ENHANCING BUILDING RESILIENCE: THE ROLE OF FUTURE WEATHER DATA IN BUILDING DESIGN

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Abstract: With climate change driving unprecedented shifts in global weather patterns, the need to future-proof building designs has become critical. Current design practices predominantly rely on simulations and analysis that use Typical Meteorological Year (TMY) files, which are based on historical weather data and may not reflect future climatic conditions. This could result in buildings that may not be able to adapt to long-term climate change. Our study examines whether the use of future weather data in design analysis points to different strategies and is necessary to successfully predict building performance.

We used predicted future weather data for 2080 in Bangalore, India, which forecasts a global temperature of 4°C temperature increase and historical Typical Meteorological Year (TMY) data, compared these data, conducted analysis to determine the passive and active strategies that get prioritised from the analysis and compare these. We used a calibrated Building Energy Simulation (BES) model of a building in Bangalore to determine how the performance of the building changes under future weather conditions.

The future weather indicates significant temperature rise across all seasons, increase in summer temperatures of 10°C; decreasing relative humidity in summer and increasing in winter; a reduction of 16.2% for number of hours in the comfort range. The design analysis indicated that different active and passive design strategies gets prioritised for the future weather scenario.

The calibrated models shows that while the passive design features incorporated in the building are adequate for the TMY weather conditions, they may fail to maintain thermal comfort in the future. The percentage of discomfort hours in the future condition increased by 37%.

These findings indicate for future-proof our buildings it is necessary to use future weather data during the design stages while selecting climate-responsive strategies. Analysis methods must incorporate future weather conditions for climate resilient building. The findings also indicate that the sole use of current weather data results in passive and active strategies that will not be appropriate for future climate-changed forced weather conditions.

Keywords: *Building performance, calibrated model, future weather data, passive strategies*

1. Introduction

Traditional building energy simulation practices primarily rely on Typical Meteorological Year (TMY) files, which use historical weather data to represent "typical" climate conditions for a location (Siu & Liao, 2020). While appropriate in the past where weather patterns were largely consistent, such TMY files may not accurately represent the weather patterns changing rapidly in coming decades forced by climate change. Thus, the use of TMY files for design of buildings now, could results in buildings that do not perform well in the future. There is a growing awareness and use of future weather data in building design (Dyson, 2023). However, the use of future weather files is limited due to accessibility issues, and a complicated method for generating them, while climate models are also being updated every year (Manapragada al., 2022). This raises the question: how important is it to use these difficult-to-access future weather files for building simulations to evaluate and optimize building design and performance?

The Intergovernmental Panel on Climate Change (IPCC) warned that if carbon emissions remain at current levels, the average global temperature increase could surpass the 1.5°C mark above pre-industrial levels (Calvin et al., 2023). Building designs must be simulated to **get the best optimised performance that lower carbon over their life.**

This paper examines the comparison between using TMY files and future weather data through a quick digital design tool that integrates advanced climate analysis and provides quick design recommendations for the two weather files. Additionally, we analyse the thermal behaviour of a building through energy simulation, comparing the results from TMY and future weather files. The aim of this paper is to investigate the necessity and impact of using future weather data in climate analysis, building design and energy simulation. The objective is to evaluate whether use of future weather files

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leads to different passive design decisions compared to traditional TMY files-based building energy simulation. By addressing these gaps, the findings from the study highlight the critical need for the future weather data in enabling future-proof building designs with climate-responsive strategies to adapt to changing environmental conditions. This study highlights the importance of integrating future weather data into building design to address the challenges of climate change. By comparing predicted 2080 weather data for Bangalore with historical TMY data, we observe significant temperature increase of 10°C and changes in humidity of 10% on an average, indicating hotter, drier summers and warmer, more humid winters. Our analysis shows a shift in comfort hours from 26.8% to a drop of 9.3%, emphasizing the need for building designs that account for future climate conditions. Despite the limited use of future weather files in current practices due to accessibility issues and complex methods, the study reveals that current passive design features may not ensure thermal comfort in the future, with discomfort hours increasing by 37%. This research underscores the critical role of future weather data in creating resilient, energy-efficient buildings for a changing climate.

2. Methodology

The methodology has four steps. It includes generating future weather data, characterizing the weather data, evaluating design interventions using climate consultant and observe the performance evaluation using a BES. Each step is elaborated as follows.

2.1. FUTURE WEATHER DATA GENERATION

To generate the future weather data files for this study, an open-source tool 'Epwshiftr' is used. This tool uses a statistical downscaling technique known as the morphing method, which uses Global Climate Model (GCM) output from the latest CMIP6 project to generate future weather data for BES (Jia et al., 2023). The morphing method calculates future weather conditions by applying stretching and shifting factors to historical weather data. The tool is developed using R-language and can process multiple GCM outputs to create future EPWs. The input file here is an '.epw' file of Indian Society of Heating, Refrigeration, Air-conditioning and Engineering (ISHRAE) 2014 TMY file.

The IPCC AR-6 describes the different climate change paths based on actions taken on various levels from construction, transportation, population to socio-economic risks. Hence Shared Socio-economic pathway (SSP) are presented for different scenarios (Calvin et al., 2023). The worst scenario is SSP5-85, that exceeds the global warming temperature by 4°C. The generation of future weather data is derived based on this worst-case scenario. We have generated the future data for 2080 which is 56 years from 2024, and within the average lifespan of a building (if designed in 2024 and built by 2027).

2.2. CHARACTERIZING THE WEATHER DATA

Before delving into the design recommendation method using the weather files, its crucial to understand the characteristics that differentiates 2080 future weather projections and TMY weather data. To quantify these differences, we conducted a comparative analysis of the TMY and the generated future weather data. This analysis was facilitated by an excel tool developed specifically for this purpose, which compared the two weather files based on three parameters: Dry Bulb Temperature (DBT), Wet Bulb Temperature (WBT) and Relative Humidity (RH). The comparison focused on key metrics such as maximum (max), minimum (min) and average (avg) values for these parameters, both day and night, and across different seasons. For the analysis, daytime was defined as 7am-6pm, while nighttime was from 7pm-6am. Seasons were categorised as winter (November to February"), summer (March to June) and monsoon (July to October).

2.3. DESIGN INTERVENTION RECOMMENDATIONS

Building designers and their consultants who are interested in designing high-performance buildings, start their conceptual design with quick, climate-file based analysis tools like Climate Consultant and Ecotect Weather Tool (Yacob Arsano and Christoph Reinhart, 2017). We used Climate Consultant 6.0 (Milne, 2021), a digital design tool that integrates advanced climate analysis and quickly provides visualizations of thermal comfort zones on a psychrometric chart and recommendations for design strategies based on the input weather file

The design strategies and their corresponding comfort hours generated by Climate Consultant 6.0 tool are used to compare the current TMY weather data and predicted 2080 future weather data. This comparison is done to understand

1. How the ranking of the design strategies provided by such quick tool like climate consultant is different for the TMY and the future climatic conditions. By analysing these differences, we aim to determine if the ranking of specific design strategies changes as climate evolves.
2. How the quantity of comfort hours for each design strategy change between the TMY and future weather conditions.

Climate Consultant allows users to upload standardized EPW format climate data, which can be visually analysed, and provides thermal comfort areas and boundaries of climatic conditions within which various building design strategies that can provide comfort. There are 16 design strategies (as shown in figure 1) and its corresponding comfort hours are also mentioned. We used the EPW files of the 2080 predicted weather file and historical TMY weather file and then compared the ranking of the design strategies and the percentage of comfort hours the strategies provide. The psychrometric chart

(Figure1) generated by climate consultant shows the results of the design recommendations. Design strategies with its percentage are given by the tool, that are calculated based on American Society of Heating, Refrigeration, Air-conditioning and Engineering (ASHRAE). Both passive and active design strategies are covered by the tool.(Milne, 2021)

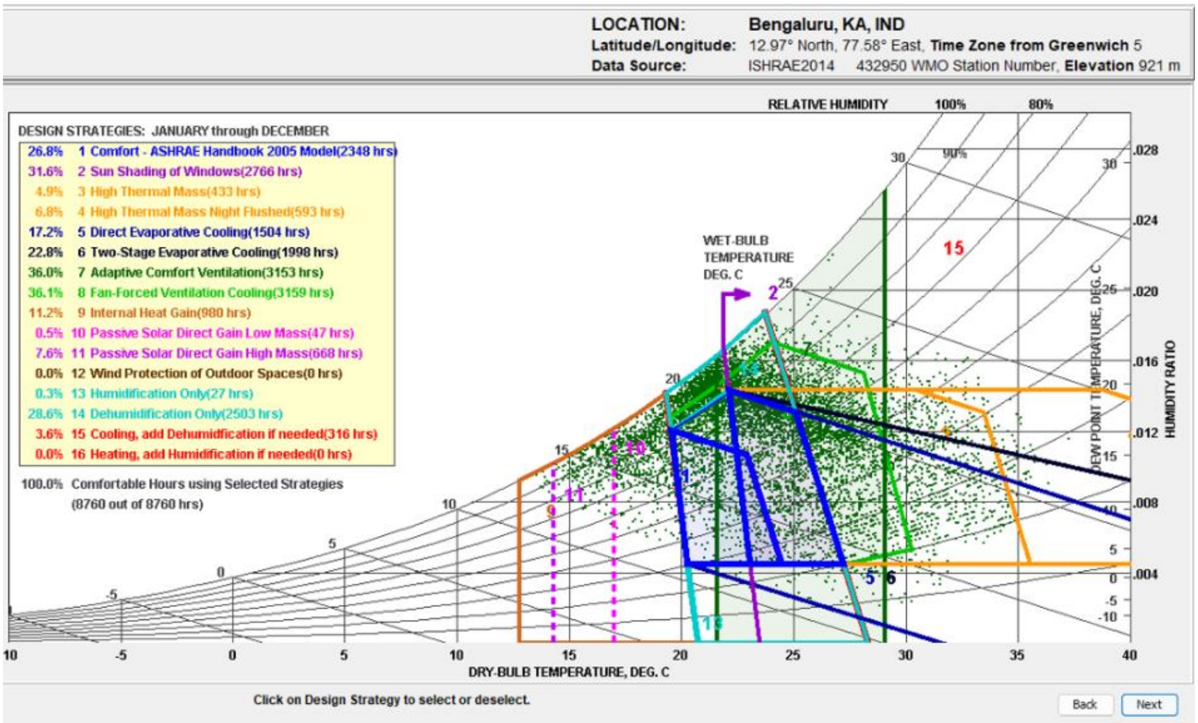

Figure 1: Design strategies suggested by Climate Consultant for TMY data of Bangalore city

2.4 BUILDING PERFORMANCE ANALYSIS

Apart from using a quick climate based tool as Climate Consultant, we also used a calibrated Building Energy Simulation (BES) model detailed insights into a building's thermal behaviour and energy demands using the two weather file (Chong et al., 2021). Climate consultant tool, which is used for initial analysis doesn't provide detailed thermal behaviour of the building design. It is only based on the weather file. So, we used a calibrated BES of an Experimental Building (EB) (shown in figure 2) in Bangalore, which employs passive design techniques and acts as a testbed for new technologies and practice to compare the thermal behaviour of the building when simulated with TMY and future weather file (Thounaojam et al., 2024).

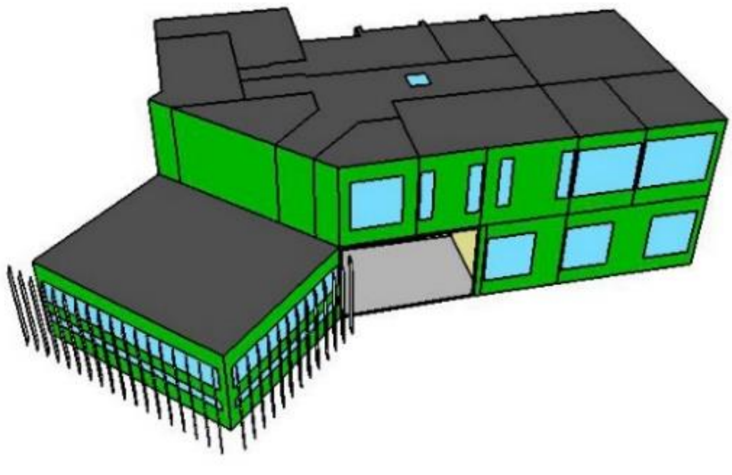

Figure 2: Calibrated BES thermal model of the experimental building

A calibrated BES model is fine-tuned with real-world data to simulate scenarios accurately (Royapoor & Roskilly, 2015). Such models are crucial for providing reliable predictions of a building's thermal performance and energy use.

Our focus was to evaluate how this passively designed building performs under both TMY historical weather data and predicted future climate data. We analysed the Operative Temperature (OT) within naturally ventilated spaces over a year and compared it to the adaptive comfort bands from the National Building Code of India (NBC) (2016). By comparing discomfort hours between historical and future conditions, we assessed how future climate scenarios might impact thermal comfort.

3. Results

Our study examined the necessity and impact of using future weather data as described above. The results and findings are below.

3.1. WEATHER DATA CHARACTERISTICS

Figure 3 and 4 present the characteristics of TMY and future weather data. Each figure is divided into three segments: year, day, and night. Within each segment, data is further sub-divided into three categories—minimum, maximum, and average values—observed for the entire year, as well as for different seasons. Seasonal data is represented using coloured rectangles for easy differentiation:

- Blue rectangles represent the winter season.
- Yellow rectangles represent the summer season.
- Grey rectangles represent the monsoon season.

Figure 3, compares DBT (°C) between the TMY and the 2080 weather, highlighting a consistent warming trend in 2080. Yearly maximum temperature shows a 7°C increase (44°C in 2080 vs. 37°C in TMY) and a 2°C rise in average temperatures (26°C vs. 24°C), with a slight 1°C increase in minimum temperatures (14°C vs. 13°C). Daytime temperatures show significant rises, with summer and monsoon with maximum temperatures increasing by 7°C and 4°C respectively, while daytime minimums and averages also rise, especially in summer. Nighttime temperatures follow a similar pattern, with a 7°C increase in maximum temperatures (40°C vs. 33°C) and a 2°C rise in average temperatures (24°C vs. 22°C), though minimum temperatures remain unchanged at 14°C. This analysis indicates that by 2080, temperatures will be warmer across all times and seasons compared to TMY, with the most significant increases occurring in summer. Winter will experience a mild warming effect, with a 1°C increase in maximum and average temperatures, while minimum temperatures stay the same.

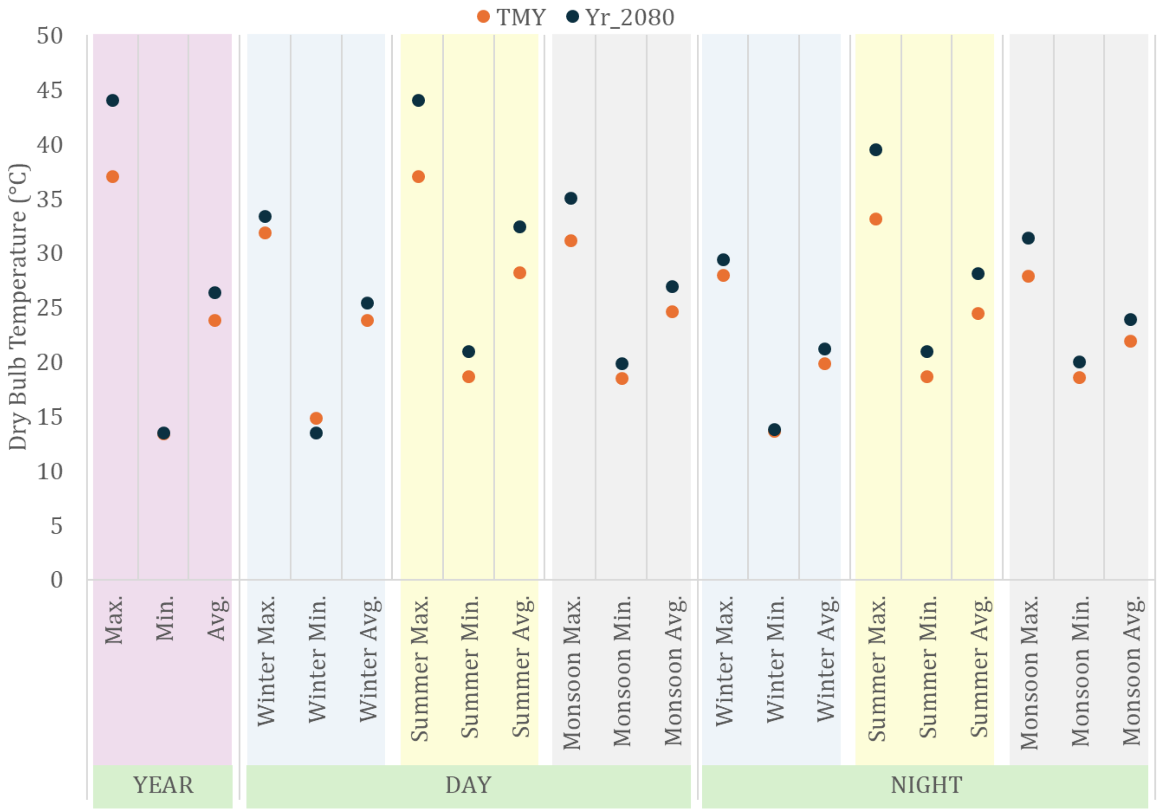

Figure 3: Comparison of Dry Bulb Temperature of historical TMY and predicted 2080 weather data

Figure 4 compares RH (%) between TMY and 2080, showing stability in yearly averages (68%) and maximum RH (100%), with a slight decrease in minimum RH from 10% to 9%. Daytime RH trends vary during winter that shows a slight increase in average RH (54% to 58%) in 2080, while summer experiences a decrease in average RH (54% to 46%) in 2080. Monsoon average RH increases from 85% to 89%, with other values unchanged. Nighttime RH follows similar trends, with winter average RH rising from 75% to 82%, while summer sees decreases in average (69% to 60%).

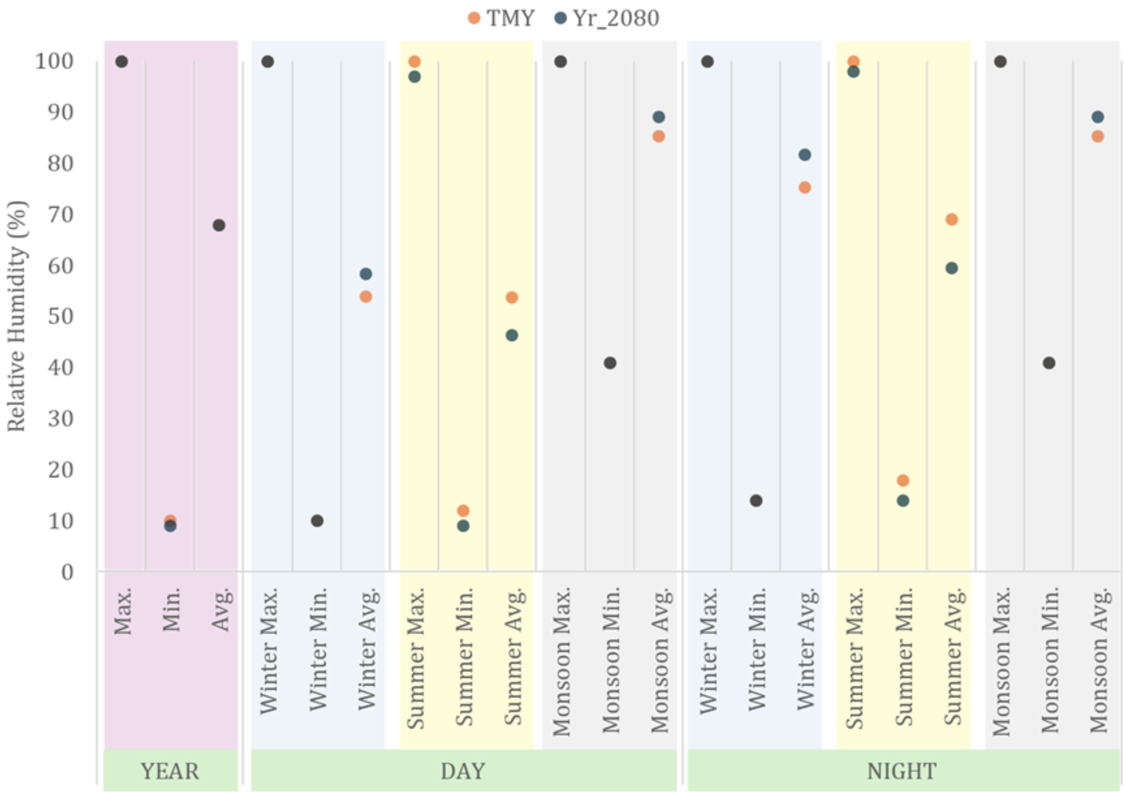

Figure 4: Comparison of Relative Humidity (RH) of historical TMY and predicted 2080 weather data

Overall, the analysis shows that while RH remains relatively stable throughout the year and during the monsoon season, there are more notable changes in winter and summer. Winter has an increase in average RH, particularly at night, whereas summer experiences a general decrease in RH both during the day and at night. By 2080, RH is expected to remain steady overall, with a slight drying trend in summer and increased moisture levels in winter, especially at night.

Based on the two parameters studied for the historical and predicted future, we observed that by 2080, temperatures are expected to increase significantly across all seasons, with the most pronounced warming occurring in summer. While winter will experience a slight temperature rise, RH trends will vary, showing a decrease in summer and an increase in winter, particularly at night. This suggests a future climate characterized by hotter, drier summers and warmer, more humid winters.

3.2. DESIGN INTERVENTION RECOMMENDATIONS

The Climate Consultant 6.0 analysis by comparing the TMY weather file with the predicted 2080 future weather file evaluated the ranking of design strategies and their corresponding comfort hours. The results provided insights into potential shifts in design priorities and the effectiveness of passive design strategies in response to changing climate scenarios. To do this, we segregated the recommended design strategies into passive and active strategies.

Figure 5 shows the comparison of passive design strategies and their comfort hours between the TMY and future weather file. When examining, we found that "Adaptive Comfort Ventilation", "Sun-Shading of Windows," and "Internal Heat Gain" consistently ranked as the top three strategies for both the TMY and 2080 weather data, indicating they provide the highest percentage of comfort hours and contribute significantly to building comfort if these strategies are implemented. Adaptive comfort ventilation allows occupants to naturally adjust indoor conditions by increasing airflow, either through operable windows or controlled ventilation, to maintain thermal comfort, particularly in warmer periods. Sun shading of windows enables the building to reduce direct solar heat gain, thus minimizing overheating in summer months and keeping interior temperatures within a comfortable range. Internal heat gain refers to the controlled use of heat from occupants, lighting, and equipment, The strategy "Passive Solar Direct Gain High Mass" which utilizes thermal mass to absorb and store solar heat during the day for release during cooler periods ranked fourth for the TMY weather data but dropped to fifth place under the 2080 scenario. Conversely, "High Thermal Mass Night Flushing" a strategy that uses cool night air to lower the temperature of high-mass materials, which then absorb heat during the day, reducing indoor temperatures and cooling loads and this ranked fourth in the 2080 weather data. Strategies such as "High Thermal Mass" and "Passive Solar Direct Gain Low Mass" consistently ranked lowest across both weather conditions.

While the ranking of passive design strategies remained consistent between the TMY and Year 2080 weather data, the percentage of comfort hours varied significantly, revealing key insights into their future performance. Adaptive Comfort

Ventilation increased its comfort hours from 36% to 39.1%, indicating its growing importance in warmer climates. In contrast, Sun-Shading of Windows saw a slight decrease from 31.6% to 30.6%, and the ASHRAE 55 Model dropped sharply from 26.8% to 9.3%, suggesting that traditional comfort models may become less effective under future conditions. Internal Heat Gain also decreased from 11.2% to 6% highlights the importance of a tighter building envelope to minimize infiltration and manage internal heat gain. Additionally, strategies like Passive Solar Direct Gain High Mass and High Thermal Mass Night Flushed saw reductions in comfort hours, indicating that reliance on thermal mass may be less effective in the future.

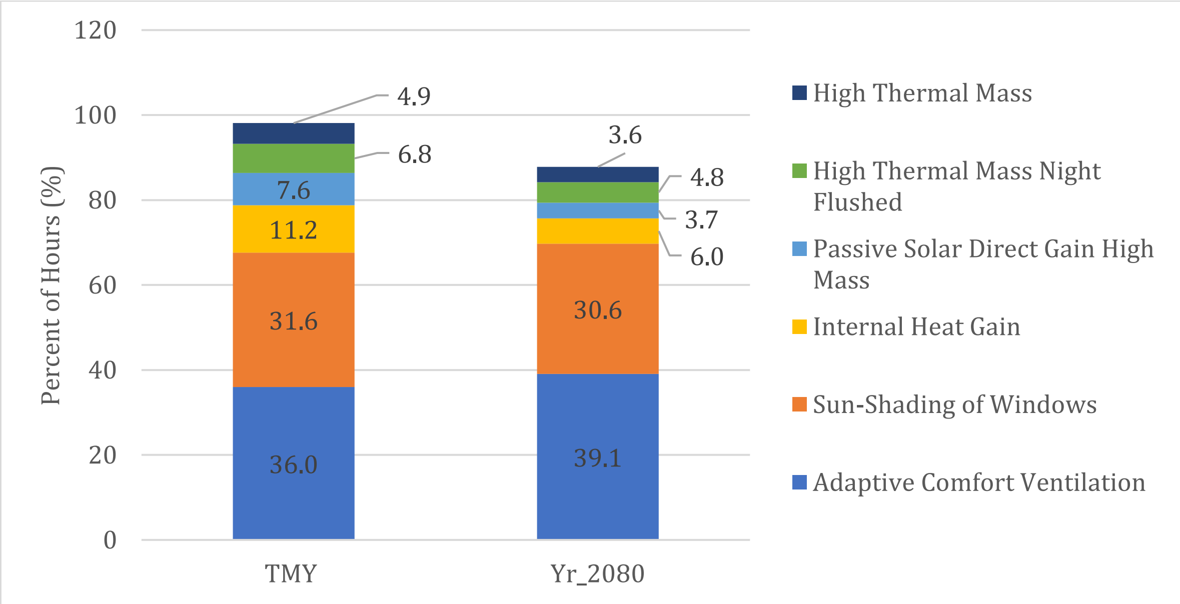

Figure 5: Comparison of Passive Design Strategies and their comfort hours

Figure 6 shows the comparison of Active Design Strategies and their comfort hours between the TMY and future weather file. When examining the ranking of active design strategies as shown in figure 6, the ranking changes significantly from the TMY scenario to the year 2080. In the TMY scenario, Fan-Forced Ventilation Cooling ranks highest, offering the most comfort hours, followed by Dehumidification, Two-Stage Evaporative Cooling, Direct Evaporative Cooling, and Cooling and Dehumidification. Fan-Forced Ventilation Cooling improves comfort by increasing air movement. Dehumidification as a strategy reduces excess moisture in the air, improving thermal comfort by maintaining an optimal indoor humidity level. Two-Stage Evaporative Cooling allows for enhanced cooling by using both indirect and direct evaporation processes to cool air more efficiently, reducing energy consumption compared to traditional methods and Direct Evaporative Cooling lowers the air temperature through the evaporation of water. Cooling and Dehumidification combines both cooling and moisture removal, making it effective for maintaining comfort in hot and humid conditions. Humidification which adds moisture to the air, and increases the perceived warmth and reducing cooling effectiveness, and this ranked lowest. By 2080, the ranking shifts. Dehumidification becomes the top strategy, reflecting its growing importance in a warmer, more humid climate. Cooling and Dehumidification move up to second place, while Two-Stage Evaporative Cooling and Direct Evaporative Cooling drop to third and fourth. Fan-Forced Ventilation Cooling falls significantly in rank, and Humidification becomes irrelevant.

When comparing the comfort hours provided by each active strategy between TMY and 2080, dehumidification increases its contribution from 28.6% to 38.9%, highlighting its essential role in managing indoor comfort as future humidity levels rise. Similarly, Cooling and Dehumidification sees a marked rise from 3.6% to 21.4% of comfort hours, reflecting the growing need for combined strategies to cope with future climate challenges.

In contrast, Fan-Forced Ventilation Cooling shows a steep decline, from 36.1% to just 3.2%, indicating that simple ventilation will be far less effective in a hotter, more humid future climate. Direct Evaporative Cooling and Two-Stage Evaporative Cooling also see reductions, with their contributions dropping from 17.2% to 9.4% and 22.8% to 10.9%, respectively. This suggests that these strategies will become less efficient as the climate evolves.

Overall, the significant shift in the ranking and effectiveness of these strategies emphasizes the growing importance of dehumidification and integrated cooling methods in future climates, while traditional strategies like ventilation and evaporative cooling are likely to become less effective.

The ranking of design strategies shows minimal change between current (TMY) and future (2080) climate scenarios. This suggests that, despite slight variations in the effectiveness of some strategies due to evolving climate conditions, the overall priority and effectiveness of most design strategies remain consistent. However, it is crucial to further investigate the extent of thermal comfort provided by these strategies as climate conditions change, to understand how their performance might shift in magnitude over time.

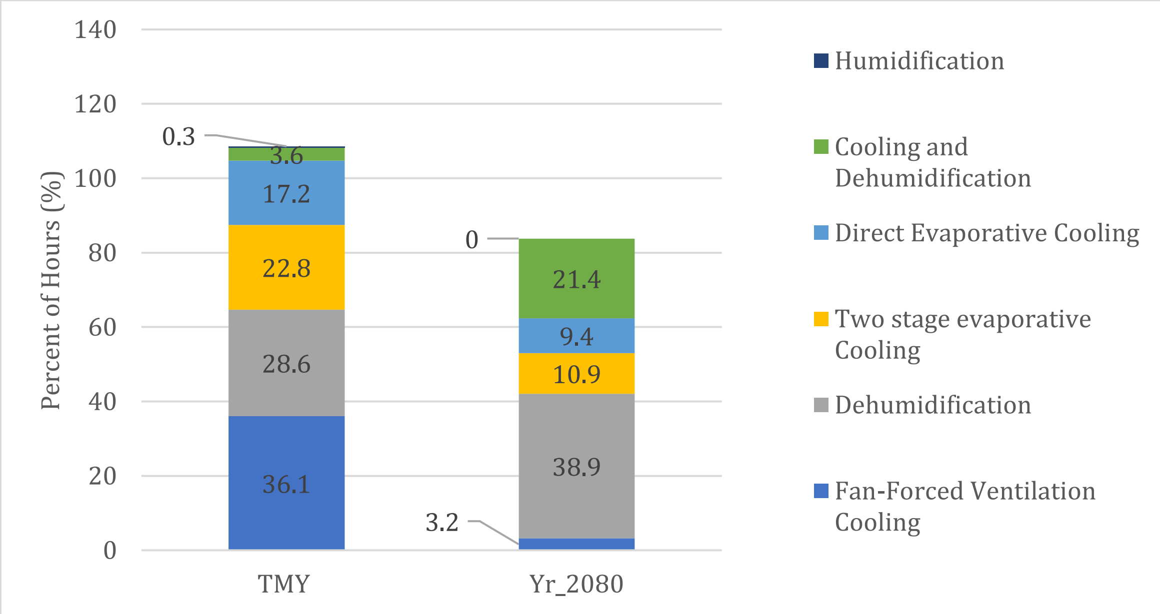

Figure 6: Comparison of Active Design Strategies and their comfort hours

The overall percentage of comfort hours changes notably from the TMY to the Year 2080 scenario for both active and passive design strategies. This highlights the need to reassess building design strategies based on changing climate conditions, rather than relying solely on TMY data.

3.3. BUILDING PERFORMANCE ANALYSIS

We used the calibrated BES model to assess the thermal behaviour inside the building. By using the calibrated BES of an Experimental Building in Bangalore, we evaluated its performance under both TMY historical weather data and predicted 2080 future climate conditions. We analysed the Operative Temperature (OT) within naturally ventilated spaces over the course of a year and compared it with the adaptive comfort bands from the NBC.

Figures 7 illustrate the OT achieved with natural ventilation for a rammed earth wall with insulation using historical TMY weather data. When compared with the NBC adaptive thermal comfort band, only 26% of the annual hours are identified as uncomfortable, with all discomfort hours falling below the thermal comfort band. Under these historical conditions, cooling issues are minimal and can be managed by closing windows during periods of low ambient temperatures.

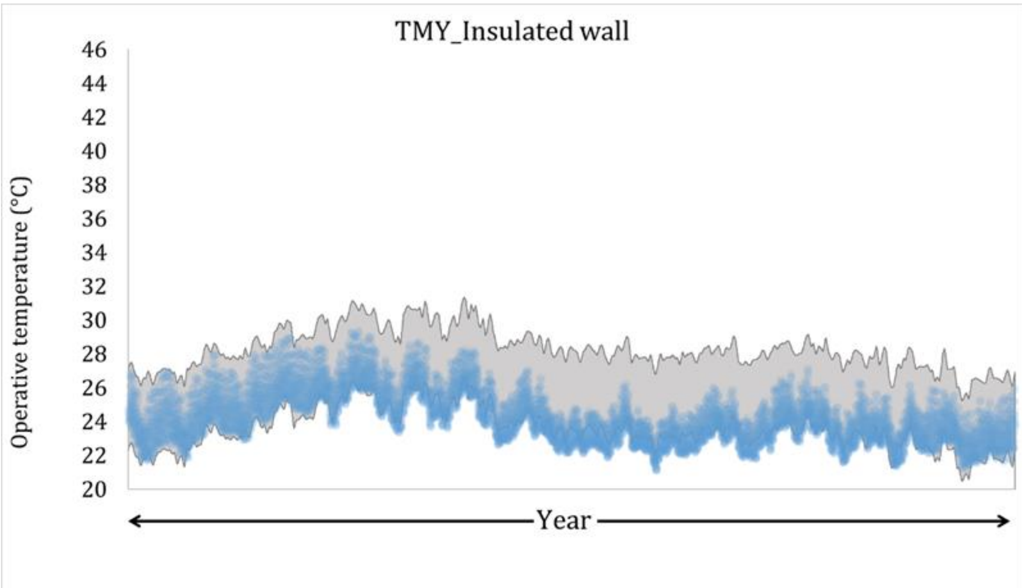

Figure 7: Operative Temperature in Natural Ventilation mode of TMY

In contrast, Figure 8 displays the OT for the same design under future (2080) weather conditions. The OT results, compared against the National Building Code (NBC) adaptive thermal comfort band for naturally ventilated operations, reveal that 63% of the annual hours may be uncomfortable, with OT exceeding the upper limit of the comfort band by a maximum of 8°C. The discomfort hours above the band (26%) are lower than those below it (43%) as shown in figure 9. This indicates that future conditions will present significant cooling and heating challenges, unlike in the TMY scenario.

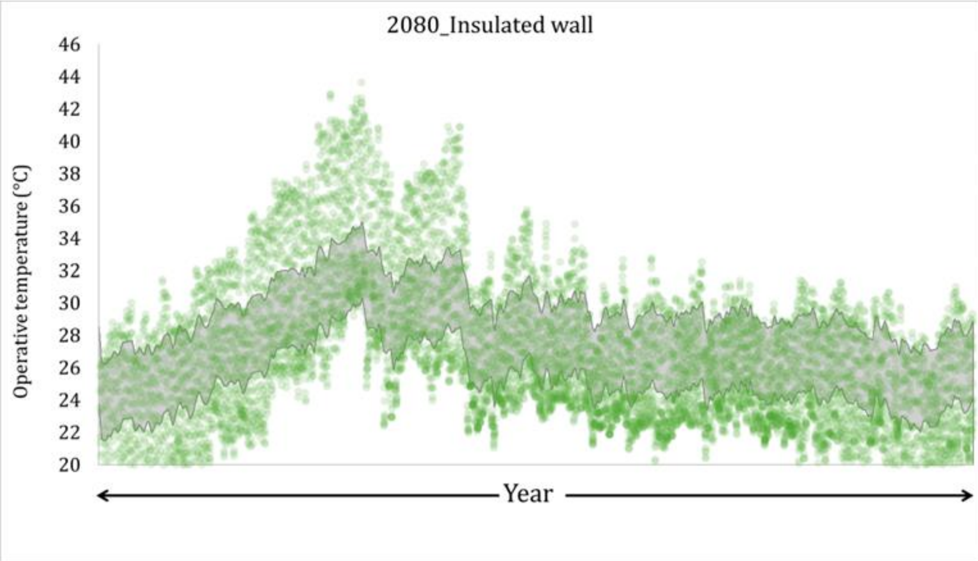

Figure 8 Operative Temperature in Natural Ventilation mode of year 2080

This comparison highlights that while the building's passive design effectively manages thermal comfort in historical conditions, it will face substantial challenges in maintaining comfort under future climate conditions. Therefore, incorporating future weather files into building design is crucial, as buildings designed using only TMY weather conditions may not provide sufficient comfort in the future, necessitating additional or enhanced cooling strategies.

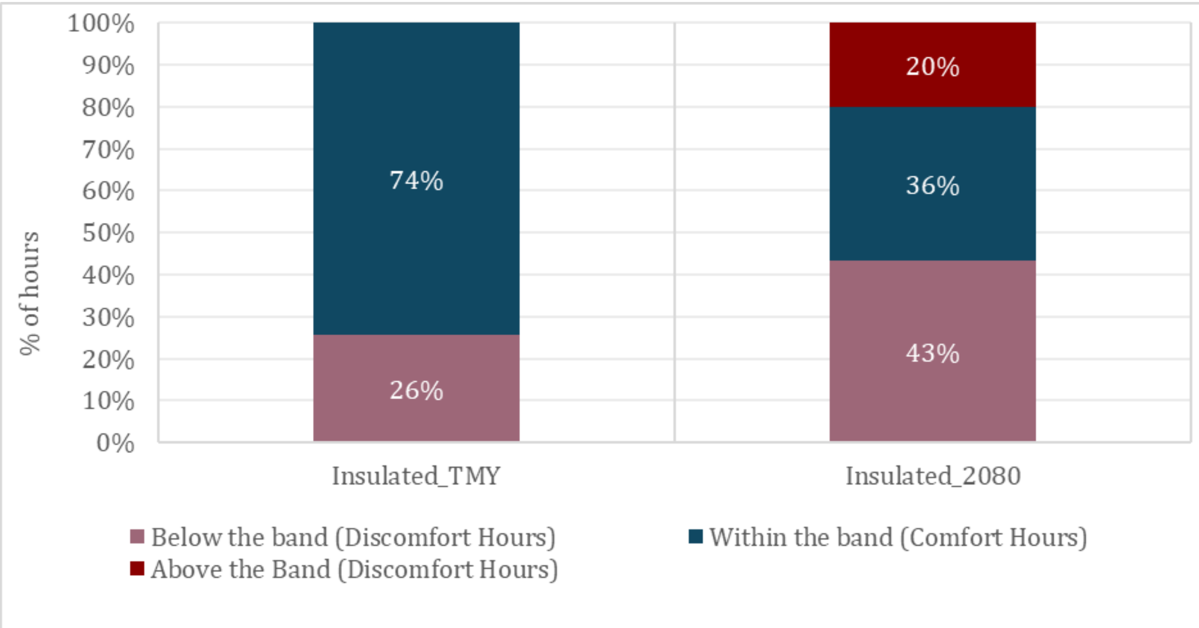

Figure 9: Comparison of Discomfort Hours

4. Conclusion

This study examines the necessity and implications of integrating future weather data into building design, given the challenges posed by climate change. We used predicted weather data for 2080 in Bangalore, and compared them with historical Typical Meteorological Year (TMY) data.

Our findings reveal significant temperature increase of 4°C on an average across all seasons, alongside notable change of 13% on an average for all the seasons in relative humidity: a decrease by 9% in summer and an increase 7% in winter, particularly at night. This indicates a future of hotter, drier summers and warmer, more humid winters.

Our analysis, employing climate-file based tools, demonstrates a substantial shift in comfort hours from the TMY (74%) to the 2080 (36%), with a difference of scenario for both active and passive design strategies. This underscores the importance of adapting building design approaches to future climate conditions rather than relying solely on historical data.

A calibrated Building Energy Simulation (BES) model of a typical Bangalore building confirms that while current passive design features are adequate for today's climate, they may fall substantially short of maintaining thermal comfort under future conditions. The percentage of discomfort hours in the future condition increased by 37%.

Our research highlights the critical role of future weather data in shaping building design and performance of the building to make it resilience in future. As climate conditions evolve, buildings designed with historical TMY data may fail to provide adequate thermal comfort, leading to increased cooling demand and more energy consumption. The study's comparative analysis of future and historical weather files, coupled with the evaluation of design strategies and thermal comfort analysis, emphasizes the need for a proactive approach to incorporate climate change projections of weather patterns into building design and analysis practices. By doing so, we can develop buildings that are not only energy-efficient but also resilient to the changing climate, thereby reducing discomfort hours and contributing to sustainable urban development.

5. Limitation

The Climate Consultant and calibrated BES model analysis is done for one location, and in order to draw an overall conclusion about the impact of changing climate this analysis should be done in multiple locations in different climate zones.

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