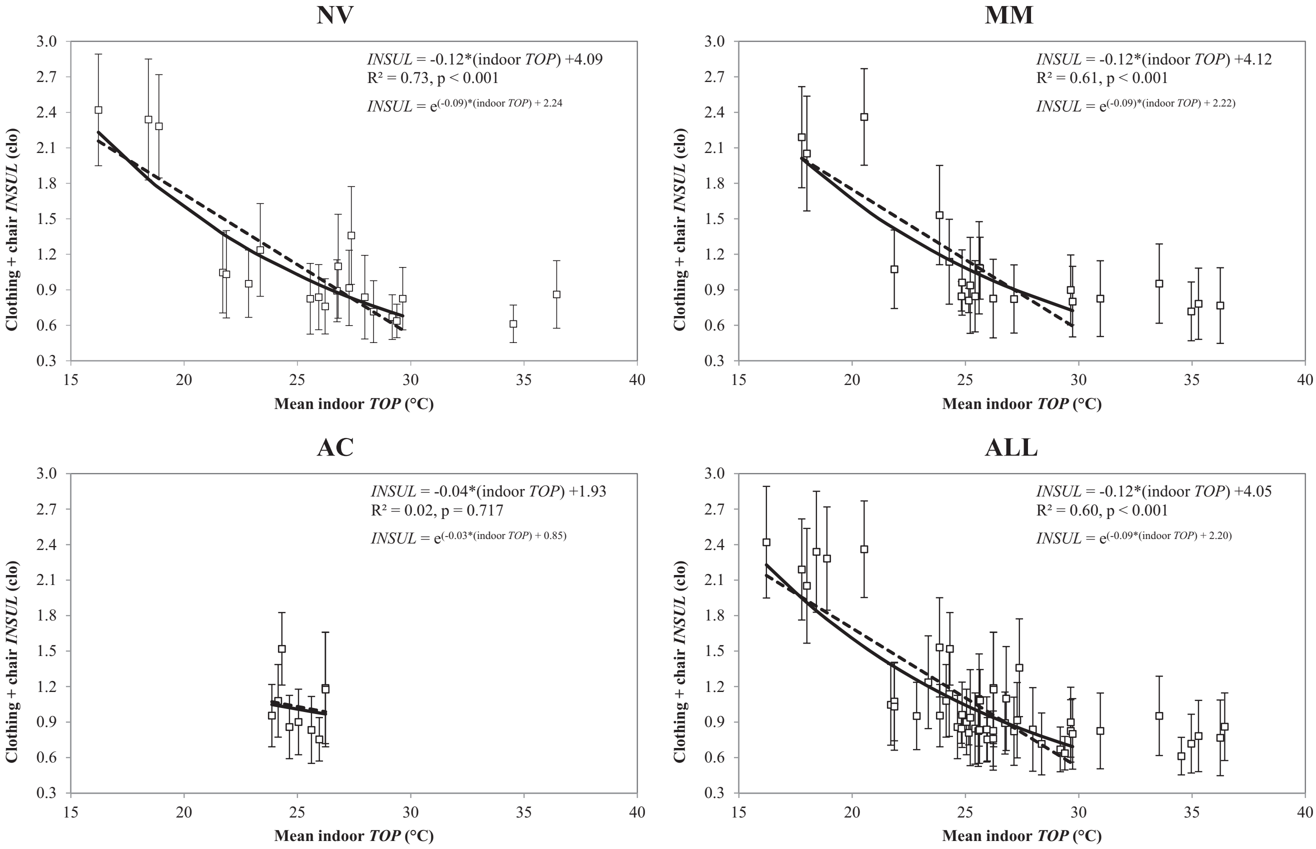

Fig. 5. Clothing insulation inside buildings (mean ± SD) as a function of mean indoor operative temperatures.

for 64% of the variance in insulation. However, in the case of AC buildings, a straight line regression model produced the best fit for the data, with only 47% variance being explained. The rate of insulation change with respect to 30-day outdoor running mean air temperature was almost one tenth of an *INSUL* unit for every five degrees of outdoor temperature change. This gradient was steeper in NV and MM buildings.

4.2. Air speed adjustments

Adjusting local air velocity through the use of ceiling fans and/or windows is one of the most significant behavioural adaptation mechanisms. In the IMAC study, these adaptive mechanisms were an integral part of all the NV and MM buildings studied. The role of air velocity in the thermal comfort sensation of building users in the IMAC NV buildings has been discussed in detail elsewhere [2]. Table 12 presents the mean and SD of the indoor mean air speeds. There was a general decrement in mean air speeds from summer to winter in NV and MM buildings. The mean air speeds in AC buildings did not change significantly from summer to winter season, indicating limited control over windows and fans. The summer sample indicates mean air speeds within MM buildings were twice as high as in the HVAC sample. As seen in Fig. 7 and Fig. 8, air speed was generally negligible at lower temperatures, curving up in the moderate temperature range from about 24 °C. Potential irritation from higher air speeds due to shifting paperwork around the desk caused the mean air speed to plateaus about 0.6 m/s for the highest temperature range (30–36 °C).

Fig. 7 plots the linear and weighted exponential trend lines for indoor air speeds in relation to the mean indoor *TOP*, while removing the outliers (<20 °C and >30 °C indoor temperatures) from the trend line plots. The relationship was best approximated by the exponential models across all building types. In NV and MM buildings, more than 80% and in AC buildings almost 77% variance

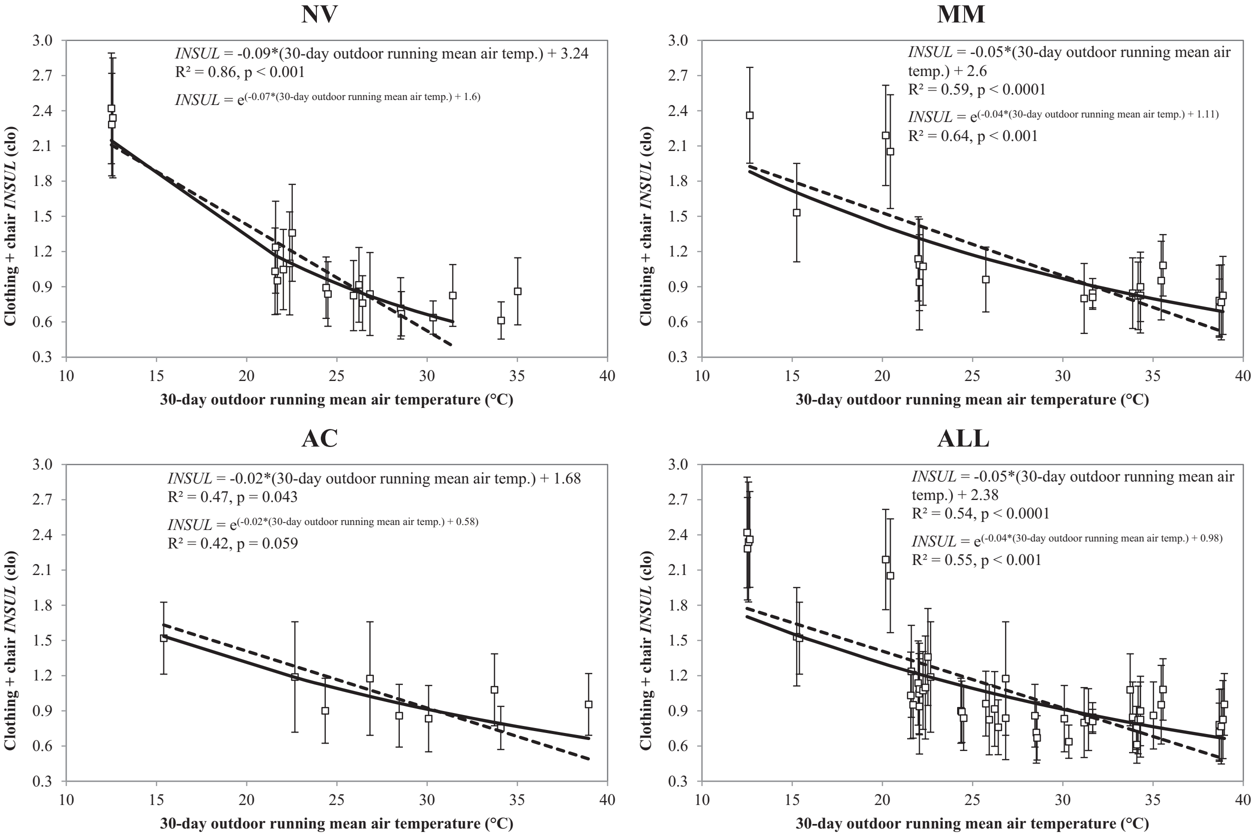

Fig. 6. Clothing insulation inside buildings (mean ± SD) as a function of outdoor temperature.

Table 12
Statistical summary of mean indoor air speeds (m/s).

	NV	MM	AC
No. of 'Building + Season' aggregates results in summer*	7	7	3
Mean *VELAV* (±SD) in summer °C	0.27 (±0.24)	0.36 (±0.22)	0.17 (±0.11)
No. of 'Building + Season' aggregates results in monsoon*	7	10	3
Mean *VELAV* (±SD) in monsoon °C	0.22 (±0.25)	0.30 (±0.24)	0.12 (±0.04)
No. of 'Building + Season' aggregates results in winter*	7	7	3
Mean *VELAV* (±SD) in winter °C	0.12 (±0.13)	0.06 (±0.01)	0.16 (±0.08)

in the mean indoor air speeds could be accounted for by the exponential trend lines. The error bars on either side of the plotted points in the figure represent ± one SD around the mean value of the dataset. The SD bars indicate the variability of indoor air speeds which increased with the increase in indoor temperatures.

Fig. 8 plots the linear and weighted exponential trend lines for mean indoor air speeds against the 30-day outdoor running mean air temperatures. The model for NV buildings shows a moderate correlation between mean indoor air speeds and outdoor temperatures with the straight line model providing a better fit than the exponential model and explaining almost 70% of the variance in indoor air speeds by variations in outdoor temperature. Mean air speeds as well as the variability in speeds within NV and MM buildings increased with increase in outdoor temperature. This relationship was weaker for MM dataset but better explained by an exponential model which accounted for 55% of the variance. The AC buildings sample did not show any discernible systematic relationship between mean indoor air speeds and outdoor temperature.

5. Adaptive models for India

The adaptive models for NV and MM put forward in the previous section are explained in Fig. 9 and Fig. 10. In addition to the solid line depicting the relationship of neutral temperature with outdoor temperature, it includes the temperature acceptability bands indicated using dashed lines that show the range of acceptable temperatures w.r.t outdoor temperature for 80%, 85% and 90% of the occupants.

For NV buildings (Fig. 9), the IMAC model indicates a unit change in neutrality for every 2 °C change in outdoor temperature. It is a robust model with significant correlation coefficients and is applicable for 30-day outdoor running mean air temperatures ranging from 12.5 to 31 °C. The model indicates that occupants in NV buildings thermally adapt to the outdoor temperature of their location and the neutral temperature varies from 19.6 to 28.5 °C for the above outdoor limits.

The IMAC model for MM buildings (Fig. 10) indicates a unit change in neutrality for roughly every 3 °C change in outdoor temperature and is applicable for 30-day outdoor running mean air

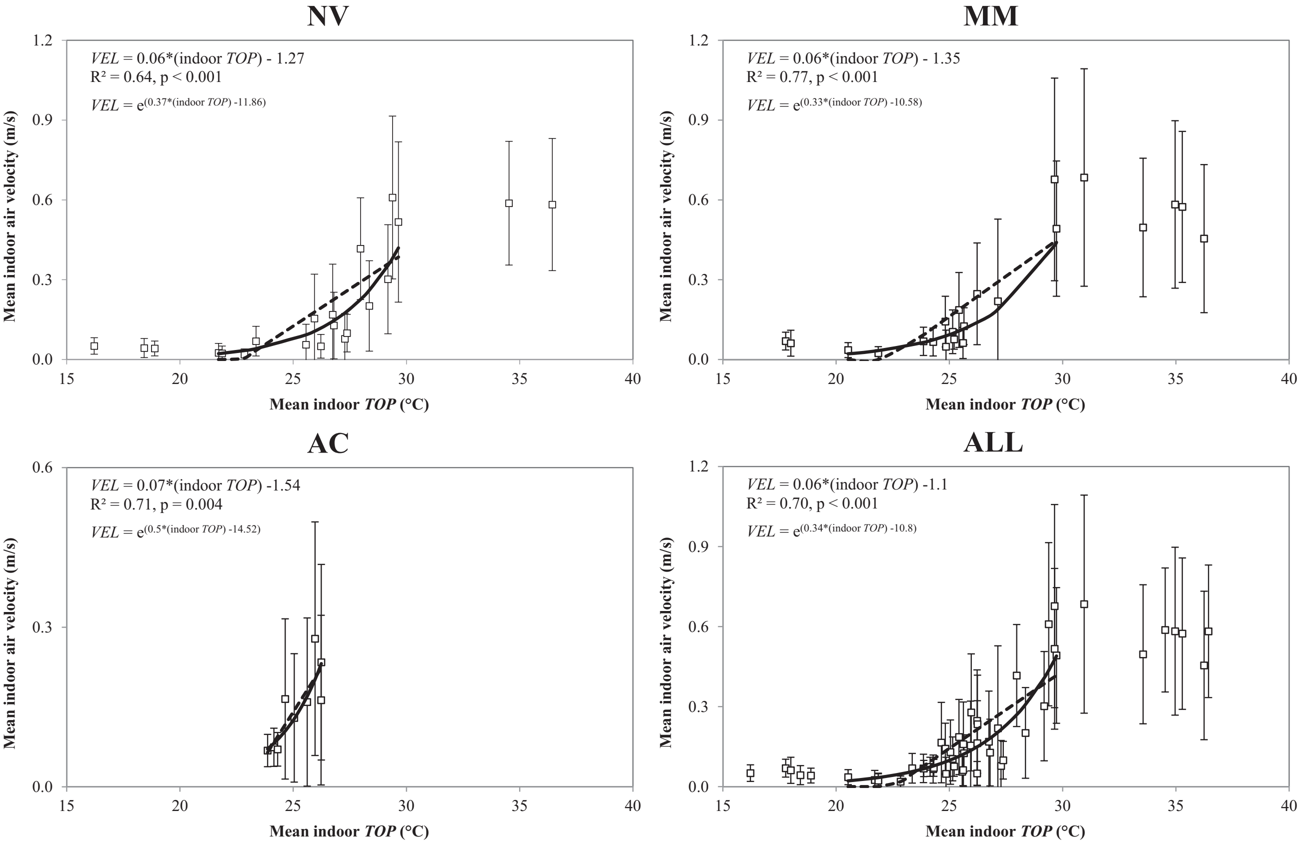

Fig. 7. Indoor air speeds within buildings (mean ± SD) as a function of mean indoor operative temperatures.

temperatures ranging from 13.0 to 38.5 °C. The neutral temperature for MM building varies from 21.5 to 28.7 °C for these limits.

The acceptability limits derived from the IMAC data are wider for MM buildings model than NV. This may be a result of the occupants knowing that the required comfort systems exist and will be operational when the external conditions are extreme. Though not all MM buildings provided individual control of the mechanical conditioning systems to the occupants, there was a building or zone level control with the facility or the floor manager leading to 'assured' thermal comfort when needed.

6. Comparison with existing models

The IMAC models for NV and MM were compared with the ASHRAE and EN15251 adaptive thermal comfort models in Fig. 11. It should be noted that while the ASHRAE Standard 55 refers to outdoor mean monthly temperature, the IMAC models use 30-day outdoor running mean air temperature.

The slope of the IMAC NV model was higher than that of the ASHRAE-55 adaptive model (Fig. 11a), indicating that the outdoor climate influences the thermal adaptation by the occupants in Indian offices more strongly than predicted by the ASHRAE-55 adaptive model. For outdoor 30-day running mean temperatures higher than 22 °C, the IMAC NV model predicted higher neutrality than the ASHRAE-55 model, while the neutrality predicted by the IMAC NV model was lower than the ASHRAE-55 model for temperatures below 22 °C. The applicability of the IMAC NV model for 30-day outdoor running mean air temperature is up to 31 °C and falls 2 K short of the outdoor temperature at which the ASHRAE model is applicable. This might be a reflection of current practice where buildings in warm climate zones tend to resort to air-conditioning when it becomes increasingly difficult to maintain thermal comfort conditions solely with natural ventilation as the monthly mean exceeds 31 °C. Although this may need verification through further detailed studies on building operation, during the IMAC study it became apparent, particularly in warm climate zones, that fully NV office buildings which were fairly common 5–10 years ago, are now becoming rare and are being replaced by MM buildings. While the 90% acceptability range for the IMAC NV and ASHRAE-55 models were similar, the 80% acceptability range for IMAC NV model (±4 K) was 1 K wider than ASHRAE-55.

The IMAC MM model slope is comparable with the ASHARE-55 model (Fig. 11b), indicating similar level of sensitivity to the outdoor temperature. While ASHRAE-55 adaptive model predicts higher neutralities for NV buildings than the IMAC model does for MM buildings, the difference in neutralities ranged between 0.3 and 1.1 K. The IMAC model limits (13 → 38.5 °C) extend the applicability of the MM model by a 5.5 K over the upper model limit of 33 °C for ASHRAE-55model. Acceptability bands of IMAC MM model were considerably wider than those of the ASHRAE adaptive model; the 90% acceptability band being wider by 2 K and 80% band by 4.8 K.

For comparison with the EN15251 adaptive model (Fig. 11c, d), 85 and 90% acceptability limits were plotted where Category III of the EN model coincided with 85% acceptability and Category II with 90% acceptability. The slope of the IMAC NV model (Fig. 11c) was higher than the EN model. The EN model acceptability ranges were wider than the proposed IMAC NV model. The IMAC MM model acceptability bands were wider than the EN adaptive model by 1 K for 80% acceptability and by 1.7 K for 90% acceptability (Fig. 11d). The slope of the IMAC MM model was lower than the EN model, indicating lesser sensitivity of the neutrality to the 7-day outdoor

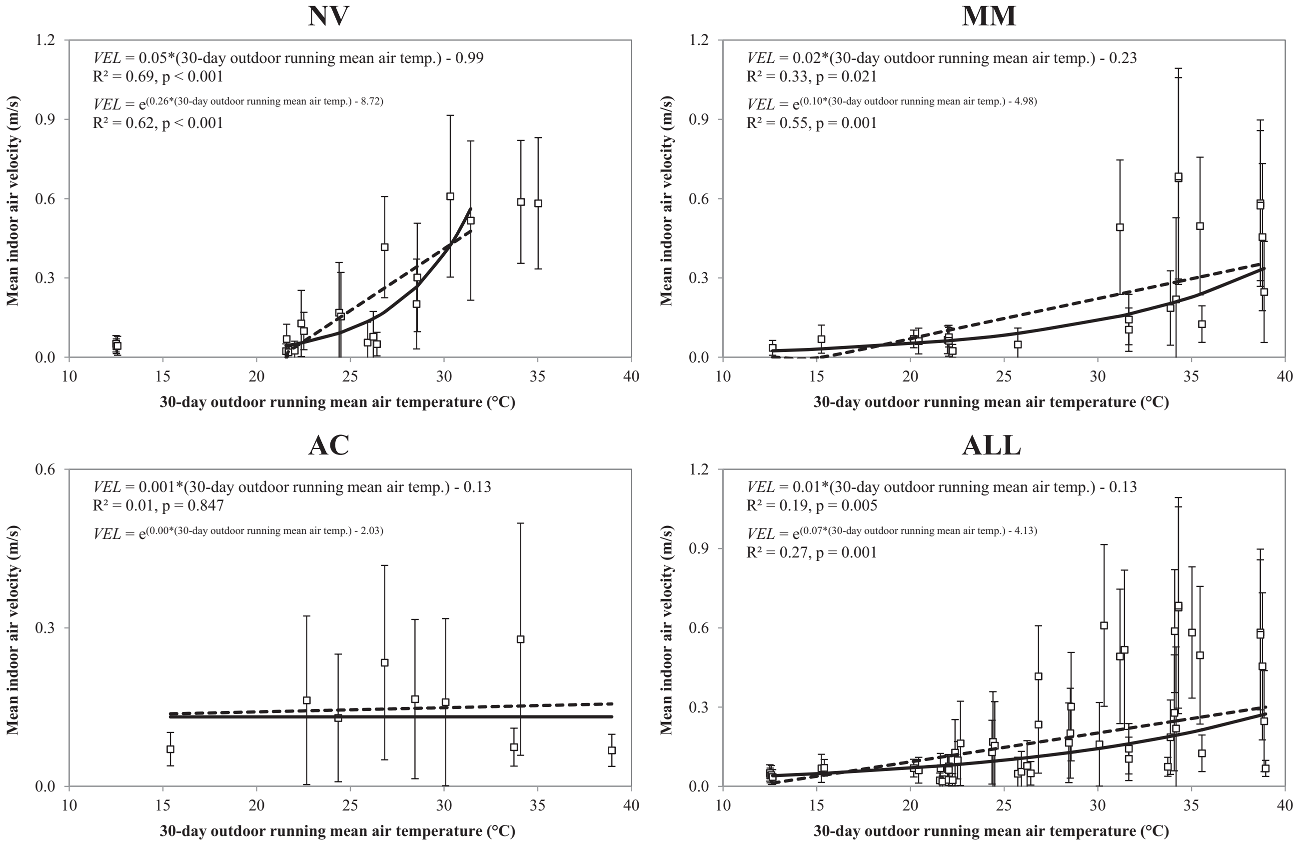

Fig. 8. Indoor air speeds within buildings (mean ± SD) as a function of outdoor temperature.

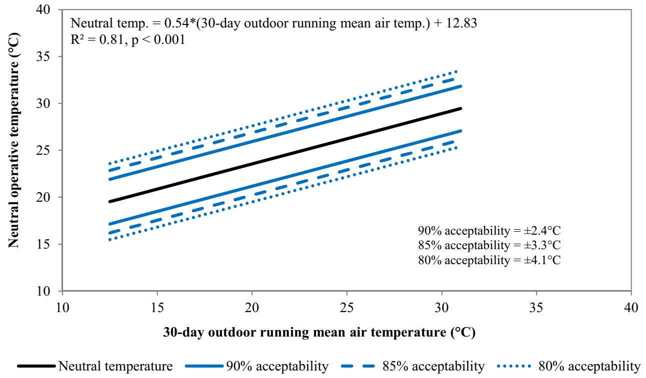

Fig. 9. IMAC model for naturally ventilated buildings.

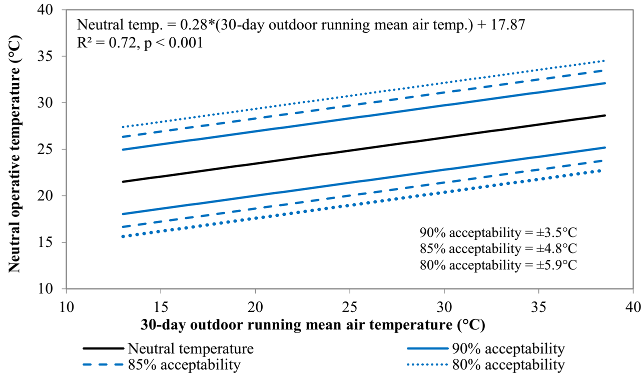

Fig. 10. IMAC model for mixed mode buildings.

weighted running mean temperature. IMAC MM model also predicted lower neutralities, the difference in the neutralities ranging from 1.2 to 2.3 K as compared to the EN15251 adaptive model.

7. Conclusions

The India Model for Adaptive (thermal) Comfort study draws on a total of 6330 thermal comfort study responses gathered from 16 buildings in five Indian cities representative of five climate zones prevalent in India — warm & humid, hot & dry, composite, moderate and cold and is aimed at developing an adaptive thermal comfort model for India. The responses analysed separately for naturally ventilated, mixed mode and air-conditioned buildings yield a number of key findings.

A significant finding of the IMAC study across the three types of study buildings is that occupants in Indian offices are more adaptive and tolerant of warmer temperatures. The IMAC study indicates that Fanger's static PMV model over-predicts the sensation on the warmer side of the 7-point sensation scale. Even where both predicted and observed sensation were on the warmer end of the scale at higher indoor temperatures, predicted sensation was always higher than observed sensation for all building types. The IMAC study also indicates that on average there was a unit change in sensation vote for every 4 °C change in indoor operative temperature in AC buildings, while in NV and MM buildings a unit change in sensation occurred for every 7 °C.

The IMAC study derived a statistically significant model for buildings operated in naturally ventilated mode throughout the

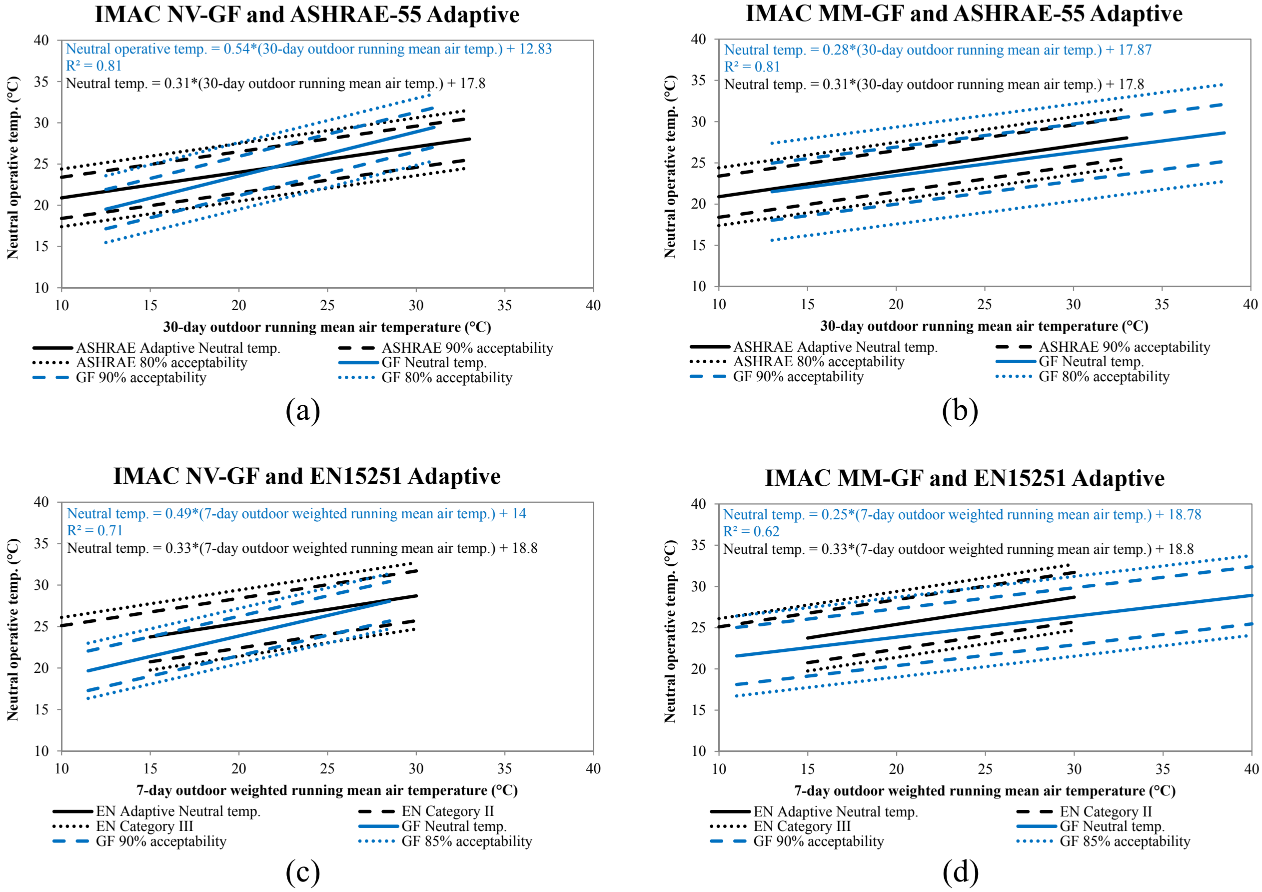

Fig. 11. Comparison of IMAC models with ASHRAE-55 (a) naturally ventilated buildings and (b) mixed mode buildings; Comparison of IMAC models with EN15251 (c) naturally ventilated buildings and (d) mixed mode buildings.

year that shows Indians are more adaptive than the prevailing ASHRAE and EN models would suggest: **Neutral temp. = 0.54 * outdoor temp. + 12.83**, where neutral temperature is the indoor operative temperature (°C), and outdoor temperature is the 30-day outdoor running mean air temperature (°C) ranging from 12.5 to 31 °C.

Another significant finding from the IMAC study is that the adaptive model continues to be valid and robust for both naturally ventilated and air-conditioned modes of operation within mixed mode (MM) buildings. The IMAC study proposes a single model for this building type. In this case, the neutral temperatures ride (not surprisingly) lower than the ASHRAE Standard-55 and EN15251 models for free running buildings: **Neutral temp. = 0.28 * outdoor temp. + 17.9**, where neutral temperature is the indoor operative temperature (°C), and outdoor temperature is the 30-day outdoor running mean air temperature (°C) ranging from 13 to 38.5 °C.

The IMAC results that indicate that outdoor temperature has very little effect on thermal comfort in air-conditioned buildings are in alignment with the past thermal comfort studies (de Dear & Brager, 1998) conducted in air-conditioned buildings. In the absence of a statistically significant result, an adaptive model is not put forward for AC buildings. However, findings from this study clearly demonstrate that Fanger's static PMV model consistently over-predicts the sensation on the warmer side of the 7-point sensation scale even in AC buildings. Coupled with observed neutralities for IMAC AC buildings in the range of 23.5–25.5 °C and 90% acceptability range derived as ±2 °C for this building type, the results clearly question reliance on the PMV model as well as recent trends to operate such buildings at 22.5 ± 1 °C all year round.

In conclusion, the IMAC study models for neutral temperatures and acceptability limits for naturally ventilated and mixed mode buildings, as derived through an empirical field study specific to the Indian context, offer an energy efficient pathway for its commercial building sector without compromising occupant comfort.

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Nomenclature

ASHRAE thermal sensation scale [−3,+3] ASH
Ensemble clothing insulation [clo] CLO
Insulation of the occupant's chair [clo] UPHOLST
Clothing plus chair insulation [clo] INSUL
Globe temperature at 0.85 m above floor [°C] TG
Air temperature [°C] TA
Average of horizontal and vertical air flow air speed [m/s] VELAV

Operative temperature [°C] TOP
New effective temperature index [°C] ET*
Mean ASH m_ASH
Mean PMV m_PMV
Linear regression LR
Probit regression PR
Average operative temperature for a ‘Building + Season’ aggregate avg_TOP
Average observed thermal sensation for a ‘Building + Season’ aggregate avg_ASH
Difference between the operative temperature for each individual vote and average operative temperature (for each ‘Building + Season’ aggregate) deltaTOP
Difference between each ASH vote and average ASH (for each ‘Building + Season’ aggregate) deltaASH
Griffiths method GF
Griffiths constant (regression coefficient) b
Adjusted regression coefficient for Griffiths method b_{adj}
Variance of operative temperature σ^2_{TOP}
Error variance of operative temperature σ^2_{err}
Neutral operative temperature for a ‘Building + Season’ aggregate derived using Griffith's method GFneut_TOP
‘Right-here-right-now’ instantaneous thermal comfort surveys TCS
Naturally ventilated buildings NV
Mixed mode buildings MM
Air-conditioned buildings AC
All data ALL
Standard deviation SD

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