A building bio-climatic design tool incorporating passive strategies in residential dwellings design of composite climate of India

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Abstract: The objective of the present work is to assess the potential of different passive design strategies using the bio-climatic approach in residential spaces across the composite climate in India. For this purpose, a modified building bio-climatic design chart based on composite climate specific adaptive thermal comfort zone (CZ) has been used. The climates of four major cities namely Delhi, Jaipur, Lucknow, and Hyderabad, have been selected for bio-climatic analysis using typical meteorological year (TMY) data. The results from the bio-climatic analysis showed that comfort can vary 30% to 60% of the total time during summer and 43% to 70% of the total time during the winter season, respectively. During warmer half of the year (March–October) natural ventilation, sun shading, and direct evaporative cooling proved to be the better choice for passive cooling. However, passive solar heating only provides the noticeable result for improving indoor comfort conditions during the colder half of the year (November–February) for all selected cities. Finally, this study put forward a guideline matrix for the use of passive design schemes in buildings for composite climate of India.

Keywords: bio-climatic design chart; adaptive comfort zone; passive design; composite climate; India.

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1 Introduction

In emerging economies such as India, buildings are of significant importance for increasing sustainability through energy efficiency in the built environment. Buildings are responsible for around 35% of India's total energy consumption, and this is increasing by 8% annually (Bureau of Energy Efficiency, 2016). It is projected that urban India will contribute about 75% of national GDP in the next 15 to 20 years while another 300 million people get added to the existing 300 million dwelling in Indian urban centres (Planning Commission of India, 2014–15). In order to manage this high level of urbanisation, Government of India has thus decided to develop 100 smart cities in India (Bhattacharya and Rathi, 2015). In this unique circumstance, one of the essential objectives of a sustainable built environment is to design buildings which are local climate responsive. A climate responsive buildings design gives the designer, architects and building engineers a prospect to investigate the scope of passive design strategies contextual to the building location and design (Olgyay, 1963; Givoni, 1969; Szokolay, 1982).

To know the potential of particular passive design strategies it is sophisticated, time-consuming and economic intensive to estimate using other methodologies such a simulation or experimental investigation. Therefore, a simple tool for climate analysis used in the preliminary design phase of building construction is essential. In this regard, the building bio-climatic design charts are simple and reliable tools which analyse the climate for passive design and suggesting a reasonable estimate of its potentials from the viewpoint of human thermal comfort (Milne and Givoni, 1979; Pajek and Kosir, 2017; Lomas et al., 2004). The other important advantage of this tool is that it gives a visual representation of entire passive design strategies and their potentials in a particular region or particular climatic zone. This visual representation is easily understood by architects and building engineers thus enhancing the possibility of adoption of the passive design strategies in new construction projects. However, the reliability of results predicted depends on the accuracy of the thermal comfort boundaries and boundaries of passive design strategies defined on a psychometric chart for a climatic region (Visitask, 2007).

1.1 Overview of passive design and bio-climatic studies done in India

Over the past few decades, there have been several attempts to develop a systematic bio-climatic approach to be adapted for human requirements. Olgyay (1963) developed first bio-climatic building design chart for hot humid locations. The chart was suggested for lightweight buildings with no internal gains. Later, Milne and Givoni (1979) developed building bio-climatic charts based on indoor environments rather than outdoor conditions through some experimental studies on high mass residential and climatic chambers. The emphasis was on the influences of climatic characteristics on human comfort as well as the thermal response of buildings. Szokolay (1982) used psychrometric charts to develop the control potential zones (CPZ) for evaluating the potential of passive cooling design strategies in hot and humid climates. It was emphasised that a comprehensive bio-climatic analysis of the location is necessary for developing passive building design strategies. The findings were later also listed in the design strategies using Mahoney tables (Koenigsberger et al., 1975) and emphasised to be employed at the pre-design stage of buildings, especially in hot and humid conditions.

Lam et al. (2006) carried out a bio-climatic analysis using building bio-climatic design chart approach for different climates in China. A total of 18 cities representing the five major climatic types were selected for climatic analysis. The passive design potential for these 18 cities ranged from 7% to 50% of the colder half of the year depending on the climate severity. Santamouris et al. (2007) describe a process for designing and applying several techniques based on bioclimatic architecture criteria and based on passive cooling and energy conservation principles to increase the thermal comfort conditions in an outdoor space located in the Great Athens area. Hassaan (2011) used a building bioclimatic design approach for Egypt. The bio-climatic analysis for each climatic zone of Egypt has been attempted to determine the potential of passive design strategies for maintaining thermal comfort in outdoor spaces. Nguyen and Reiter (2014) developed a new climate analysis tool using the conventional psychrometric chart and examine the potential of improving thermal comfort under the climates of Vietnam for four case cities using climate responsive passive strategies.

Comparing India with the world scenario, investigation related to the bio-climatic analysis of different built environment for indoor comfort has advanced rapidly in past decade. Bansal and Milne (1995) under 'Passive Space Conditioning' project, a survey of vernacular architecture was undertaken for 32 represented locations in India. The most significant passive design elements used in the construction of the houses were identified and listed. Tiwari et al. (1994) carried out a comparison of passive cooling techniques of an unconditioned apartment for Delhi climate. The results revealed that the evaporative cooling was the best option to reduce the incoming heat flux through the roof and the air cavity also reduced the incoming flux entering through walls.

Singh et al. (2007) presented reclassification of climatic zones for North-East part of India based on average ambient data collected from regional meteorological centres in North East India. Further to the analysis, the authors developed bio-climatic design charts to evaluate the potential of passive design schemes during summer and winter season of modified climatic zones. Chandel and Aggarwal (2008) conducted a thermal comfort field study for passive solar building in the cold climate of India. The impact of passive solar features on heating, cooling, and energy savings was evaluated using e-Quest simulation software. The space heating, cooling and mechanical ventilation loads and total annual energy consumption were found to be reduced due to passive solar design features in the building. Dili et al. (2001) reported the effectiveness of passive control methods in vernacular architecture widespread in the southern part of India for indoor comfort in summer, rainy and winter months. Sharma et al. (2002) discussed the alarming cost of energy use in buildings and various energy conservation passive design techniques in Indian buildings.

Comprehensive research on the development of a building bio-climatic design chart modified over Givoni's bio-climatic chart for one passive solar design namely high thermal mass has been undertaken for the composite climatic zone of India (Kumar et al., 2017, 2018). One of the commonly used passive solar design strategy for this climatic zone of India is the use of thermal mass in building envelope. The authors based on thermal performance of high mass residential buildings proposed a new bio-climatic boundary of high thermal mass modified over Givoni's bio-climatic design chart using extended comfort boundaries for composite climate of India.

In a recent study by Khambadkone and Jain (2017), a new bio-climatic design tool is developed for composite climatic conditions, adopting the methodology presented by Nguyen and Reiter (2014). A modified thermal comfort zone based on tropical summer index (TSI) (Sharafat and Sharma, 1986) is proposed specifically for the composite climate. The comfort zone of the chart was further extended to evaluate the potential of passive heating and cooling design boundaries for office buildings situated in a composite climate of India. However, this research has some significant limitations which can't be ignored otherwise.

- Firstly, the proposed comfort zone was based on the results of thermal comfort study conducted by Sharafat and Sharma (1986) in late 1980 for naturally ventilated office buildings in Roorkee, falls under composite climate in India. In addition, TSI did not include the behavioural and acclimatisation adaptations of occupants during the field study. The thermal adaptations and social-cultural set up of occupants changed rapidly in last past decade due to an economic revolution in India (Indraganti, 2010).
- Secondly, the upper limit of relative humidity for summer comfort zone was 90% which is questionable. Thermal comfort studies conducted by different researchers (Indraganti, 2010; Kumar et al., 2016a, 2016b; Indraganti et al., 2014) for composite climate of India have shown that the occupants perceived relative humidity up to 80% as comfortable especially during rainy months in the summer season of composite climate.
- In addition, the acceptable limits defined for a thermal comfort zone for the winter season is merely based on assumption not including the behavioural adaptations, i.e., clothing adaptations, use of controls, etc.
- The modified building bio-climatic design chart was defined for office buildings in a composite climate of India. However, it is well-known fact that adaptation behaviours like opening/closing of windows, on /off fans and heating or cooling equipment's vary substantially between residential and office environments (Lomas et al., 2004; Kumar et al., 2018).

1.2 Objectives of the study

Bio-climatic design charts are also widely used in India for potential passive solutions to a particular climate. From time to time researchers have identified the need for developing these charts considering Indian building typologies, climates and comfort preferences of Indian subjects (Singh et al., 2007; Kumar et al., 2017; Khambadkone and Jain, 2017).The current bioclimatic classification and sparsely conducted bioclimatic studies of India do not adequately address the climatic diversity of the country (Kumar et al., 2017). Furthermore, in case of India, it is found that only three studies are done so far for bio-climatic analysis of different climatic zones in India. Nevertheless, the existing bio-climatic analysis approaches, i.e., Givoni-Milne bio-climatic charts (Milne and Givoni, 1979) for evaluating the indoor comfort conditions with regards to outdoor environments, is not universal in its approach and depends upon local climatic conditions. Since, India is geographical and climatological diverse, hence these bio-climatic analysis methods or tools may possibly not truly reflect the actual comfort potential of different passive design schemes for a particular climate. Moreover, the composite climate of India is still a challenge for architects and building designers due to its vast geographical, climatological and social-cultural variations leading to differences in thermal expectations and preferences of its native for indoor comfort.

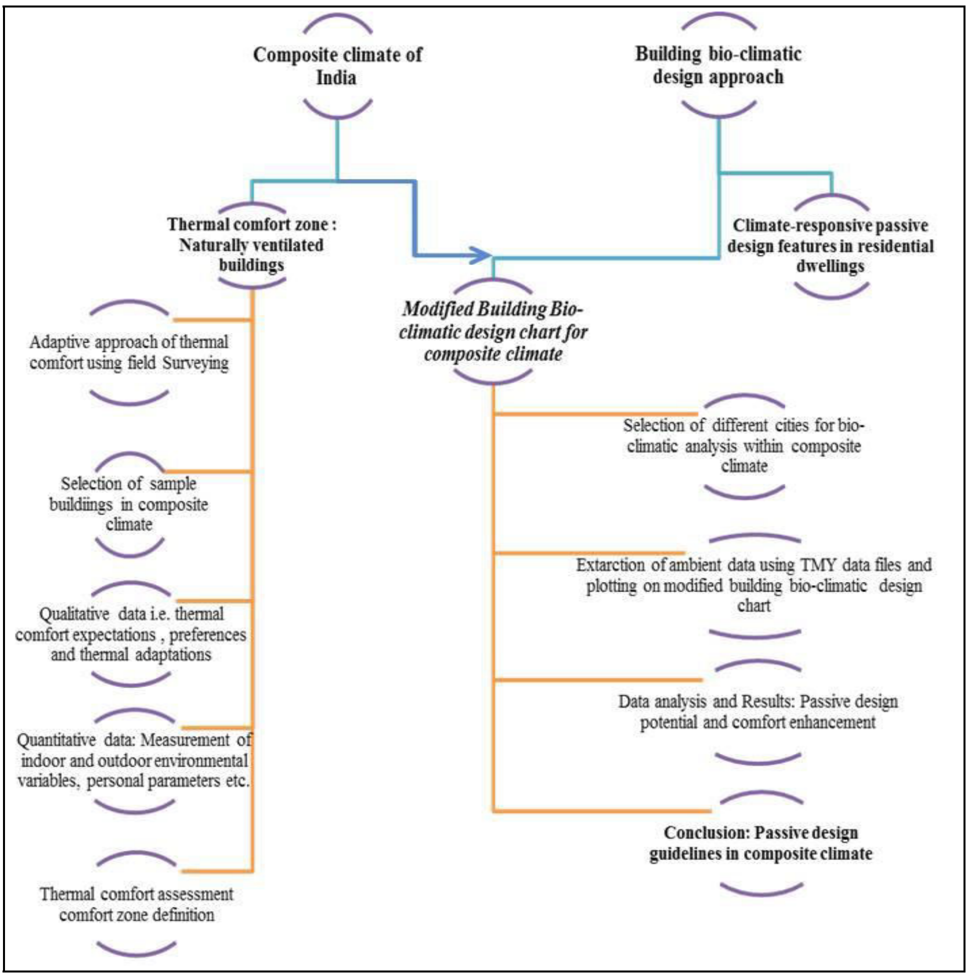
These research gaps stimulated us to perform a study for development of a customised building bio-climatic design chart for assessing the indoor comfort potential of selective passive design strategies in a composite climate of India. So, the present study has been conducted considering the aforementioned issues with following objectives:

1 Development of a simple and modified building bio-climatic design chart most suitable for composite climate of India.

2 To evaluate the potential of various passive heating and cooling strategies from the viewpoint of human thermal comfort.

To fulfill the objectives of the present study, the methodology flow chart is shown in Figure 1.

Figure 1 Methodology flowchart for the present study (see online version for colours)



2 Methods and materials

2.1 Climatic classification and selection of climatic zone for the study

India is a tropical country, lies to the north of the equator between 6°44’ and 35°30’ north latitude and 68°7’ and 97°25’ east longitude. India comprises the Himalayas in the north and north-eastern region, separating the country from the Tibetan plateau in the south. With a diverse geography and climatic conditions spread over the entire country, National Building Code of India (NBC) (BIS, 2017), India has been divided India into five climatic zones (Figure 2), namely:

1 hot-dry

2 warm-humid

3 composite

4 temperate

5 cold.

Figure 2 Climatic classifications for India (National Building Code, India) (see online version for colours)

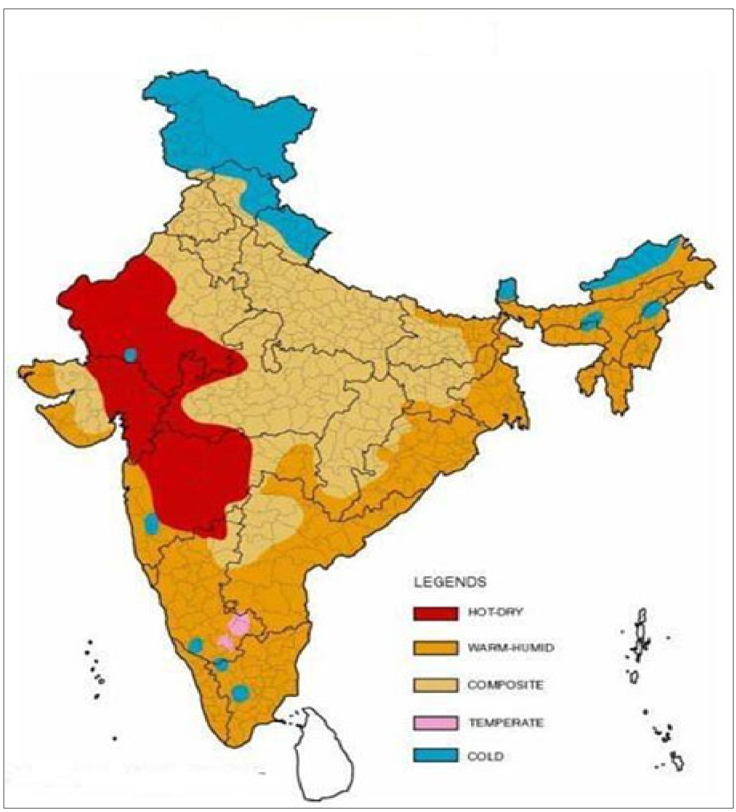


Table 1 Classifications and characteristics of different climates zones in India

Bio-climatic zones	*Summer max*	*Summer min*	*Winter max*	*Winter min*	*Relative humidity*	*Rainfall (mm)/year*	*Sky conditions*	*Major states*
Hot and dry	40–45°C	20–30°C	5–25°C	0–10°C	25–40%	<500	Cloudless, high solar radiation	Rajasthan, Western Madhya Pradesh, Central Maharashtra
Warm and humid	30–35°C	25–30°C	25–30°C	20–25°C	70–90%	>1,200	Overcast ~40–80% causing unpleasant glare	Kerala, Tamilnadu, Coastal parts of Orrisa and Andhra Pradesh
Temperate	30–34°C	27–30°C	27–33°C	16–18°C	60–80%	>1,000	Mainly clear, cloudy particularly in summer season	Banglore, Goa and parts of Deccan
Cold	20–30°C	4–11°C	(−7)–8°C	(−14)–0°C	50–80%	<200	Clear, cloud cover < 50%	Jammu & Kashmir, Ladakh, Himachal Pradesh, Uttaranchal, Sikkim
Composite	32–43°C	27–32°C	10–25°C	4–10°C	Dry periods = 20–50% Wet period= 50–90%	Variable, 500–1,300 mm	Variable overcast and dull in the monsoon	Uttar Pradesh, Haryana, Punjab, etc.

The criteria for the classification of climatic zones are presented in Table 1. A place is assigned to one of the first five climatic zones only when the defined conditions prevail there for more than six months. In cases where none of the defined categories can be identified for six months or longer, the climatic zone is called composite climate. However, recently, Bhatnagar et al. (2018a) carried out an analysis for reclassification of Indian climatic zones revisiting the different built environment of Indian offices and based on different methods adopted worldwide for climate classification like ASHRAE, etc.

The composite climate of India covers more than 30% geographical area and known for its variable landscape and seasonal climatic diversity. A very high-intensity solar radiation with diffuse radiation in summer season increases the ambient temperature up to 32–43°C in the daytime and while during night-time ranges between 27–32°C. During the months of April and May relative humidity falls below 20% because warm winds blow during that period. During rainy period i.e. from July to September, the ambient relative humidity is relatively high even more than 90%. In the winter season, the conditions are severe cold and ambient diurnal swing observed between 10–25°C during the day and 4–10°C at night, respectively. Subsequently, during the winter season, the ambient conditions are mostly dry for composite climate of India.

2.2 Seasonal diversity in a composite climate of India

The calculation method used to segregate the months into the season for selected cities in a composite climate of India has been referred from the studies like Dhaka and Mathur (2017) and Kumar et al. (2016a, 2016b, 2018). According to the calculation procedure, a particular month meets the conditions of summer month when the temperature was found to vary between 27–43°C for equal/more than 20 days in a particular month. Following this criteria month from April to September are considered summer months. Whereas, a month has been found to show hourly variations in temperature within 4–25°C (≥20 days in a month), therefore, the months from Nov–Feb have been considered in the winter season. The months such as March and October did not fall under either summer or winter season, and thus has been considered as the moderate season.

2.3 Selection of cities for bio-climatic analysis

Considering the vast diverse geographical, climatic and seasonal differences within composite climate, the present study selected four distinct locations namely Delhi (28.36°N, 77.13 °E and 318m mean sea level), Jaipur (26.82°N, 75.80°E and 390 m mean sea level), Lucknow (26.8°N 80.9°E, 120 m from mean sea level), and Hyderabad (17.3°N, 78.3°E and 540 m above the mean sea level), situated in the composite zone for detailed bio-climatic analysis (Figure 3). Though the selected cities represent typical composite climatic conditions however each city represents typical geographical, climatic and social variety. Delhi, Jaipur, and Lucknow lie in the northern part of India, near tropical cancer (23.5°N), causing severe cold winter and very hot summer conditions. Hyderabad city is situated near Deccan plateau and south of India. For Hyderabad City, the climate is basically hot and humid. However, as per climatic zone selection criteria for India, this city falls under a composite climate of India. Lowest temperatures, especially during winter months, are often found well above 11°C and hence no typical cold winter months for this city. Contrary, during the summer, the highest temperature may sometimes exceed 40°C. Detailed descriptions of seasonal variations in ambient conditions, i.e., temperature, relative humidity and global radiations for selected locations are tabulated in Table 2. Differences in geographical characteristics and attitudes of the four sites cause some climatic differences (Figure 4).

Table 2 Descriptive statistics of ambient temperature, relative humidity, and of global radiation for different cities in composite climate of India

Cities	*Parameters (in range)*	*Delhi*	*Jaipur*	*Lucknow*	*Hyderabad*
Summer (April–September)	Maximum temp. (°C)	36–45	37–43	36–44	32–41
	Minimum temp. (°C)	17–25	18–23	16–25	20–23
	Max. relative humidity (%)	97–99	82–100	80–98%	86–98%
	Min. relative humidity (%)	9–40	3–47	11–56%	14–50%
	Max. global radiation (W/m^2)	1,168	1,100	1,256	1,252
Moderate (March and October)	Maximum temp. (°C)	32–34	35–37	31–34	32–39
	Minimum temp. (°C)	9–15	13–17	10–16	17–20
	Max. relative humidity (%)	95–97	65–90	75–99	91–97
	Min. relative humidity (%)	12–23	10–20	18–28	12–29
	Max. global radiation (W/m^2)	990	990	1,020	1,090
Winter (November–February)	Maximum temp. (°C)	25–35	25–34	25–30	28–35
	Minimum temp. (°C)	5–9	5–14	6–10	11.7–15.4
	Max. relative humidity (%)	87–99	75–98	82–99	95–97
	Min. relative humidity (%)	10–30	10–20	18–34	8–24
	Max. global radiation (W/m^2)	900	874	1,000	1,050

Figure 3 Selected case cities for bio-climatic analysis in composite climate of India (see online version for colours)

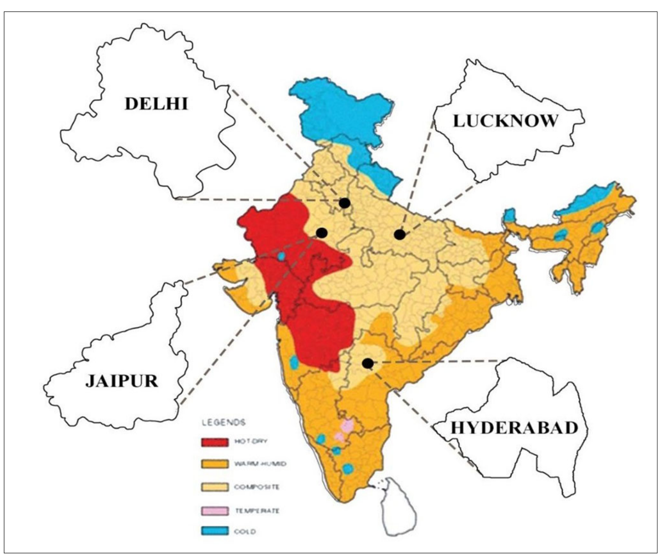
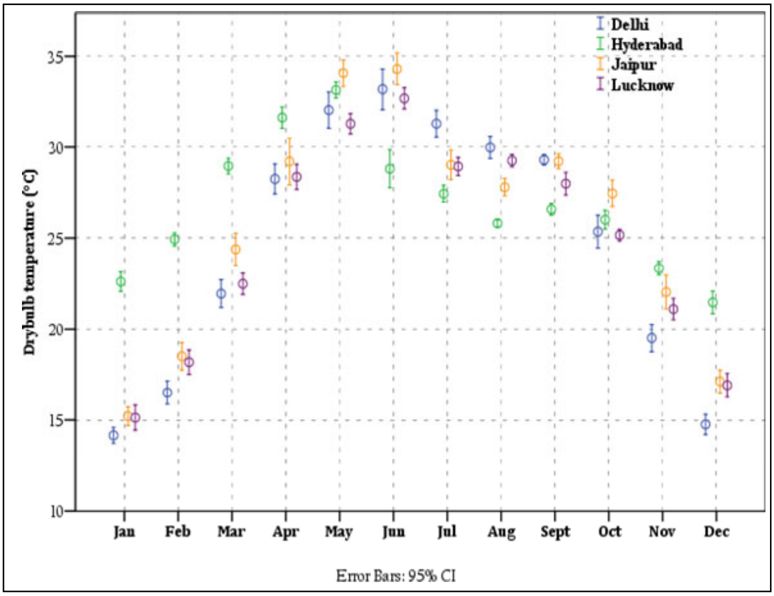
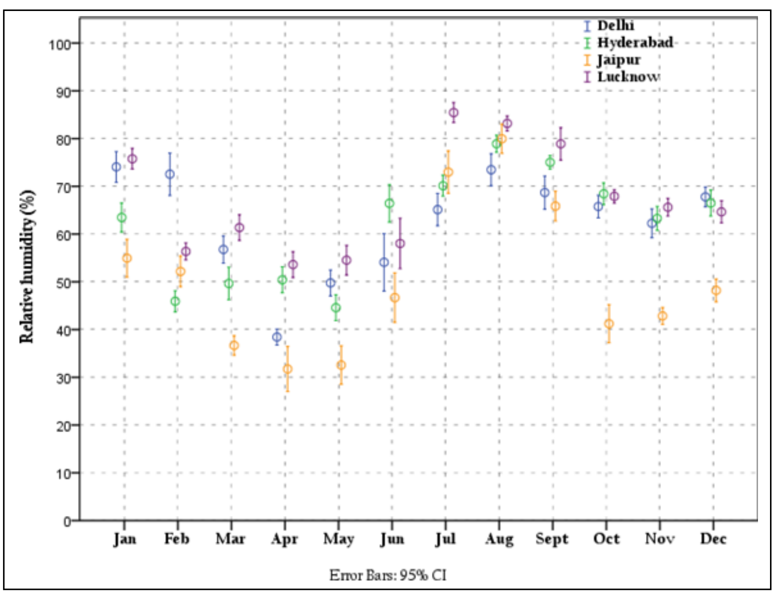


Figure 4 Statistical data of (a) ambient air temperature and (b) relative humidity in a year for selected case cities (see online version for colours)



(a)



(b)

3 Defining thermal comfort boundaries for composite climate in India

ASHRAE Standard 55-2017 (2017) defines an acceptable thermal comfort zone on a psychrometric chart, specifying boundaries of operative temperature and humidity for occupants with sedentary activity level (1−1.3 met) and defined clothing (0.5−1 clo). The existing bio-climatic analysis charts and tools like Givoni-Milne bio-climatic chart, Ecotect, Climate consultant etc. use this ASHRAE Standard 55 comfort zone for defining passive design architecture for a particular climate. However, researchers around the world have raised the questions of its uniformity for different climatic conditions and building types ignoring occupant's region specific psychological, physiological, and behavioural adaptations.

Researchers in past decade have shown that thermal comfort is contextual to various thermal adaptations and other factors (Brager and de Dear, 1998; Yao et al., 2009) for different climates and different buildings. Following this hypothesis and adaptive comfort approach of thermal comfort, new boundaries were defined on the conventional psychrometric chart for composite climate of India (Kumar et al., 2016a, 2016b). ASHRAE Standard 55-2017 comfort boundaries were extended considering this climate's specific thermal adaptations and occupant's thermal expectations in naturally ventilated spaces. The adaptive comfort zone, i.e., CZ's were drawn on psychrometric chart for different seasons considering comfort expectations and the role of airspeed to offset higher temperatures. The CZ's were based on the results of a thermal comfort field study conducted for more than four years collecting more than 3,200 transverse type surveys in 32 naturally ventilated buildings. Comfort (±1 votes) votes were plotted on the traditional ASHRAE Standard 55-2013 psychrometric comfort zone including the effects of clothing, activity and air speed for different seasons. Subsequently, boundaries have been extended reflecting the results of this study, particularly for naturally ventilated buildings. The CZ boundaries proposed reflects that subjects are comfortable at the temperature up to 32°C and relative humidity of 20%–80% in still air conditions of 0–0.2 m/s. The CZ is further extended up to 34.5°C between the relative humidity of 20–80% at the higher indoor air speed of 1 m/s, particularly during the summer season. During the winter season the lower limit for this CZ was observed to be 18°C for 80% acceptability of the occupants.

3.1 Defining passive design zones for modified building bio-climatic design chart

Milne and Givoni (1979) based on their experimental investigation for high mass buildings (mostly unoccupied), recommended five passive design strategies, i.e., passive solar heating (direct gain), natural ventilation, shading, thermal mass, thermal mass with night ventilation and evaporative cooling mainly for maintaining indoor comfort in tropical and subtropical climates. So, for the present study we have chosen six passive heating and cooling design strategies based on previous works and delineated their application zones to CZ to define the modified bio-climatic chart particularly for composite climate of India. A brief description of how delineation of different zones of passive strategies over thermal comfort zone for development of modified bio-climatic design chart is presented in subsequent section.

3.1.1 Passive solar gain

The basic principle of passive solar heating involves allowing solar irradiation into building through openings (south-facing glazing façade) or walls then using this solar energy to heat up the indoor environment (Givoni, 1969). The lowest ambient temperature to at which heat delivered by passive solar system can maintain indoor comfort conditions are calculated as per the energy balance and steady-state heat transfer model provided in ASHRAE Handbook of Refrigeration (ASHRAE, 2010). Nguyen and Reiter (2014) have discussed these empirical relations briefly to calculate the lowest ambient temperature for effective use of passive heating system that can provide indoor comfort conditions during winters. The zone is defined assuming an average solar radiation during peak winter days for entire composite climatic zone. The zone of the 'passive solar gain' (PSG) bounds all the conditions of relative humidity ranging between 20–80% and the ambient dry-bulb temperature ranging between 15–18°C.

3.1.2 Conventional heating

Passive solar designs under extreme winter conditions (during months of December and January under composite climate of India) might not be sufficient to provide indoor thermal comfort conditions (Bansal et al., 1994). In such cases, it becomes necessary to use some conventional heating system by means of heat pumps or radiator heating systems for maintaining indoor comfort. In Figure 5, conventional heating zone is represented by CH in the modified bio-climatic design chart. This zone bounds all conditions of relative humidity and dry bulb temperatures which fall below lower limit of passive heating zone, i.e., 15°C dry bulb temperature.

3.1.3 Solar protection through shading

The maximum heat flow in a passive building space takes place through windows ~80% including transmitted as well as reflected radiations from opaque surfaces (Agugliaro et al., 2015). So, proper shading and glazing area can improve indoor thermal conditions inside the buildings during extreme climatic conditions i.e. summer and winters (Yao et al., 2018). Milne and Givoni (1979) have suggested that when outdoor dry bulb temperature exceeds the lower limits of the comfort zone, there is need of proper shading for openings or envelop for cooling purpose. Considering the same hypothesis, we defined a zone solar heating zone (SZ) for shading on modified bio-climatic chart. This zone extends for all conditions (relative humidity as well as dry bulb temperature) above the lower limit of winter CZ, i.e., 18°C.

3.1.4 Natural ventilation

Natural ventilation is particularly important in hot and humid climates because the increased air speed over the body enhances sweat evaporation and reduces discomfort (Nguyen and Reiter, 2014). Results from the various field studies in such climates found that subjects, expressing a desire for greater air movement and comfort zones increasing with the aid of air movement (Kumar et al., 2016a, 2016b; Indraganti et al., 2014). However, ASHRAE standard recommend a maximum wind speed of 0.82 m/s for sedentary activity with some provision of using elevated air speed for comfort. According to Givoni (1992), the upper limit of the ventilation effectiveness boundary is a wind speed of 1.5 m/sec that will not create annoyance conditions for building occupants. Nicol (1974) noted that air velocities up to 1.5 m/s were acceptable for subjects in hot and warm countries. Similarly, authors conducted a field study of thermal comfort in composite climate of India and concluded that occupants of naturally ventilated buildings were comfortable up to 35°C when indoor air speed was noticed 1 m/s (Kumar et al., 2016a, 2016b). So, the present study limits the air speed up to 1 m/s for comfort while no paper blowing, less energy consumption and reducing noise due to fan operation in naturally ventilated buildings of composite climate in India.

Subjects in naturally ventilated buildings are more receptive to various adaptive actions, viz. opening of window and doors, using fans to maintain comfort, and this phenomenon is more pronounced at the elevated temperatures and relative humidity in the summer season. Considering the potential of natural ventilation techniques in providing thermal comfort, the comfort zone has been extended for air speed up to 1 m/s. This limit is corresponds to the conditions of no annoyance by means of noise or paper blow through natural ventilation. The area of natural ventilation (NV) corresponds to temperatures between 20–34°C and relative humidity 20–90% on redefined building bio-climatic design chart.

3.1.5 High thermal mass with night ventilation

Givoni (1992) investigated the effect of thermal mass through experimental chamber studies and established that high mass buildings with nocturnal ventilation could be used as a passive design strategy in hot and dry climates to maintain indoor comfort conditions. The boundary on bio-climatic chart was based on the relationship between diurnal variation in temperature and average vapour pressure during summer season. Adopting a similar approach, authors (Kumar et al., 2017) carried out a long-term thermal monitoring study of high mass residential buildings for their thermal performance during summer season of composite climate in India.

Based on experimental field results, new bio-climatic boundary was proposed which extends up to a maximum ambient temperature of about 38.4°C at 2 g/kg specific humidity and follows a tilted line up to 35°C at 20 g/kg specific humidity. Furthermore, the high mass polygon can be extended to a limit of 45.5°C when the thermal mass is used in conjunction with nocturnal ventilation (Noct). The zone corresponding to high thermal mass (HTM) and nocturnal ventilation (Noct) on redefined bio-climatic design chart is shown in Figure 5.

3.1.6 Evaporative cooling

During summer season of composite climate, the climatic conditions are mostly hot and dry (Figure 2). On a particular day of summer season, ambient temperature can rise up to 45°C with low humidity level around 20%. At such severe conditions natural ventilation and other passive strategies are not recommended by bio-climatic architecture (Tiwari et al., 1994; Bansal et al., 1994). Rather an alternative passive technique called Evaporative cooling can be used effectively when conditions are very hot and dry. Evaporative cooling is an adiabatic saturation process that increases moisture level in the air to provide air at low temperature (Nguyen and Reiter, 2014).

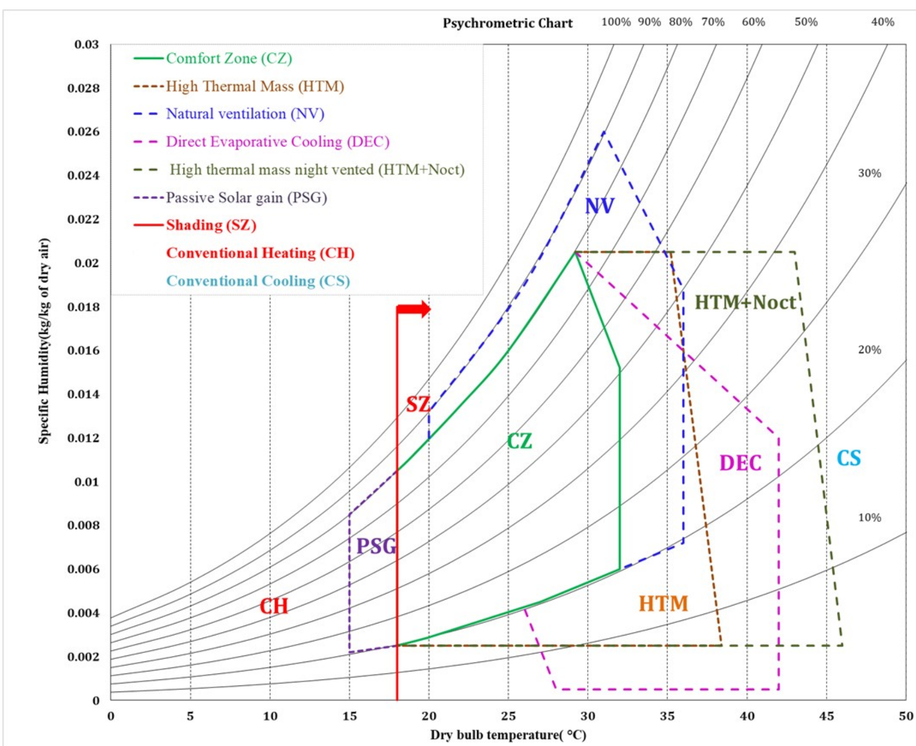
The cooling performance or leaving air temperature of the cooler may be empirically evaluated as:

$$T_l = T_b - \varepsilon\left(T_b - T_w\right) \quad (1)$$

where T_l – leaving air dry-bulb temperature; T_b – inlet dry-bulb temperature; T_w – inlet wet-bulb temperature; and ε – efficiency of the evaporative cooling system. Under typical operating conditions, an evaporative cooling system will nearly deliver the air cooler than 27°C.

Givoni (1969) based on experimental investigations for hot and arid climates concluded that ambient air can be cooled by 70–80% of wet bulb depression. He further suggested that it is impractical to lower dry-bulb temperature more than 11°C by direct evaporative cooling. Further in India, Kant et al. (1999) carried out a simulation study for assessing the potential of direct evaporative cooling system for a south walled office building situated at composite climate of Delhi. Results of study suggested that this strategy is capable of maintaining indoor temperature between 27-31.8°C if proper combination of ACH and bypass factor (BPF) is reached. Based on findings of Givoni (1969) and Kant et al. (1999), this study defines a zone of direct evaporative cooling (DEC) which extends along constant wet bulb temperature line and overlaid to proposed adaptive comfort zone (CZ). This zone corresponds to temperature range of 25.4°C to 42.5°C and a dotted line that extends from temperature of 29°C at 80% relative humidity and intersects at 42.5°C and 30% relative humidity point, respectively.

Figure 5 The modified bio-climatic design chart for composite climate of India (see online version for colours)



3.1.7 Conventional cooling

The study also defines a zone for conventional cooling (CS) when passive bioclimatic architecture strategies are not efficient enough to provide thermal comfort condition indoors. This zone is extended above the upper limit of summer comfort zone, i.e., 32°C. However, it is recommended in bio-climatic architecture that efficient thermal insulation of the space will enable the reduction of the cooling demand in the summer. Moreover, if solar radiation is prevented through opening and walls or roofs by means of shading during the summer, significant savings can be achieved in cooling.

Figure 5 shows the modified building bio-climatic design chart considering the zones of passive heating and cooling techniques for the composite climate in India.

4 Results and analysis

The selected passive design schemes (as discussed in above section) with regards to indoor comfort potential has been carried using the bio-climatic approach as presented in previous studies (Lam et al., 2006; Hassaan, 2011; Singh et al., 2007). The procedure includes the monthly climatic lines overlaid on psychrometric charts taking into consideration the maximum relative humidity and minimum temperature as one point and the minimum relative humidity and maximum temperature as another point. The potential use of the passive design strategies is accessed according to the positions of the monthly climatic lines in relation to the comfort zone and the different passive design zones on the bio-climatic design chart.

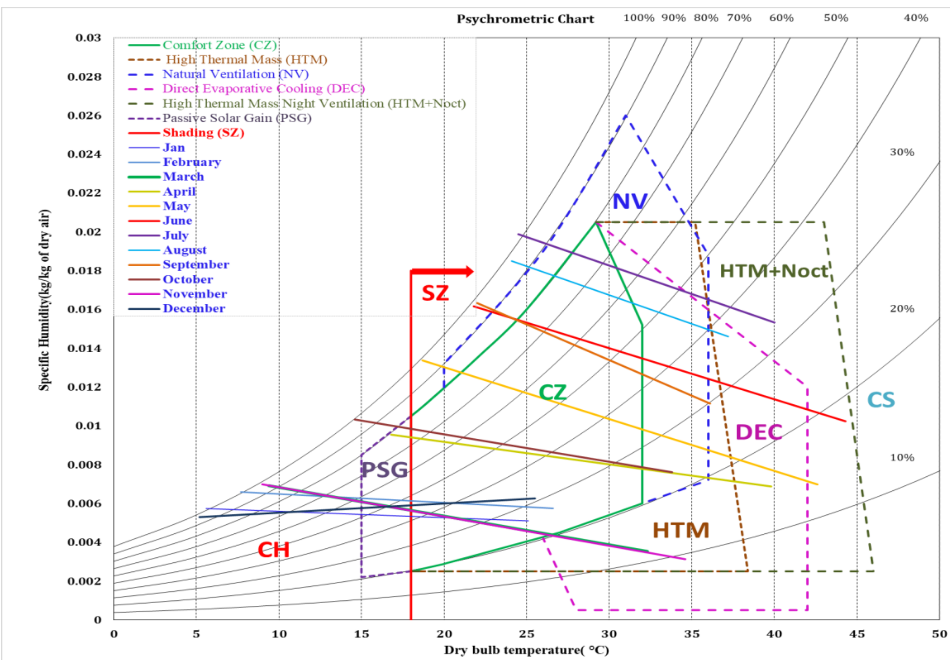
In determining the percentage of potential use, the 12 monthly climatic lines were grouped into a warmer half (March−October) and a colder half (November–February) of the year. The first part is used for assessing the potential use of passive cooling, whereas the second part is used for passive heating. To provide a more holistic view, if passive design solution is not sufficient to maintain indoor comfort conditions for a particular period of time, use of the active heating or cooling methods, namely conventional heating or air-cooling system is also recommended in the bio-climatic design charts.

4.1 Bio-climatic design chart analysis for Delhi climate

Delhi is the capital of India and a well-represented of composite climate in India. Figure 6 illustrates the building bio-climatic design chart for residential dwellings in Delhi region. The analysis of bio-climatic chart divulges that a significant portion of the monthly lines falls within the comfort zone, representing natural comfort of about 38.4% of the total time during the warmer half. For Delhi City, the main suggested passive alternatives in the warmer part of the year are natural ventilation (15.5% of the total time), high thermal mass with night ventilation (~21.5% of the total time) and direct evaporative cooling (~25.8% of the total time) [Figure 7(a)]. Apart from this, sun shading is essential for entire summer season representing 95% of total time. The direct evaporative cooling shows a comparatively higher comfort potential for this region especially during peak summer period about 35.5% of total time particularly in months of April, May, and June. A study conducted by IIT Delhi (Kant et al., 1999) for summer conditions in Delhi showed that an evaporative cooler could provide indoor thermal comfort in April and May in Delhi. However, during rainy months of July and August, relative humidity is high in this region, peaks at more than 95%. So, natural ventilation can be useful in these particular months representing 15.5% of the time in warmer half of a year. However, for about 5.2% of the total time during the warmer half, some form of dehumidification and cooling of air may be required through conventional cooling techniques.

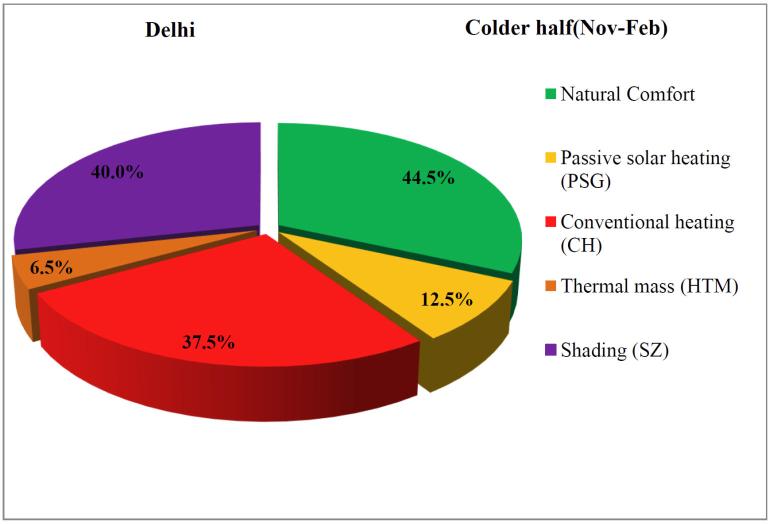
While for a colder half, natural comfort attained for Delhi city is comparatively small representing about 44.5% of the time. Moreover, passive solar heating through direct gains (~12.5% of the total time) and high thermal mass (~6.5% of the total time) shows noticeable results to overcome cold discomfort conditions during peak winter season (Figure 7(b)). Interestingly, shading is also required for about 40% of time during winter months. This is because during months of November and February the maximum temperature during daytime reaches up to 35°C. In addition to this, the bio-climatic design chart for Delhi suggests a significant requirement of conventional heating representing about 37.5% of the time during the colder half.

Figure 6 Bio-climatic design chart for Delhi City (see online version for colours)

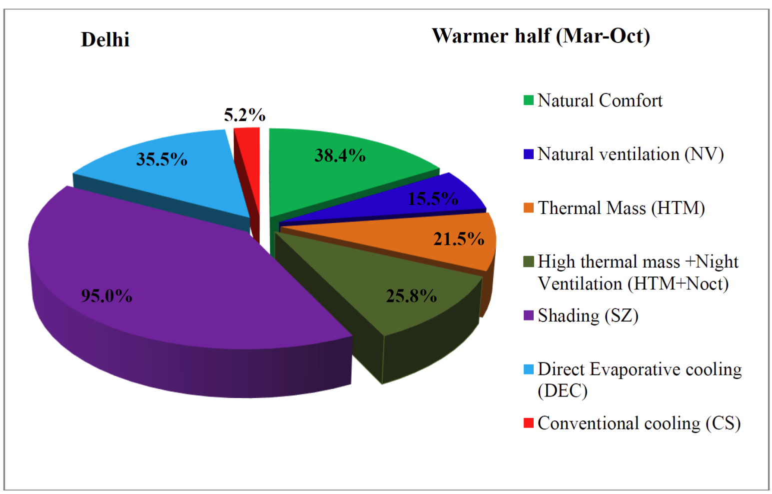


Parameters	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*
Maximum temperature (°C)	25.1	26.6	32.3	39.8	42.6	44.4	40	37.2	36.1	33.8	34.6	25.5
Minimum temperature(°C)	5.6	7.7	9.4	16.8	18.7	21.8	24.5	24.1	22	14.6	9	5.2
Maximum humidity (%)	99	99	97	79	97	97	99	98	98	97	98	98
Minimum humidity (%)	26	26	12	15	13	18	33	37	30	23	9	30

Figure 7 Summary of potential use of different passive design strategies for Delhi climate during (a) colder (Nov–Feb) and (b) warmer half (Mar–Oct) of year, respectively (see online version for colours)



(a)

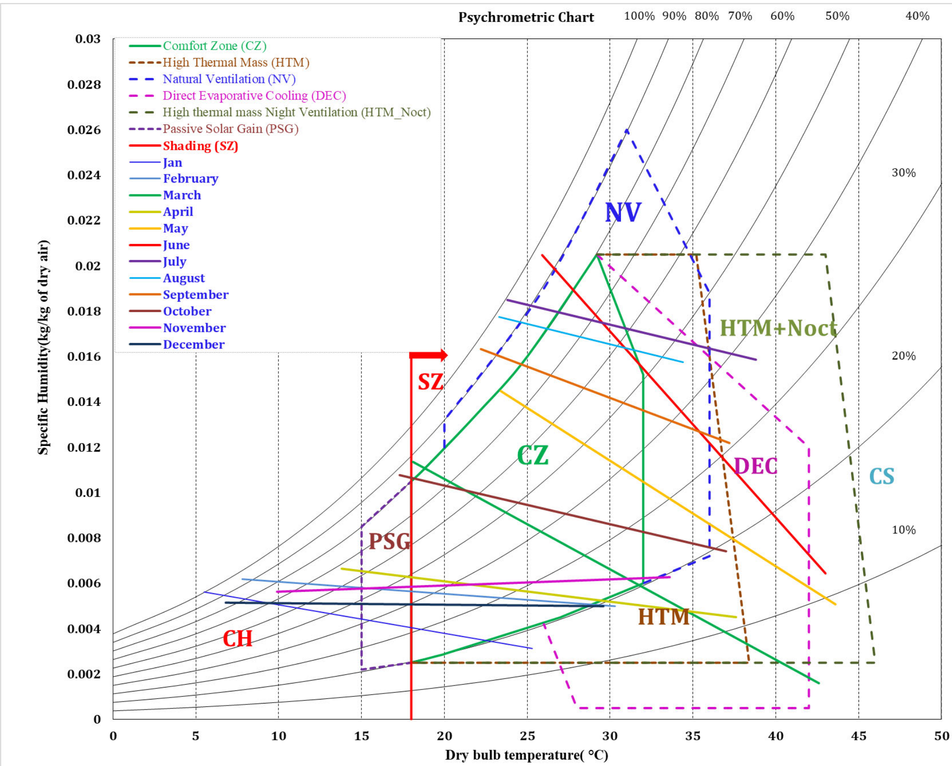


(b)

4.2 *Bio-climatic design chart analysis for Jaipur climate*

Jaipur City lies close to hot and dry desert area of India. So, the temperature during summer months often remains very high and above comfort limits. This adds the intense discomfort conditions during summer especially in peak summer months like April, May and June. The outdoor maximum temperature in summer is perceived in the range of 35–43°C while the minimum temperature varies from 18–27°C. Whereas, in winter the maximum temperature varies from 25–34°C and minimum temperature vary from 4–16°C. The average relative humidity is found very low during peak summer months, namely, April, May and June and ranges between 20–50%. The rainy month comprises of July and August and the average relative humidity is found more than 80% during these months.

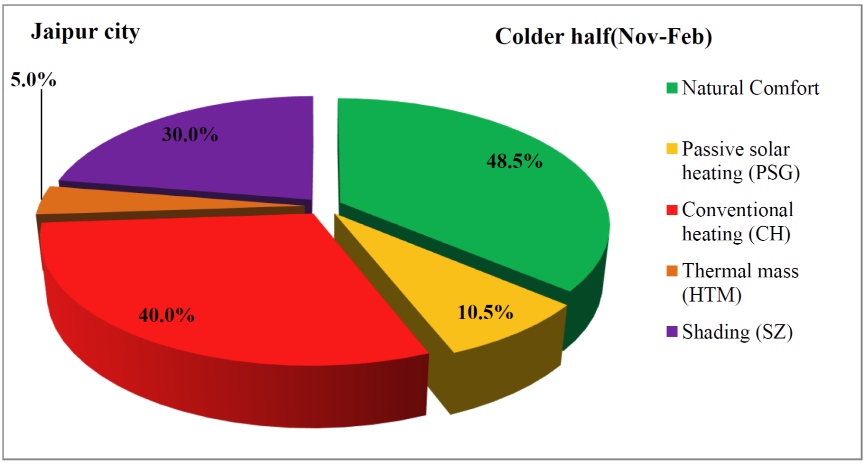
Figure 8 Bio-climatic design chart for Jaipur city (see online version for colours)



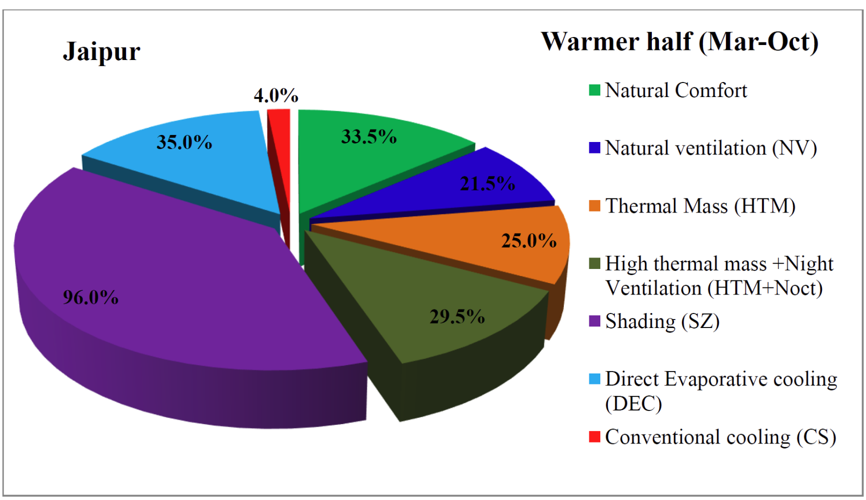
Parameters	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*
Maximum temperature (°C)	25.3	30.3	37.6	42.6	43.6	43	38.8	34.4	37.2	37	33.6	29.6
Minimum temperature(°C)	5.5	7.8	13.8	18.1	23.4	25.9	23.8	23.3	22.2	17.3	9.9	6.8
Maximum humidity (%)	97	93	67	88	82	96	98	100	98	89	74	83
Minimum humidity (%)	16	19	11	3	9	12	36	47	31	19	19	19

Figure 8 shows the building bio-climatic design chart of Jaipur climate. During the warmer half, natural thermal comfort can be attained for about 33.5% of the time, while for colder half it is about 48.5% of the time. High thermal mass with night ventilation (~29.5% of the total time) and direct evaporative cooling (~35% of the total time) are key passive cooling strategies to provide thermal comfort in buildings during the warmer half for this climate region (Figure 9(a)). In addition to these, natural ventilation has a potential of about 21.5% of the time for comfort especially during rainy months of July and August. Sun shading is required for more than 96% of total time during the warmer period. The results further recommend a conventional cooling requirement for a time representing only 4% of the total time during the same period. It can be noted from the analysis of bio-climatic design chart a conventional heating requirement for about 40% of the total time during the colder half (Figure 9(b)). The Jaipur city is situated near to the desert part of India and has a larger portion of the summer season (more than six months) than winter season (span less than two months), so passive cooling is required more often than passive heating.

Figure 9 Summary of potential use of different passive design strategies for Jaipur city during (a) colder (Nov–Feb) and (b) warmer half (Mar–Oct) of year, respectively (see online version for colours)



(a)



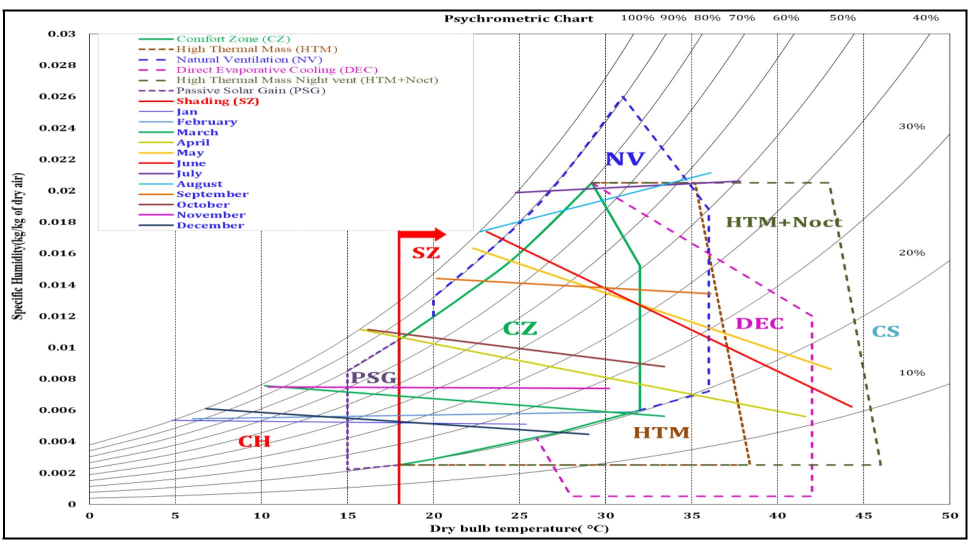
(b)

4.3 *Bio-climatic design chart analysis for Lucknow climate*

Lucknow has a composite climate with cool, dry winters from mid-November to February and dry, hot summers from late March to June. In the winter season, the maximum temperature is around 25°C and the minimum temperature varied between

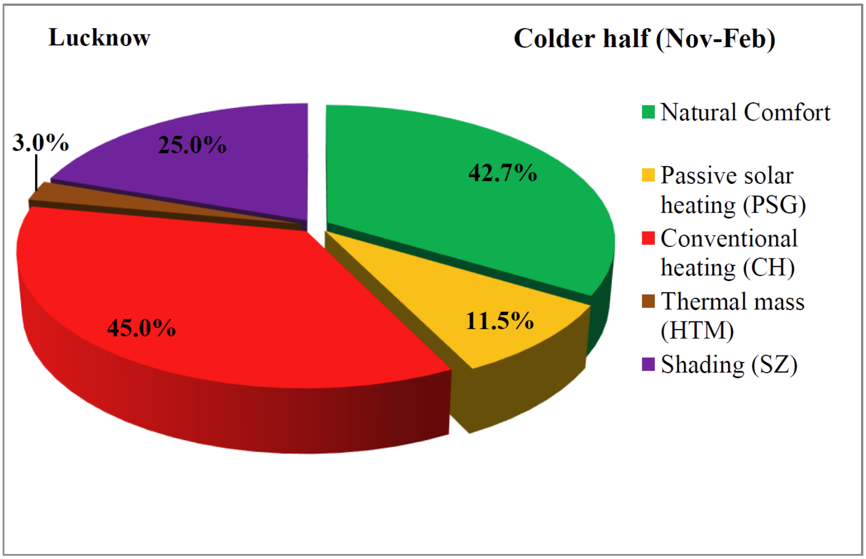
3–7°C. Summers are very hot for the region with maximum temperatures varied between 40–45°C while minimum ranges between 20–26°C. The analysis of bio-climatic design chart (Figure 10) reveals that natural thermal comfort can be achieved for about 42.7% of the time in colder half while 30.8% of the time in the warmer half, respectively. The key passive cooling strategies in the warmer half of the year include natural ventilation (~15.6% of the time), sun shading (~96% of the time), evaporative cooling (~36.8% of the total time) and high thermal mass with night ventilation (~27.5% of the total time). In fact, high thermal mass with proper shading of façade and openings, and natural ventilation are preferred passive design strategies during warmer half for this city. Direct evaporative cooling can be used subsequently when the temperature exceeds more than 35˚C as natural ventilation during daytime can lead to discomfort conditions. However, some form of conventional cooling is also required during peak summer months like May and June due to very hot and dry ambient conditions prevailing during this period. Conventional cooling contributes to about 8% of the time in warmer half of a year. Also, during peak winter conditions, i.e., during the months of December and January, passive solar contributes for a small portion of time representing only 11.5% of the time in colder half. The results also suggested that a significant amount of conventional heating (45% of the total time) is also required for this region during the colder half. Figures 11(a) and 11(b) represent the bio-climatic potential of different passive heating and cooling strategies for Lucknow city on annual basis.

Figure 10 Bio-climatic design chart for Lucknow City (see online version for colours)

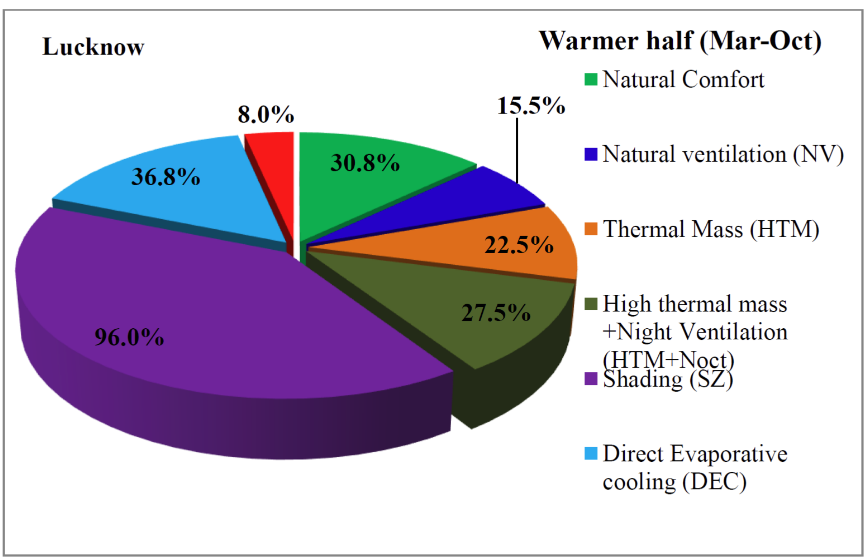


Parameters	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*
Maximum temperature (°C)	25.4	31.8	33.4	41.6	43.1	44.3	37.8	36.1	36.1	33.4	30.2	29
Minimum temperature (°C)	4.8	6	10.2	15.8	22.3	23.1	24.8	22.7	20.2	16.2	10.4	6.8
Maximum humidity (%)	99	94	99	98	98	98	99	98	98	98	98	98
Minimum humidity (%)	34	20	18	11	16	11	49	56	36	28	28	18

Figure 11 Summary of potential use of different passive design strategies for Jaipur climate during (a) colder (Nov–Feb) and (b) warmer half (Mar–Oct) of year, respectively (see online version for colours)



(a)

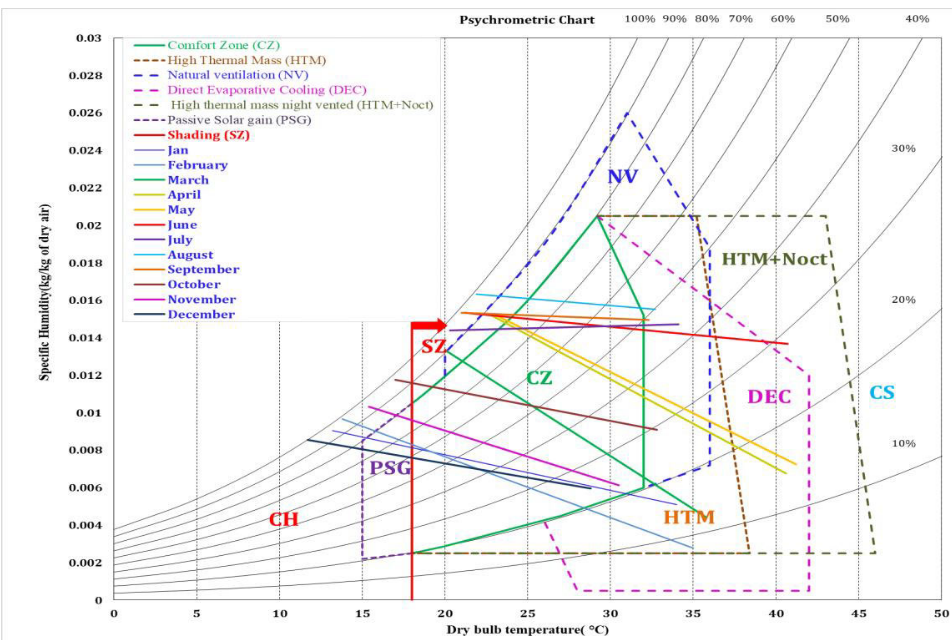


(b)

4.4 Bio-climatic design chart analysis for Hyderabad climate

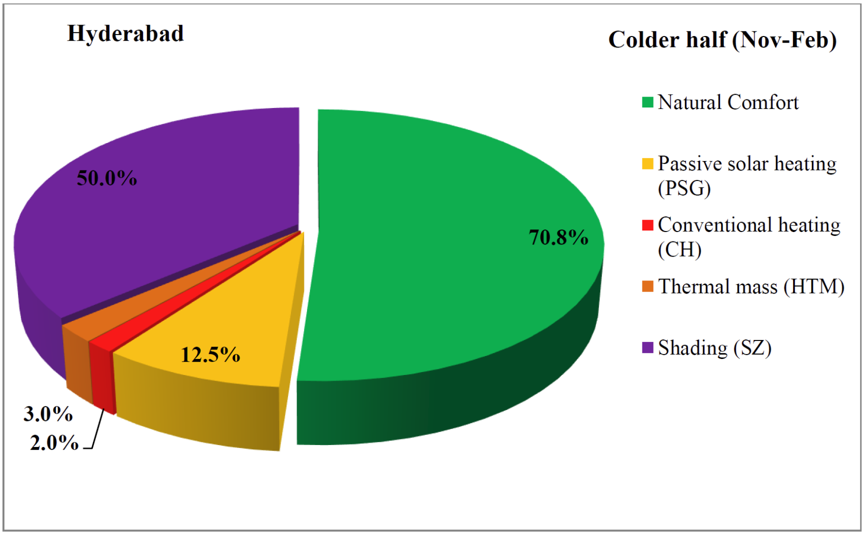
Hyderabad has composite climate and lies in southern part of India. The city is largely known for its emerging role in the information technology and pharmaceutical industries in India. The outdoor maximum temperature during summer varies from 30–40°C, while the minimum temperature varies from 22–28°C. Although, the winter season begins in the month of December and lasts till February, the minimum temperature does not fall below 10°C during winter. In the winter season, the maximum temperature varies from 29–36°C and minimum vary from 11–22°C. Thus, the Hyderabad city has no typical winter season in the true sense (Bhatnagar et al., 2018a). The building bio-climatic design chart for the Hyderabad city is illustrated in Figure 12. It can be noted that about 62.5% of the time, the natural comfort can be achieved during the warmer half of this city. The passive design strategies like natural ventilation (~21.5% of the total time), sun shading (~98% of the time), high thermal mass with night ventilation (~21.5% of the total time) and direct evaporative cooling (~31.7% of the total time) are the advocated passive cooling methods during the warmer half of a year in this city. In addition, direct evaporative cooling (~31.7% of the time) and high thermal mass (~17.5% of the time) can be advantageous for peak summer period, particularly in months of April, May, and June, when conditions are very hot and dry and exceed more than 40°C. Nevertheless, the bio-climatic analysis further suggested that conventional air conditioning is required for a small portion of time i.e. about 2% of the time in the warmer half [Figure 12(a)].

Figure 12 Bio-climatic design chart for Hyderabad city (see online version for colours)

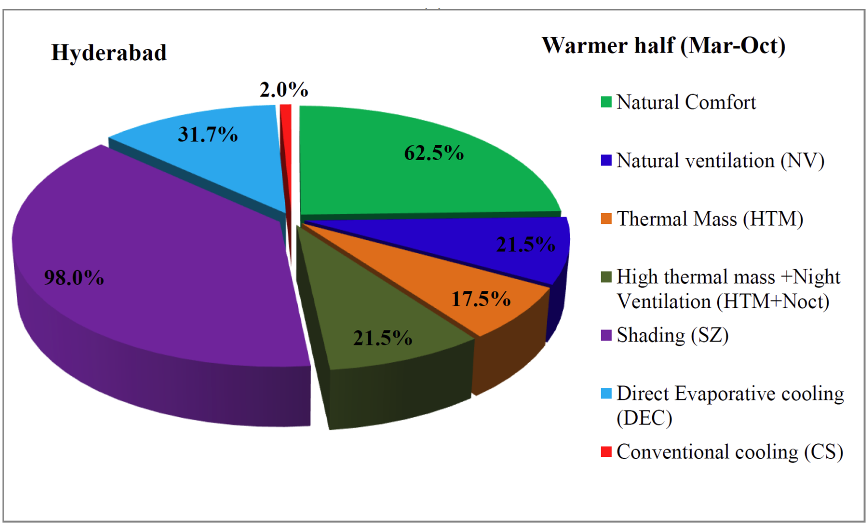


Parameters	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*
Maximum temperature (°C)	35	35.8	40.6	41.2	40.7	34.1	32.7	32.3	32.8	30.5	28.8	35
Minimum temperature (°C)	13.2	13.8	20	22.8	23.1	21.2	20.3	21.9	21	17	15.4	11.7
Maximum humidity (%)	97	97	91	86	86	98	98	98	98	97	97	98
Minimum humidity (%)	15	8	12	14	15	28	44	49	50	29	22	24

Figure 13 Summary of potential use of different passive design strategies for Hyderabad climate during (a) colder half (Nov–Feb) and (b) warmer half (Mar–Oct) of year, respectively (see online version for colours)



(a)



(b)

While for a colder half, the bio-climatic design chart of Hyderabad city recommends a 70.8% of the time there is a natural thermal comfort. Such results were expected as Hyderabad has no typical winter months and ambient conditions during this period were pleasant and comfortable. Furthermore, a significant portion of monthly lines during colder half falls within the passive solar heating zone, demonstrating about 12.5% of the time. In addition to passive solar heating, thermal mass also contributes marginally i.e. only 3% of the time. Sun shading is also required for a significant time i.e. 50% of the time during colder half for this city. However, during severe winter conditions i.e. in

January month, the bio-climatic design chart for the region shows a conventional heating requirement for about 12.50% of the time [Figure 12(b)].

5 Discussion

The present work is a subsequent analysis of our previous findings regarding adaptive thermal comfort approach of field study in which authors defines adaptive thermal comfort zone on the conventional psychrometric chart using India specific adaptive comfort approach (Kumar et al., 2016b). The thermal comfort zones were defined over existing ASHRAE Standard 55 comfort zones considering this region-specific thermal, behavioural adaptations as well as the role of airspeed to offset the elevated temperatures.

Also, primary objective of the development of building bio-climatic design charts for climate responsive building design is to decide the region-specific comfort zone. In the present paper, the potential of passive heating and cooling strategies, using modified building bio-climatic design chart, are explored for four major cities viz. Delhi, Jaipur, Hyderabad, and Lucknow situated in a composite climate of India. The selected sites were having geographical as well as climatological differences. The bio-climatic analysis of selected locations was carried out in which monthly climatic lines were determined and plotted to assess the potential of passive design strategies in warmer (March–October) and a colder half (November–February) of the year. Result derived from the bio-climatic analysis showed that natural ventilation, sun shading, high thermal mass with night purge, and direct evaporative cooling can be the key passive design solutions for cooling period of the year. Natural ventilation is cost-effective passive strategies and more useful when ambient conditions are wet i.e. during the rainy period. Effective natural ventilation can be achieved by arranging landscape site structures such as fences, and trees to maximise airspeed by reducing the area of airflow before it strikes building surfaces as suggested in a previous study for regions having similar climatic variations (Hassaan, 2011). Also, the traditional architecture in Indian building typologies from ancient times provides natural ways to enhance the natural ventilation in buildings through different opening arrangements (Bansal and Milne, 1995; Tiwari et al., 1994).

Use of high thermal mass in construction is another passive design strategy which is commonly used in residential and commercial buildings of tropical country India. The positive effects of high thermal mass in hot and dry climates, especially during hot periods, are cited in the history of literature (Milne and Givoni, 1979; Bansal and Milne, 1995; Tiwari et al., 1994). Proper shading of building envelops i.e. facades, roofs and its opening further reduces the direct gain inside the buildings. This lead to decrease in discomfort conditions as well as cooling load reduction. Since the composite climate exhibits typical hot and dry conditions during peak summers, so thermal mass can improve the indoor conditions for comfort (Kumar et al., 2017, 2018) and should be considered by architects and designers for climate responsive design. Another key passive design solution observed was direct evaporative cooling as conditions are mostly dry during peak summer months (mid-April–June). Evaporative coolers like swamp cooling systems are commonly used in both residential and office buildings for this region (Kant et al., 1999). However, the bio-climatic design charts also divulge some conventional cooling requirement in analysed locations in the case when passive designs are not sufficient enough to produce thermal comfort indoors.

Table 3 Summary of design guideline matrix for passive design in the selected cities in composite climate of India

Cities	*Colder half of the year (November–February) (% wise)*				*Warmer half of the year (March–October) (% wise)*					
	Natural comfort	*Passive solar heating (PSG)*	*Shading (SZ)*	*Thermal mass (HTM)*	*Natural comfort*	*Natural ventilation (NV)*	*Thermal mass (HTM)*	*Thermal mass and night ventilation (HTM + Noct vent.)*	*Direct evaporative cooling (DEC)*	*Shading (SZ)*
Delhi	44.5	12.5	40	6.5	38.4	16	21.5	25.8	35.5	95
Jaipur	48.5	10.5	30	5	33.5	21.5	25	29.5	35	96
Lucknow	43	12	25	3	31	16	23	28	37	96
Hyderabad	71	13	50	3	63	21.5	17.5	21.5	31.7	98
6 design guidelines	Region specification adaptation and preferences	Window to wall ratio, internal gain, orientation	Louvers, Trees, Exterior blinds, slats	Use of high thermal storage material s in construction like brick or stone	Region specification adaptation and preferences	Building orientation, trees and fences to allow more air flows in buildings	Use of high thermal storage materials in construction like brick or stone	Use of high thermal storage materials in construction like brick or stone with night ventilation	Use of swamp coolers, roof ponds, etc.	Louvers, trees, exterior blinds, slats

It is noted that a very limited portion of monthly lines falls in the passive heating region for all selected sites during the colder half (October–February) of the year. This proposes that some form of conventional heating arrangement is required for a significant portion of time in buildings during the winter season. Moreover, the peak winter season (November–February) spans not as much of summer season (April–September), suggesting cooling is required more often compared to heating. Based on this discussion, preliminary design guidelines for passive design in residential buildings of composite climate in India can be presented as shown in Table 3. It will help building designers and architects to get a quick summary of the passive design in the initial design phase of building construction for energy efficiency and sustainability.

6.1 Limitations of present study

The method proposed in this paper is rather simple and can provide approximate passive design solutions during pre-design phase for landscape design for selected locations in a composite climate of India. However, the method proposed in this study has its own limitations.

Firstly, the passive design zones proposed in the present study for estimating the potential of selected passive strategies for warmer (March–October) and cooler (November–February) period of a year may not represent the immediate hourly conditions during the months or season. The passive design of buildings is also affected by site selection, region specific construction, social-cultural and seasonal variations in climatic conditions. For example, in delineating the sun shading zone we considered the ambient temperature as deciding factor but studies has shown shading must be activated well before this point, at a time more closely related to the incident solar radiation on a window than to the outdoor air temperature, to avoid overheating later in the day (Tzempelikos and Athienitis, 2007).

Passive solar heating assumes that it cannot be useful enough unless it can bring indoor conditions into the comfort zone by itself. In contrast, case studies in passive buildings in different climates have been shown to benefit from sun tempering (Zirnhelt and Richman, 2015). Lomas et al. (2004) have also predicted conditions during peak summer season, when direct evaporative cooling system may not produce thermal comfort conditions although the bio-climatic charts were confirming the same.

Lastly, the availability of reference weather data for most of the locations in India is still not available. The typical meteorological year weather files available in India counts only for 62 locations for different climatic zones (ISHRAE, 2014). In addition to this, the work considered one climatic zone thermal adaptations and expectations of occupants to define thermal comfort zone. The study proposes the further examination of thermal and behavioural adaptations of inhabitants for different building types through field study in different climatic zones of India. This will provide a better valuation of comfort expectations of subjects considering region-specific adaptations. However, the methodology presented in this paper will remain valid for any climatic conditions even if a different approach is being used to define the thermal comfort zone.

7 Conclusions

The present work is subsequent to our previous findings which define the adaptive thermal comfort zone (CZ) over ASHRAE Standard 55-2017 comfort zone considering this climate zone specific thermal expectation, preferences and behavioural adaptations of inhabitants (Kumar et al., 2016b). This study proposed a modified building bio-climatic design chart more suitable for evaluation of the potential of passive heating and cooling design strategies in a composite climate of India. Four cities, which are geographical and climatological diverse within composite climate of India, have been selected for detailed bio-climatic analysis during cooling and heating period of the year. The results derived from the bio-climatic analysis are further used to frame the passive design guidelines for heating and cooling period for investigated locations. Following are the main conclusions of the present study:

- This climatic zone specific adaptive thermal comfort zone (CZ) shows a significant time of natural comfort for selected locations. The natural thermal comfort varied from 30–60% and 43–70% of the total time during warmer half (March–October) and a colder half (November–February) of the year, respectively.
- During warmer half of year natural ventilation, sun shading, thermal mass with night purge and direct evaporative cooling in most of the cases proved to be the better choice for passive cooling. The direct evaporative cooling and sun shading were identified as necessary passive design strategies particularly during peak summer months i.e. mid-April to June for hot and dry regions like Delhi, Lucknow and Jaipur, respectively.
- Hyderabad climate is hot and humid during the summer season and no typical winter months are there. Hence, natural ventilation and direct evaporative cooling could be key passive design strategies during summer season while for mild winter season passive solar gain with proper shading of thermal mass can improve the indoor conditions for thermal comfort.
- Passive solar heating only provides the noticeable result for enhancing indoor thermal comfort in the winter season (November–February) for all selected locations. The results are obvious as typical winter season in analysed locations spans less than three months (~December to February) in a year. So, cooling is required more often than heating in a composite climate of India.
- Further to the results, bio-climatic analysis of three locations revealed that relying entirely on these passive strategies to maintain thermal comfort is not feasible especially during peak summer and winter months and conventional cooling and heating is required for a considerable time.

The bioclimatic design charts presented in this study would facilitate a quick overall representation for the composite climate of India, which can be used on a purely qualitative basis, to arrive at basic design decisions solutions during building's initial design stage. However, the results presented in this work have certain limitations which should be considered wisely for sustainable and passive design buildings in composite climate of India.

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Nomenclature and abbreviation used

Symbol	*Abbreviation*	*Units*
CZ	Comfort zone	–
TMY	Typical meteorological year	–
CPZ	Control potential zones	
ASHRAE	American Society of Heating Refrigeration and Air conditioning	–
TSI	Tropical summer index	–
NBC	National Building Code of India	–
PSG	Passive solar gain	–
NV	Natural ventilation	–
HTM	High thermal mass	–
ACH	Air change per hour	–
BPF	By pass factor	–
DEC	Direct evaporative cooling	–
CS	Conventional cooling	–
T_a	Ambient temperature	°C
T_l	Leaving dry bulb temperature	°C
T_b	Inlet dry bulb temperature	°C
T_w	Inlet wet bulb temperature	°C
ε	Efficiency	–