Building thermal simulation-based climate classification of India

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Abstract
Climate classification of a region serves different applications including agriculture, hydrology, biodiversity and geography. Climate classification is an essential criterion to define building performance. Depending on the application, climate variables like temperature, precipitation, vapour pressure, solar radiation and wind movement are adopted for classification. This paper aims to develop a climate classification of India for building performance analysis related applications. The classification is based on building energy simulations performed at a grid resolution of 50km x 50km across India. The comfort indoor degree hours are used to develop spatial clusters. The fuzzy c-means classification resulted in 9 climatic zones. These climate clusters can be used to create bioclimatic design guidelines for buildings.

Key Innovations
- The study develops building design specific climate classification of India.

Practical Implications
This study will help in deducing zone-specific building design and performance guidelines. It will be useful for defining realistic thermal performance benchmarks. It will serve as a simple tool to identify energy efficient strategies.

Introduction
A climate classification by Bansal and Minke (Bansal and Minke 1988) used four variables (temperature, humidity, precipitation, and the number of clear sky days) and classified India into six climate groups. Though classifications were intended for climatic design purposes, the number of climate groups is too small to address wide variations throughout the country. This is especially demonstrated in the "composite climate zone that encompasses a vast expanse of lowland areas, which is otherwise proven in several studies to have climate differences (Naveen Kishore and Rekha 2018), (Khambadkone and Jain 2017). (Rijildas and Rajasekar 2016). Additionally, differences due to topography in the "cold climate" are neglected to a more considerable degree. An analysis of the Indian cold climate (Rajasekar, Thakur, and Zeleke 2020) showed that National Building Code(NBC)'s classification could be subdivided into 11 zones, indicating varying thermal performance requirements. A recent study on advanced climate classification in china stresses the need for adequate climate zones for building energy efficiency(Bai et al. 2020).

To depict the relation between climate and building energy performance, climate clustering with building performance simulation provides robust tools (Walsh, Cóstola, and Labaki 2017). Climate classification can be arrived at through either supervised or unsupervised techniques. Supervised techniques are based on a predetermined class type and identity (Yang et al. 2020). Most of the climate classification techniques follow the supervised method. Unsupervised methods are used in cases where no predetermined classes exist or exploratory classification is required. One of the unsupervised classification techniques is cluster analysis. Clustering is a process of grouping data into classes based on class similarity and difference between classes. Clustering is an experimental technique and aims to identify structures in data (Jain 2010). This method is used where the number and identity of groups are not known in advance. In recent decades, cluster analysis is being frequently used to perform climate classification for various purposes (Praene et al. 2019),(Sathiaraia, Huang, and Chen 2019),(Zscheischler, Mahecha, and Harmeling 2012),(Saxena et al. 2017). Each of these studies used a combination of varying climate variables and clustering techniques.

The climate clustering for building energy performance in recent years are combined with building simulation output data to verify and prove the significance of dedicated climate clustering for buildings. For fewer cluster groups in a smaller area country, mean percentage mean misclassified areas was used in a study to identify the overlap of discomfort hours (Walsh, Cóstola, and Labaki 2018). Another study used building heating and cooling load to validate a hierarchical clustering (Xiong et al. 2019). Study to evaluate comfort performances used comfort indoor degree hours (Pellegrino, Simonetti, and Chiesa 2016). The same is as parameters for clustering the climatic zones using unsupervised fuzzy c-means clustering.
Method

Typical meteorological year (TMY) data is extracted across India at a 50km x 50km grid resolution using Meteonorm software tool. This amounts to 1157 locations across India. The synthetic data is validated for 60 locations at which the ground station based TMY data is available.

The overall process of the study is shown in Figure 1. Building energy simulation is performed for a case naturally ventilated residential building, which is part of the government’s mass housing program. A total of 1157 simulations are performed in EnergyPlus. The simulation uses thermo-physical properties based on the base values recommended by National Building Code of India. The buildings’ windows are operated based on temperature control for natural ventilation referred from the national building code. The initial building settings are shown in Table 1, and the building’s plan shown in Figure 2.

The Cooling indoor degree hours (CIDH) is the difference of zone air temperature from the base neutral temperature calculated using a running mean zone temperature (EN15251) for the whole year in all locations. A Python-based custom data extraction code is used to get the expected output of cooling indoor degree hours and heating indoor degree hours (HIDH). A consistency check using IMAC (Manu et al. 2016) indicated a similarity in the trend of discomfort hours variation though with a difference in magnitude. For comparability we adopt the EN15251 model in this study.

\[
UL = (0.33 \times Trm) + 18.8 + 3
\]
\[
LL = (0.33 \times Trm) + 18.8 - 3
\]
\[
Tn = (UL + LL)/2
\]

Where U.L. is the upper limit, L.L. is the lower limit, \(Trm\) is running meant temperature, \(Tn\) is neutral base temperature.

Table 1: Description of building parameter considered for the thermal simulation

<table>
<thead>
<tr>
<th>Building details</th>
<th>Case 1a</th>
</tr>
</thead>
<tbody>
<tr>
<td>U–Value (W/m²K)</td>
<td>2.3</td>
</tr>
<tr>
<td>Wall composition (mm)</td>
<td>12.5mm plaster+ 200mm brickwork+ 12.5mm plaster</td>
</tr>
<tr>
<td>WWR (%)</td>
<td>20%</td>
</tr>
<tr>
<td>Kappa (kJ/m²K))</td>
<td>156</td>
</tr>
<tr>
<td>Shade length</td>
<td>500mm</td>
</tr>
<tr>
<td>Natural Ventilation conditions</td>
<td></td>
</tr>
<tr>
<td>Ventilation- Indoor set point</td>
<td>24°C</td>
</tr>
<tr>
<td>Ventilation-Minimum Outdoor Temperature</td>
<td>18°C</td>
</tr>
<tr>
<td>Ventilation-Maximum Outdoor Temperature</td>
<td>32°C</td>
</tr>
<tr>
<td>Delta T</td>
<td>0°C</td>
</tr>
</tbody>
</table>

Figure 1: Method for building simulation-based climate classification

Figure 2: Case building for building simulation
Fuzzy c-mean clustering

Clustering is an approach in which unsupervised objects can be grouped based on similarity. Fuzzy c-mean clustering (Dunn 1974) allows an object to belong to each cluster based on associated membership value. The monthly degree discomfort hours values (24 variables) are used to perform clustering using fuzzy c-means clustering to minimise the objective function.

\[ J = \sum_{i=1}^{n} \sum_{j=1}^{c} u_{ij}^m ||x_i - v_j||^2 \]  \hspace{1cm} (4)

Where \( J \) represent the objective function, \( u_{ij} \) is membership to which an \( i \)th object belongs to \( j \)th cluster, \( v_j \) is the centre of the cluster \( j \), \( n \) is total number of objects present in dataset and \( m \) is the fuzzifier. Fuzzifier control the membership value. Fuzzifier varies from 1 to \( \infty \). The value 1 represent the hard clustering in which object is associated with binary membership value either by 0 or 1 and \( \infty \) represent the fuzziest clustering at which object is associated with each cluster with equal membership value of \( 1/c \), where \( c \) is the total number of cluster. Studies like (Pal and Bezdek 1995), suggest range of fuzzifier is \([1.5, 2.5]\) and mid value \( m=2.0 \) can be preferred for the analysis.

\[ C_j = \sum_{x \in j} u_{ij}^m x / \sum_{x \in j} u_{ij}^m \]  \hspace{1cm} (5)

The algorithm is initialized by random or preassigned membership matrix \( U \) \( [u_{ij}] \) and with their help, cluster prototype centroid is calculated using the following equation (5).

Further, the calculated prototype centroid value is used to estimate prototype membership matrix \( U \) from the following equation (6).

\[ u_{ij} = 1/\sum_{k=1}^{c} ||x_i - v_j||^2 / ||x_i - v_k||^2 (m-1) \]  \hspace{1cm} (6)

The algorithm is get terminated when the difference between two consecutive objective value become less then predefined convergence value.

The algorithm grouped the all object into \( c \) cluster. Since there is no prior knowledge of number of clusters. Hence algorithm is run for all plausible value of number of cluster \( c \) \( [c_{\text{min}}, c_{\text{max}}] \). Where \( c_{\text{min}} \) is minimum number of cluster and \( c_{\text{max}} \) is maximum number of clusters. Where \( n \) is number of objects in dataset.

Since, FCM algorithm will give unique fuzzy partitioned clustering for each value of \( c \). Hence a cluster validity index is required which evaluate performance of clustering for all plausible value of \( c \). Cluster validity index \( (V) \) evaluate cluster performance by measuring within cluster compaction and separation from neighbour cluster. Xie and Beni (Xie and Beni 1991) \( (V_{XB}) \) is a commonly used cluster validity index. The index measure cluster compaction and separation by considering itself data type characteristics and also membership matrix calculated from the FCM algorithm. Xie and Beni cluster validity Index is mathematically represented by following equations (7) and (8).

\[ V_{XB} = \text{Compaction/Seperation} \]  \hspace{1cm} (7)

\[ V_{XB} = \sum_{i=1}^{n} \sum_{j=1}^{c} u_{ij}^m ||x_i - v_j||^2 / n \cdot \min_{j k} ||v_j - v_k||^2 \]  \hspace{1cm} (8)

The value of \( V_{XB} \) is calculated for all value of \( c \), lowest value of \( V_{XB} \) refer to best performance clustering which give optimised solution of high compaction and high separation value simultaneously.

Results and discussion

The CIDH and HIDH for each month in a typical year in all 1157 locations is found. The locations falling to respective clusters are assigned from the final cluster map. The national building code(NBC) has 5 zone classification based on a limited number of station data. But more distinctive portions of the country fall into one particular zone, which generalises building guidelines and energy conservation codes. There is a need to diversify the climate zoning. So, the number of clusters are set to a range from 2 to 16.

FCM algorithm is executed for all plausible value of \( c_{\text{min}}, c_{\text{max}} \) at fuzzier \( m=2.0 \) (Pal and Bezdek 1995). The algorithm is initiated from \( c_{\text{min}}=2 \), considering at least 2 clusters must be present in the dataset. The selection of \( c_{\text{max}} \) is subjective, for this study \( c_{\text{max}}=16 \) is regarded by the hypothesis that as the number of cluster increase clustering lead to over classification. FCM results in a set of membership matrix \( U[ulij]ncx \) and a set of cluster centroid \( V[v_{ij}]xc \). Further membership matrix and cluster centroid are utilised to estimate Xie Beni \( V_{XB} \) validity index for all value of \( c \). The results of \( V_{XB} \) are plotted in figure 3. Figure 3 shows the optimised weight of compaction and separation found at the location corresponding to 9 clusters. Hence, the cluster validity index suggests that cluster 9 is the best solution to depict the Indian subcontinent region's building performance-based climate zoning. The 9-class classification shown in figure 4 is distinctly different from climate zoning adapted in National Building Code of India. The zones are also statistically analysed to evaluate the distribution of degree discomfort hours and climate variables such as air temperature, relative humidity and solar radiation.
The warm humid region of the national building code are subclassified into 4 clusters—6,5,3,1 in the proposed classification. The details of 9 class cluster maps are discussed in detail.

The cold region is subdivided into 2 clusters 1,4 in the proposed classification. Cluster 1 is spread in eastern parts and the lower extents of northern region where settlements are found commonly. Some points in southern India (western ghats) and central India are categorised as cluster 1 which constitute hilly regions. The Cooling degree discomfort hours (CIDH) in this cluster is 360 in summer and heating degree discomfort hours(HIDH) is 4090 in winter, as seen from figures 6 and 7. The average air temperature(AT) ranges between -5.5 and 30°C. The average relative humidity(R.H.) is between 35% and 90%. Average hourly solar radiation(S.R.) is between 228 and 370W/m².

Cluster 4 is extremely cold and mostly consist of mountain ranges with higher altitudes where settlements are sparse. The CIDH is zero throughout the year and HIDH is above 5600 every month.

Hot and dry regions is represented by 4 clusters—9,3,7,8 in the proposed classification.—cluster 9 consist of desert areas with extremely hot days and cold nights with low relative humidity. The average CIDH is around 3380 in summer and HIDH is 2460 in winter. Cluster 3 is in parts of west and central east regions (Gujarat, Andhra Pradesh, Odisha). The CIDH is 2440 in summer, and HIDH is 1650 in winter. The average air temperature ranges between 17°C and 34°C combined with average relative humidity between 40% and 80% across all months, with average above 350W/m². The solar radiation is high throughout the year.

Cluster 7 is majorly present in central India with an average air temperature between 13°C and 34.5°C. The CIDH is around 2440 in summer (May), and HIDH is 2150 in winter (Jan). The relative humidity is above 80% in monsoon(Jul, Aug, Sep) and below 40% in summer(Mar, Apr, May). The average hourly solar radiation in cluster 7 is between 330 and 430W/m². Cluster 8 is below central regions with CIDH of 2860 in summer and HIDH of 1490 in winter. The temperature is between 20°C and 35°C showing hot summers and cool winters. The R.H. is between 33% and 85%, Solar Radiation between 350 and 410W/m². The composite climate region of national building code is classified into three clusters [2, 7, 8]. Cluster 2 has dry, hot summer and cold winters with CIDH of 2580 in summer and HIDH of 3000 in winters. The average temperature ranges between 10°C and 35°C, whereas R.H. ranges between 25% and 87%.
Cluster 5 consists of central southern swathes of India away from coastal regions. The CIDH is 930 in summer, and HIDH is 1310 in winters. The climate is sunny and warm in summers and cool in winters. The average temperature is between 20°C and 30°C. The average R.H. is between 36% and 88% in winters and high humidity in summer and monsoon period. The average solar radiation is between 340 and 420W/m². Cluster 6 is located along the coastal regions of south-eastern and south-western India. The CIDH 2000 in summer and HIDH is below 1100 in winters. The summers are Hot humid, and winters are comfortably cool. The average temperature is between 20°C and 34°C. The humidity is high throughout the year with average R.H. above 60% for all the months.

Figure 6 and 7 present the CIDH and HIDH values for all 12 months in each cluster in the form of interval plot of mean values. Figure 8 present mean AT, R.H. and S.R. for 12 months in each cluster. The interval lines represent the standard deviation from the means and the bubbles represent the mean. Cluster 4, 1, 9 are significantly different from each other. The high HIDH values of cluster 4 increased the plot’s overall scale, but the remaining clusters variation is distinctly seen when the maximum limit is rescaled. Cluster 2 and 9 are similar in terms of HIDH, but they exhibit difference in CIDH and Relative humidity across months. When compared, the HIDH of cluster 5 is higher than cluster 6 during the second half of the year and the CIDH of cluster 6 is more than cluster 5. Cluster 7 has a slightly higher HIDH than cluster 8 but a lower CIDH range. Clusters 2 and 3 exhibit difference in terms of HIDH.

Design response can be further developed for each of the climate zones. For example zone 6 remains warm and humid throughout the year. Improved natural ventilation will improve thermal comfortable and energy efficiency in this zone. A summary of average weather parameters is shown in table 2.

![Figure 4: Interval plot of HIDH for 12 months in each cluster](image)

![Figure 7: Interval plot of CIDH for 12 months in each cluster](image)

![Figure 8: a) Interval plot of mean AT, b) Interval plot of mean R.H. and c) Interval plot of mean hourly S.R. for 12 months in each cluster](image)

**Table 2: Mean AT, R.H. and S.R. ranges within the clusters.**

<table>
<thead>
<tr>
<th>Class</th>
<th>Mean outdoor Air temperature</th>
<th>Mean R.H.</th>
<th>Mean solar radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
</tr>
</tbody>
</table>

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Conclusion
The study presented a climatic classification of India based on building performance simulations. Cooling and heating indoor degree hours calculated from building thermal simulation are used as input variables. Simulations were performed for 1157 locations spaced at 50x50km grid. Fuzzy c-means clustering technique used for classification. A 9-class climate classification is obtained using this method. The number of clusters is based on Xie Beni cluster validity which ensures there is a clear, distinct segregation of climatic zones. The proposed climate classification exhibited significant difference from the 5-zone classification adapted by India's national building code. A mapping of the new climate zones with that of the national building code climate zones was presented.

Limitations: The study used synthetic weather data since there are a limited number of weather station points available in the country. The paper used CIDH, HIDH to cluster the zones. Other parameters like RH, Cooling/Heating loads, will be incorporated in future studies.

Further research can be done on climate classification using future weather data. The classification can be further analyzed to set guidelines for building design and energy codes specific to the climate zones.

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References


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