Characteristics of thermal comfort in the offices of North-East India

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Abstract. In the context of climate change and global warming, the nexus between energy and buildings is self-explanatory. As per the ministry of statistics and program implementation, Govt. of India data, the primary energy consumption in the building sector is 37% of total primary energy consumption and about 24% to total CO2 emissions. It is evident from the research that thermal comfort, energy efficiency in buildings and sustainable architecture are interlinked and interdependent. The present study is carried out in the Naturally ventilated offices of North-East India at three representative locations i.e., Tezpur, Imphal and Shillong, from warm and humid, Cool and humid and Cold and cloudy climates, respectively. Year-long thermal comfort surveys were carried out in 81 naturally ventilated office buildings, collecting 2326 samples spread over three locations from July 2016 to June 2017. Data analysis shows that neutral temperature through regression analysis is 26.4°C, 24.7°C, and 23.4°C for Tezpur, Imphal and Shillong, respectively. Preferred temperature and relative humidity in Tezpur, Imphal and Shillong offices are 24°C, 23.5 °C and 22 °C and 55%, 55% and 63%, respectively. Probit analysis showed that occupants are more adaptive toward the warmer side of the thermal sensation scale.

1 Introduction

Humans have been spending a considerable amount of time inside built environments for ages. In recent years, more than 90% of the time being spent inside the built environment by humans because of changing lifestyles and work-related requirements [1]. It is evident from various data sources and published research that the building sector is high-energy and resource-intensive and consumes almost 40% of the world's primary energy with a high carbon footprint [2]. In India, buildings consume more than 33% of the nation’s primary energy use, with annual growth of 8% [3].

According to the United Nations projection, by 2050, 66% of the world's population will migrate to cities, and the same will be valid for India [4, 5]. Over the past two decades, several studies showed that the building sector has been severely impacted by climate change leading to a shift in energy consumption because of heat stress and unpredictable extreme weather events [6–11]. Because of this, occupant’s health and well-being inside the built environment are at stake. The problem of reducing energy consumption and optimally comfortable building design is now adding another dimension because of climate change's unpredicted and varied impact [6–11]. This has made the building designer's and engineer's tasks more complex and challenging.

North-East India is strategically crucial for India as it has the potential to become the gateway to Southeast Asia. Realizing this Government of India emphasizes North-East India to develop it as an economic hub [4, 12, 13]. Also, the literature review shows that few studies are being carried out to evaluate the indoor thermal comfort status in the offices of North-East India [12–16]. To address this research gap, the present study is being carried out at three representative locations, Tezpur, Imphal, and Shillong, in warm and humid, Cool and humid, and cold and cloudy climatic zones of North-East India. In this research, yearlong monitoring and questionnaire-based adaptive thermal comfort surveys were carried out covering all four seasons in a year, and the results are presented in subsequent sections.

1.1 Background and literature review

Climate change and global warming are now leaving more visible signs in terms of the heat wave, incessant rains, etc., over the last decade in India. The building sector in India is one of the highly energy-intensive sectors. In the context of reducing the building running energy consumption, a lot of interest has been shown by researchers in the recent past to precisely define the
thermal comfort parameters in different types of built environments. This section aims to highlight the important findings and conclusions that researchers put forth in respective studies done in India.

Indraganti et al. [17–20] studied the naturally ventilated (NV) and air-conditioned (AC) offices in Chennai, and Hyderabad, India. Occupants of NV and AC offices expressed their neutrality at 28.1°C and 26.1°C, respectively. Regarding adaptation and adaptive actions, it was found that at 29°C, almost 87% of ceiling fans are operational in NV offices. Because of enhanced air speed (1 m/s), the comfort bandwidth has increased up to 2.7K. Indraganti et al. [20,21], in their study, also estimated the clo value of traditional attire, the Sari of Indian women. It is evident from the published research that an accurate buildings-centric bioclimatic classification has a huge impact on designing low-energy and climate-responsive architecture. Singh et al. [14–16,22] carried out building-centric re-classification of the North-East region of India. Entire North-East India is classified into three bio-climatic zones (warm and humid, Cool and humid and Cold and cloudy). A thermal comfort study was carried out in the region's vernacular architecture, and it was found that comfort temperature varies approximately in the range of 7°C across the season in each climatic zone [12,15]. Singh et al. [13] conducted a thermal comfort assessment in the N.V. offices in warm and humid and cold and cloudy climates of North-East India in the autumn season. The study found that the preferred temperature of the subjects is 24.5°C which is 2.8°C lower than the comfort temperature of 27.3°C.

Comfort boundary estimation plays a significant role in thermal comfort study. The limit of comfort boundaries depends on adapting subjects to local climatic and geographical parameters. Sanjay et al. [23,24] defined comfort boundaries on a typical psychrometric chart. The defined comfort boundaries consider the effect of adaptation of subjects under different air velocities and clothing. Comfort requirements in classrooms are of tremendous importance because evidence-based research shows that a comfortable thermal environment positively impacts students learning curves. Singh et al. [25] and Kumar et al. [26-31] conducted an extensive thermal comfort survey in 30 classrooms spread over three universities with 900 student subjects. Analysis of the collected data showed that comfort temperature in the in-summer season months stood at 29.8°C, but students preferred cooler temperatures (26.4°C). Almost 90% of students felt comfortable within the comfort boundaries of 22°C and 32°C. Analyzing the data concluded a comfort temperature close to 30°C, with a preferred temperature about 3°C below the comfort temperature.

Manu et al. [32] carried out a thermal comfort study in the offices of India and found that neutral temperature in N.V. buildings varies from 19.6°C to 28.5°C and in A.C. buildings, the range varies from 21.5°C to 28.7°C. In this study, they also proposed the India model for Adaptive Comfort (IMAC). Thapa S [33-35] and Thapa and Indraganti [36] carried out thermal comfort studies in different built environments of Darjeeling district, West Bengal, India and reported the effect of gender, age and body mass index (BMI) on the thermal comfort parameters and preferences. The authors reported that the mean clothing level of male subjects was higher than female subjects, and the mean clothing level of senior subjects (above 50 years) was comfortable at a higher temperature than middle-aged (30 – 50 years).

The bio-climate and socio-cultural setup, as well as the existing architecture of the region, is quite different from the rest of India and the world. Literature review shows that very few studies are done addressing the issue of thermal comfort status in the offices of North-East India. Above mentioned facts set the context to carry out a field study to investigate the status of thermal comfort in the N.V. offices of the region. A field study was done to evaluate thermal comfort and its characteristics in the region's offices.

1.2 The objectives of the study

Considering the importance of thermal comfort and the associated well-being of subjects in a built environment, it becomes imperative to carry out a thermal comfort study based on long-term data collection. In the present study, yearlong data collection and questionnaire-based surveys were carried out in North-East India's naturally ventilated and free-running office buildings. Long-term data collection through surveys is advantageous as they capture a broad spectrum of adaptations of subjects. It becomes even more important because North-East office-built environment and functioning are quite different to that of the rest of India. The present research is carried out with the following objectives.

a) To study thermal comfort characteristics in North-East India's offices.
b) To study the subjects thermal preferences and comfort temperatures
c) Identify the different adaptive actions in the office-built environment.

![Fig 1. Study locations and climatic zones a) India b) North-East [14]](image)

2 Methodology

Questionnaire-based thermal comfort study was carried out at three representative locations, Tezpur and Shillong, in North-East India. Tezpur is in the state of Assam, Imphal is the capital city of Manipur, and
Shillong is the capital city of Meghalaya. Tezpur lies in a Warm and humid climatic zone, Imphal in a Cool and humid climatic zone and Shillong in a Cold and cloudy climatic zone (Figure 1)[14]. Elevation from the mean sea level of Tezpur, Imphal and Shillong is 48m, 786m and 1525m, respectively. Thermal comfort surveys were done at all the locations simultaneously in naturally ventilated. Above all, each study location is separated by large distances. The distance between Tezpur to Shillong, Tezpur to Imphal and Shillong to Imphal is 250km, 418km and 545km.

2.1 Characteristics of offices of North-East India

The present study is carried out in the N.V. offices of North-East India. Figures 2 show Assam-type office buildings, sitting arrangement, working environment and traditional clothing of subjects in the offices. Offices in this part of India are designed to operate under N.V. mode throughout the year. Characteristics of Assam-type buildings are light structure, slanted roofs and a high window-to-wall ratio [13]. Most of the Assam-type buildings are single-storey. Very few are up to 3 storeys high but without elevators. In modern offices, each subject has a cubicle with a wooden or metal partition. Almost all the offices have operable windows with curtains and ceiling fans. A ceiling fan is shared among the office subjects. For lighting, all the offices are fitted with Fluorescent or LED lights. In government offices, subjects are free to wear a dress per their socio-cultural requirements. Windows of the offices are single glazing with curtains. In Figure 2, we can see the office subjects in traditional attire and filling out the thermal comfort questionnaire. A thermal comfort study was carried out in 81 naturally ventilated office buildings across three locations. In Tezpur 12, Imphal, 4 and Shillong, 65 buildings were randomly selected out of normal office building stock for the study. During the survey, the day-to-day activity of office subjects was least interrupted. In Shillong, each Government department has several small offices with a very small number of office staff. So, to get an adequate number of statistically acceptable sample sizes survey must be conducted in a relatively large number of office buildings. Moreover, the surveys were conducted only on clear and sunny days only.

![Fig 2. Subjects in an office environment and Office buildings; a, b and c show subjects in traditional attire; d, e are typical office buildings](image)

2.2 Survey and protocol to record data

The questionnaire for the present study was sourced from ASHRAE standard 55-2020 information appendix L [37]. Before employing the questionnaire, the local study coordinators were selected and trained. The questionnaire was designed to capture detailed information about the subjects present sensation (about the thermal environment, air movement, humidity, air quality), preferences (about the thermal environment, air movement, humidity, air quality), preferred adaptive actions to restore comfort and their views about probable reasons of discomfort. If the office occupants are separated by more than 1.5 meters, then thermal environment parameters are recorded corresponding to their thermal sensation for each subject. During the summer and winter days, care was taken regarding the location of the subjects seating place. If the subject is seated close to the west wall in summer or the north wall in winter, it may lead to the local draft formation and consequently impact the subjects thermal sensation. Only those subjects sitting in the same place for more than a year were selected. Corresponding to each subject, an average of 3 measurements were taken at the interval of 1 min. An interval of 3 min was considered for recording globe temperature. From moving one subject to another for recording the subjects thermal preferences and corresponding physical parameters, an interval of 20 min was considered to stabilize the globe temperature. It was also ensured that the subject was sitting at the same place and doing the same work/activity for at least 20 mins.

2.3 Scales and instruments used in the study

Thermal sensation and preference scales were sourced from ASHRAE and Nicol [38]. Subjects thermal sensation and acceptability were recorded using the 7-point ASHRAE thermal sensations scale and ASHRAE's nominal acceptability scale [37]. Nicol's five-point preference scale was used to record the preference of office subjects. During the surveys, considerable time is spent interacting with subjects. This was necessary to minimize the error in recording individual subjects thermal sensations and preferences. In the Indian subcontinent, clothing value estimation is the biggest challenge in thermal comfort surveys. The difficulty level was minimal for men in North-East India offices because very few male subjects wore traditional attire. But in the case of female subjects, it was a challenge because traditional attire individual insulation values are not present in the database. So, in this case, a uniform methodology was adopted to use the nearest clo values mentioned in the ASHRAE-55 and ISO 7730 database. In North-East India, each state has distinct traditional clothing patterns for males and females, and they are allowed to wear traditional dress in offices. Figure 2 shows subjects wearing traditional dress in offices.

Instruments used in this study to record built environment parameters (air temperature, relative humidity, air velocity, globe temperature, CO₂...
concentration in ppm) are listed in Table 1, along with make and sensitivity. Table 1 also shows the range and sensitivity of the instruments. The instruments were new, and company calibrated. Figure 2 shows the deployment of the instruments at the field surveys. The measurements were taken at the neck height of the sitting subject because the subjects height and the sitting chair height varied considerably across the offices in three climatic zones.

Table 1. Details of instruments and their sensitivity [13]

<table>
<thead>
<tr>
<th>Description</th>
<th>Make</th>
<th>Parameter measured</th>
<th>Range</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermo-hygro-CO₂</td>
<td>Tr-76LI</td>
<td>Air temperature</td>
<td>0° to 55°C</td>
<td>±0.5°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO₂ level</td>
<td>100% to 95% RH</td>
<td>±5% RH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Globe temperature</td>
<td>-60° to +15°C</td>
<td>±0.3°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>surface temperature</td>
<td>-18° to +23°C</td>
<td>12°C; Temperature: -18° to +23°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Air velocity</td>
<td>0.01 to 10.00 m/s</td>
<td>0.01 m/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Air Temperature</td>
<td>-20° to +50°C</td>
<td>±0.1°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative humidity</td>
<td>5% to 95%</td>
<td>5% to 95%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lighting level</td>
<td>0.04 to 48 Lux</td>
<td>±5%</td>
</tr>
</tbody>
</table>

3 Results and Discussion

3.1 Sample size characteristics

A total of 2326 valid thermal sensation votes were collected in the study. The sample size consists of 36.2% females and 63.8% male subjects. A total of 81 offices were covered in the study through field surveys. The highest number of offices covered in the surveys was in Shillong. This is done because, in Shillong, offices are scattered in different buildings with a small number of subjects. So, surveys were done in many offices to get a good sample size. Also, the Shillong sample size is interesting because the male and female sample size is nearly equal. Looking at Figure 3, we can see that the maximum number of subjects falls in the age bracket of 41-50 years. This ensures that occupants have spent a considerable amount of time in the same climate and can give a balanced response towards thermal sensation and preferences.

3.2 Outdoor and indoor environmental conditions at study locations

North-East India is heavily vegetated with uneven topography. Outdoor climatic data of all three locations was assessed from the website weatherbase [39]. Figure 4 shows three selected sites’ monthly mean outdoor temperature and relative humidity profiles. Figure 4 shows a difference in mean temperatures between Tezpur (Warm and humid climate) and Imphal (Cold and humid climate) in the range of 3 to 5 °C. Similarly, the mean temperature difference between Imphal and Shillong (Cold and cloudy climate) is in the range of 3 to 4.5°C. The monthly relative humidity profile shows that relative humidity for all three locations is in the range of 70% to 95%. In the rainy season (May to September), relative humidity stays more than 80%. This happens because this part of India received high precipitation lasting over six months.

Offices in all three climatic zones operate under natural ventilation mode. The indoor air temperature in the offices of Tezpur, Imphal and Shillong varied from 19.8 °C to 35.2 °C, 19.1 °C to 32 °C and 13.6 °C to 28 °C respectively. Indoor air velocity in the offices of Tezpur, Imphal and Shillong varies in the range of 0 to 3.2 m/s, 0 to 2.5 m/s and 0 to 1.2 m/s, respectively. Similarly, the relative humidity in the offices of Tezpur, Imphal and Shillong varies in the range of 36% to 85%, 32% to 79% and 26% to 81%, respectively. High air velocity in the offices of Tezpur and Imphal is evident because it helps subjects to overcome the discomfort due to persistent high temperature and high relative humidity.

In the offices of North-East India, subjects are seated close to external walls (Not insulated). It is also well known that a large temperature difference between the wall surface and the subject can lead to the formation of a local draft and, consequently, to local discomfort. Analysis of wall temperature data shows that the minimum temperature of the left wall, right wall, front wall and back wall for Tezpur, Imphal and Shillong hovers around 18.7 °C to 19.5°C, 16.1 °C to 16.8 °C and 11.9 °C to 13 °C respectively. This temperature is low and will impact the clothing pattern and thermal sensation of subjects in winter. A similar phenomenon was observed in the summer (May to August) season.

The selection of a proper temperature scale is key to analyzing the data and reporting the results of the thermal comfort study. Analyzing the relationship between indoor air temperature, mean radiant temperature and indoor globe temperature, it was found that indoor globe temperature better describes the
variation in indoor air temperature. So, it is decided to use globe temperature to analyze further and report the results. Indoor air quality is one of the prime concerns in government offices. Government offices have high footfalls because they deal with public governance matters. It is also a matter of concern that CO₂ concentration in the offices of Tezpur and Imphal reaches up to 1940ppm, which is way high than the permissible limit of 800ppm [40].

3.3 Clothing characteristics

In this study, the activity level of office subjects at all three locations varies between 1 met (seated, reading) to 1.4 met (filing, standing). These activity values correspond to everyday office activity [37]. In Figure 2, female subjects in the offices of the North-East are in traditional attire. For a traditional dress, such as "saree" and "salwar-kameez" clothing, insulation was sourced from Indraganti et al. [3] and Kumar et al. [25,26,41]. Clothing insulation values vary throughout the year for Tezpur, Imphal, and Shillong in the range of 0.29 clo to 1.67clo, 0.33clo to 1.67clo and 0.29clo to 1.55clo, respectively. To study the behaviour of clothing patterns with respect to thermal sensation for combined data is shown in Figure 5. To understand the clothing behaviour of office subjects, the mean clothing values with standard deviation are plotted against thermal sensation and indoor globe temperature. Figure 6 shows that the deviation in the clo value is higher on the cooler side of the thermal sensation scale. This behaviour can be attributed to the availability of more options for clothing in autumn and winter and local discomfort due to the large temperature difference between the back wall surface and the subject. Regression analysis shows that the correlation coefficient improves drastically for combined data.

3.4 Preferred temperature

Statistical methods can be used effectively on the data to estimate the preferred temperature of subjects based on their votes on the preference scale. In most cases, preferred environmental conditions are different but lie within the acceptable environmental conditions for the subjects in different built environments. To evaluate the preferred temperature, the probit analysis technique was used. To apply this technique, it is required that the data must be in binary form. For this, the preference votes of the office subjects are transformed to binary format using the assumptions presented in Table 2. Using the assumptions, the preference scale is modified. The transformed binary data is now used to carry out ordinal regression with probit as the link function. Finally, the proportion of votes is calculated using equation 1.

\[
\text{Probability} = \text{CDF. Normal (Quant, mean, S.D.)}
\]

(1)

Where "quant" is the independent variable on which the preference votes are impacted, and "CDF" is the cumulative distribution function for normal distribution. In this case, the parameter of interest is globe temperature. "mean" in equation 1 is calculated by dividing the constant of the regression equation by the coefficient attached to the independent variable, such as globe temperature and relative humidity. Standard deviation (S.D.) is estimated by taking the inverse of the coefficient attached to the independent variable of the regression equation.

![Figure 5. Mean clothing characteristics with 95% confidence interval (mean ± 2 S.E.): Clothing insulation corresponding to different sensations for all data](image)

![Figure 6. Preferred Temperature](image)
3.5 Probit Analysis

The characteristics of thermal comfort votes can give interesting and important information about the subjects adaptation limits and external thermal stimuli in a built environment. An analysis of thermal comfort votes is carried out to generate this information. For this, ordinal regression analysis uses probit as a link function to globe temperature. The process of carrying out this analysis is described in detail by Singh et al. [13] and Rijal et al. [37]. This analysis resulted in the proportion of votes for each thermal sensation corresponding to globe temperature. Figure 7 presents the plots of the proportion of votes for each thermal sensation on the Y-axis and corresponding values of globe temperature on the X-axis for all data (Figure 7).

![Figure 7. Probit Analysis](image)

To find neutrality, if a vertical line is dropped from the sigmoid curve for "TSV = 0" at probability 0.5, the corresponding globe temperature value obtained is neutral temperature. The neutrality value for all data is 26.5°C. On further analysis of the plots, it can be found that the width of the sigmoid curves corresponding to each thermal sensation for a particular location is not identical at probability 0.5. This means that the thermal stimuli required to shift/change the sensation on the thermal sensation scale are different. This contradicts the assumption regarding the 7-point thermal sensation scale defined in ASHRAE standard 55. Recent studies also challenged the equidistant thermal sensation scales to capture the true status of thermal comfort and adaptation characteristics of the subjects in naturally ventilated and mixed-mode operated buildings [28].

3.6 Estimation of Comfort temperature

Neutrality or neutral temperature and range of comfort temperature can be estimated by conducting different statistical analyses on the collected data. If all the analysis gives approximately similar and very close results, then the estimated neutrality or neutral temperatures and the range of comfort temperatures can be termed reliable estimates. Regression analysis is carried out to estimate the comfort temperature, as shown in Figure 8a, with a 95% confidence interval. Regression analysis was carried out for all data, resulting in equation 2. Figure 8a and equations 2 show the slope of the regression line for all data is 0.3. This implies that subjects require 3.3°C changes in indoor globe temperature to shift one thermal sensation to another. The neutral temperature derived from the regression analysis is 25.7°C.

TSV = 0.3Tg - 7.69 (N=2326, R2=0.61, S.E.-0.011, P<0.001) (2)

\[ T_{cg} = T_g + \left( \frac{0 - TSV}{G} \right) \]  

Where,

- \( T_{cg} \): Griffiths comfort temperature
- \( T_g \): Globe temperature
- 0: Neutral on the thermal sensation scale
- \( TSV \): Thermal sensation vote
- \( G \): Griffiths constant (0.3)

![Figure 8. a) Regression analysis b) Griffiths comfort temperature](image)

Comfort temperature was also estimated by the following methodology proposed by Griffiths, as shown in equation (3). For every thermal sensation vote, this calculation was performed. Griffiths constant was found to be 0.3 for all data. Figure 8b shows the distribution of Griffiths comfort temperature corresponding to the Griffiths constant 0.3. The estimated comfort temperature by Griffiths method is 25.6°C.

3.7 Adaptation analysis

In a thermal comfort study, analysis of the adaptation characteristics of subjects is important to justify the results. Adaptation of subjects is responsible for the deviation in thermal sensation votes. Adaptation also provides the opportunity and degree of freedom to the subjects in the built environment to restore their comfort.

![Figure 9. Adaptive behaviour in offices of North-East India: a) Fan use b) Windows opening behaviour](image)

Based on the opportunities available to the subjects, the adaptation may be local/personal or global in nature. For example, switching ON/OFF ceiling fans, opening/closing windows etc., impact all the subjects occupying the same built environment. The global adaption opportunities available for the subjects in the offices of North-East are opening/closing windows and switching ON/OFF ceiling fans. Ceiling fans are predominantly used in naturally ventilated office
buildings of North-East India to restore comfort at higher temperature as increased air velocity help to offset the increase in air temperature. The use of fan data was collected in binary form during the comfort surveys. So, to understand the characteristics of these two adaptive behaviours of the subject, logistic regression was carried out, and output in terms of probability was analyzed. Equation 4 to 7 shows the mathematical expressions related to logistic regression. Figure 9a shows the ceiling fan use characteristics. From Figure 9a, it can be concluded that as the indoor globe temperature crosses 24°C, ceiling fans in the offices are gradually switched on, and at 31°C, almost all the fans are switched on. The logistic function can be written as follows.

\[ F(x) = \frac{1}{1 + e^{-(\beta x + C)}} \]  

Where \( y \) is the linear function of variable \( x \) and can be expressed as

\[ y = \beta x + C \]  

Where \( x \) is globe temperature (°C), and \( y \) is switching on fans in offices of NE India. Where \( \beta \) is the coefficient and \( C \) is a constant. Now equation 4 becomes

\[ F(x) = \frac{1}{1 + e^{-(\beta x + C)}} \]  

\( F(x) \) gives the probability of the "happening of an event".

Analysis of the opening/closing of windows is shown in Figure 9b. Both linear and cubic regression analysis shows that the percentage of window opening increases with the increase in indoor globe temperature, justifying non a non-linear relation. However, some windows were open at low temperatures, but the opening of a window rate increased when the indoor globe temperature reached 19°C (30% windows open) and plateaued at 31°C (70% windows open).

### 3.8 Adaptive thermal comfort

In this study, the authors tried to propose an adaptive comfort equation. The methodology described in standard ASHRAE-55-2020, Section 5.4 and Appendix I (Occupant controlled Naturally Conditioned Spaces) was followed to develop the adaptive comfort equations. To calculate the prevailing daily mean outdoor air temperature [32], we used the following equation (7).

\[ \bar{T}_{pma} = (1 - \alpha)\left[ t_{e(n-1)} + \alpha t_{e(n-2)} + \alpha^2 t_{e(n-3)} + \alpha^3 t_{e(n-4)} + \alpha^4 t_{e(n-5)} + \alpha^5 t_{e(n-6)} + \alpha^6 t_{e(n-7)} \right] \]  

\[ \bar{T}_{pma} = (1 - \alpha) t_{e(n-1)} + t_{rm(n-1)} \]  

Where,

- \( \bar{T}_{pma} \) - Prevailing daily mean outdoor temperature
- \( t_{e(n-1)} \) - mean daily outdoor temperature for the day before the day in question
- \( t_{rm(n-1)} \) - Running mean temperature for 7 days before the day in question

\( \alpha = 0.7 \) is used to calculate the prevailing daily mean outdoor temperature. It means the prevailing mean outdoor temperature for today would be the combined impact of 30% of yesterday's mean daily outdoor temperature and 70% of yesterday's running mean outdoor temperature (which is again calculated as 7 days running mean temperature before the day in question). Figure 10 shows the regression analysis where indoor globe temperature is plotted against prevailing daily mean outdoor air temperature with ASHARE-defined adaptive thermal comfort temperature bands. For plotting, we considered the comfort votes corresponding to the three central categories (−1, 0, +1) of the 7-point thermal sensation scale. The proposed adaptive thermal comfort equation is

\[ T_{ca} = 0.61T_{pma} + 12.86 \quad (N=1172, R^2=0.72, P<0.001) \]  

From the developed equations, it can be concluded that the offices' occupants are sensitive to outdoor temperature changes. The slope of the regression lines for all locations in three climatic zones is more than the slope of the ASHRAE 55 standard. It was found that the slope of adaptive comfort equations developed in the present study is comparable to the slope of adaptive comfort equations of other studies done in office and university settings. The reason for this can be attributed to the fact that an occupant in the naturally ventilated offices of North-East India experiences a narrow range of temperature daily, and thus the observed slope is higher.

### 4 Conclusions

The present study was carried out in the randomly selected naturally ventilated offices of North-East India at three locations (one in the three climatic zones). Thermal comfort surveys were carried out in 81 offices, resulting in a total of 2326 valid responses. Various statistical techniques were employed to analyze the data, resulting in the following conclusions.

- In the offices, occupants felt local discomfort due to the significant temperature difference between external walls and occupants.
- The difference between inflexion points at low and high temperatures is about 8°C across all three locations in different climate zones.
- The preferred temperature for all data is 23.5°C.
- Probit analysis concludes that different thermal stimuli (different areas under the curve for each sensation) are required to shift one sensation point on the thermal sensation scale.
• Almost 80% of occupants in the offices are comfortable in the temperature range of 25°C to 30°C.
• Window operation use of ceiling fans and curtains are the prominent global adaptation opportunities available to office occupants.
• Ceiling fans in the offices are switched on at 23°C, and almost all the fans are switched on at 32°C.
• Proposed adaptive thermal comfort equations show that the occupants are highly sensitive to changes in outdoor temperature. This result is supported by studies done in other parts of India.

This study is based on analyzing 2326 subjective responses from N.V. offices of North-East India in three climatic zones. The study estimated the range of comfort temperature, preferred temperatures and relative humidity and characteristics of prominent adaptive opportunities. The slopes of the adaptive comfort equations are on the higher side compared to the ASHRAE standard 55. This study also put forth the potential to design N.V. offices in North-East India with improved comfort duration utilizing adaptive opportunities. This study also gives architects and engineers the opportunity and degree of freedom to design occupant-centric, sustainable, low-energy buildings.

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