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Climate change impact on thermal comfort in Mexico City housing

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Abstract

A two storey terraced house was modelled in ESP-r with a simple window opening control strategy to represent typical dwellings found in Mexico City and the adjoining municipalities. Future weather data was generated for years in this century based on morphing methods developed from the literature and by the authors and a TMY weather file developed from historical data between 1975 to 1989 by WhiteBox Technologies. The population in the region under consideration is a little over 20 million which represents 16% of Mexico's population. The present day climate is such that air conditioning is rarely used in single family housing. The main cooling strategy in the hottest months (Mid February to mid June) is window opening. This was modelled considering that if the interior temperature was at or above 18°C and the exterior air temperature was below the interior air temperature then windows would be open. The air flow was modelled using the flow network model within ESP-r. It was found that in the latter part of the present century, this strategy would become increasingly ineffective. This is likely to lead to a considerable increase in installed air conditioning in single family dwellings and a consequent increase in electricity demand and consumption leading to a need for substantial investments in electricity transmission and distribution systems in the region to bring in power from distant sources.

Keywords: Building energy conservation; Thermal comfort; Climate change

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Abbreviations

h_c Convective heat transfer coefficient at surface (W/m^2K)
p_a Water vapour pressure (kPa)
PMV Predicted Mean Vote
R_t Total thermal resistance of bedding system (m^2K/W)
t_a Air temperature (°C)
t_r Mean radiant temperature (°C)uil

1. Introduction

Mexico City and its adjoining municipalities is the largest urban area in the Mexican Republic being home to a little more than 20 million people [1]. At present the region enjoys a very agreeable climate during most of the year with peak daytime temperatures in April to early June sometimes exceeding 30°C but most of the year these temperatures are in the mid to upper twenties [2]. There is thus little demand for domestic air conditioning at present. However, were the temperatures to rise sufficiently to make the use of domestic air conditioning attractive, then the demands on the power supply infrastructure would increase dramatically. It is unlikely that all of this demand could be met with rooftop photovoltaic panels and local storage. It might be of interest for the sake of medium to long term planning to have an idea of what might happen to the effectiveness of window opening as a means of obtaining thermal comfort.

2. Future climate

Since detailed thermal modelling of buildings requires local hourly meteorological parameters such as temperature, humidity, solar radiation and wind, the results of regional climate modelling cannot be directly used. This necessity has been addressed by various methods which depend to a greater or lesser extent on the local models and measured data available. Historically building thermal simulation has used representative years of hourly data derived from periods of ten to thirty years of measurement. One widely used method is the construction of a typical meteorological year (TMY) made up of selected months of measured hourly data which are close to the monthly average behaviour for the overall period [3]. As part of a wider project a TMY weather file was developed from historical data from between 1975 and 1989 by WhiteBox Technologies for Mexico City. This file was used as the basis for future hourly weather files.

Since Mexico does not have a probabilistic future weather generator as is the UK case [4] then the most readily available option for generating future weather files is the technique of adjusting historically based weather files (e.g. TMY files) on the basis of the results of regional climate modelling. There are several methods of carrying out these adjustments or morphing, one of which is that used for CIBSE´s TM49. The authors programmed this method to work with data from the CMIP5 data sets published via the World Climate Research Programme [5]. There are now a considerable number of research groups' modelling results available and there have been differing approaches to how to use these results for adjusting TMY data to estimate future building thermal behaviour. A series of adjusted files can be produced and ranked in order of the change estimated for a particular meteorological parameter e.g. temperature and then a series of building thermal simulations could be carried out to give a range of possible future impacts on energy use or thermal comfort. However, this does not give any information on the relative likelihood of the scenarios. An alternative approach would be to reduce the number of simulations by finding a criterion to select one or two regional climate models that might be considered most appropriate for the region under consideration. Sheffield et al [6] evaluated the results of the CMIP5 experiments for the North American continent including Central America and Mexico. From the regional climate models that produced the parameters necessary for applying morphing to TMY files it was found that the "Model for Interdisciplinary Research on Climate version 5" (MIRCO5) [7] was best at reproducing (hindcasting) historical temperatures for Central America and Mexico. The monthly average results from the rcp45 r1itp1between 2006 and 2100 were used to generate future TMY weather files for 2020, 2030 successively through to 2100.

3. Representative house

Most housing in Mexico City and its surrounding urban areas is relatively high density, i.e. houses are side by side built up to the edges of each plot. A typical house is a two storey building with a living/dining space and a kitchen space on the ground floor and two bedrooms and a bathroom on the upper floor. The construction used by self-builders is usually reinforced concrete columns within breeze block walls and poured concrete floors and flat roofs. Single glazing is normally used in aluminium frames which are poorly sealed. A representative house was designed for the purposes of this study considering a family of four persons who would be out of the house during working and school hours. Power consumption for a typical range of appliances and equipment was considered together with the use of a gas cooker for the casual gains. LED lighting was taken to be installed since it is likely that in the future less efficient lighting technologies will cease to be used. The house was modelled to face south onto the street and north at the back of the house with the main bedroom having a window to the North as a favourable case and with the bedroom facing West as much less favourable case. At a latitude of 19.4° North the northern façade would receive some direct sunlight at midday during the summer months but an unshaded east facing façade would receive an appreciable amount of direct sun in the afternoon. A casual examination of the predominant street orientations in Mexico City shows that many city blocks in residential zones aligned close to north-south with the long axis of the oblongs close to that north-south orientation. This results in a larger number of houses having east and west facing street side façades.

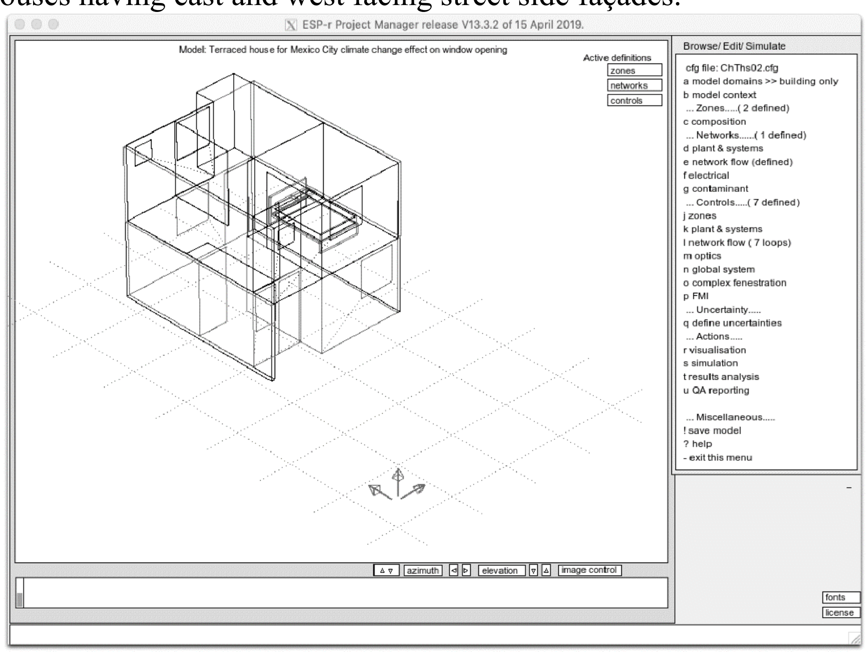

Fig. 1 Modelled two storey house

4. Simulation

The simulation was carried out using the ESP-r suite of programs. This simulation system is particularly apt for situations where building temperatures are free floating or only roughly controlled via strategies such as window opening due to its finite volume, conservation approach [8]. The modelling assumed constant physical properties of the building materials such as density, thermal conductivity and heat capacity. The flow network uses the following equation to model flows through cracks around windows and doors.

Equation 1

$$\dot{m} = \rho k\, \Delta P^{x} (kg/s)$$

where

$$x = 0.5 + 0.5\, exp(500\, W) \quad \text{W = crack width (mm)}$$

$$k = L\ 9.7\,(0.0092)^{x/1000} \quad (m^3/s\ \exists Pa^x) \quad \text{L = crack length (m)}$$

Open windows were modelled as orifices behaving in accordance with equation 2.

Equation 2

$$\dot{m} = C_d A \sqrt[2]{2\rho\Delta P} \quad (kg/s)$$

where

$$C_d = discharge\ factor\ of\ 0.65$$

$$A = opening\ area \quad (m^2)$$

The modelling was carried out on the basis of hourly weather data and four time steps per hour for the thermal and airflow modelling. A comprehensive view of the capabilities and limitations of the ESP-r suite of programs can be found in Hand J. [9]

There are few detailed studies of window opening behaviour in climates such as that of Mexico City. Lai et al [10] studied window opening in residential buildings for a range of climates throughout China. The results were reported as window opening durations and schedules related to four climate categories. Thus the results are difficult to translate into a window opening control function to simulate occupiers' actions. Other researchers have studied occupiers' actions in Danish [11] and UK [12] residential buildings. In the first case the indoor CO_2 levels and the outdoor temperature were the most important factors related to the probabilities of opening and closing windows respectively. However as is usual in Danish construction the hermeticity was likely to have been good in the buildings studied, whereas residential construction in

Mexico City is leaky in terms of outside air infiltration. Indoor air quality is thus a less likely motivator for window opening. In the case of the UK study the principal factors found to drive window operation behaviour were: outdoor and indoor temperature and humidity, wind speed, rainfall, the season and the time of day. In case of Mexico City the outdoor relative humidity is generally fairly low except in the case of heavy rain storms in the afternoon from mid-June to late October when there is an associated temperature drop and little need for extensive window opening to obtain thermal comfort. Wind speeds are generally low in the city with localized gusty wind associated with imminent rain storms, making wind a less important factor than in a maritime climate such as that of the UK. The modelling was carried out assuming a sheltered wind environment as is customary for an urban setting. Season is an undoubted factor in Mexico City but since the seasons are very different from the UK, the effect of temperature during the hot dry period from mid-February to mid-June is likely to be the strongest motivator of window operation in Mexico City housing. Markovic et al [13] have developed a window opening model based on training data from three buildings in the cities of Aachen, Frankfurt and Philadelphia. The authors have made available supplementary information to aid the implementation of their model in building simulation programs. However, the training data set, as in all such deep learning methods, is primordial in determining the resulting model's field of application.

Given that no obviously directly applicable candidates for Mexico City climate and constructions were found in the literature, a three temperature window control strategy was simulated. This was a simple multiple sensor based decision on whether a window would be open or not. Whilst the outdoor air temperature was between 10 and 30°C and the indoor air temperature exceeded 25°C the window was open.

A level of clothing and activity of the occupants was used in the results analysis based on work by Lin & Deng [14,15] on a thermal comfort model for subtropical sleeping environments (Equation 1) and their measurements of insulation values for bedding and sleepwear. None-the-less, these values are notoriously dependent on an individual's or a family's customs therefore the absolute values of PMV are not necessarily typical. However, the changes in the PMV distribution predicted to occur over the course of the rest of this century can inform about the likely consequences of climate change in Mexico City regarding thermal comfort in housing and the probability of increases use of air conditioning. For the night time occupants upstairs, a clothing level of 1.8 clo corresponding to light pyjamas under a light cotton cover turned down to 52% body exposure and 2.7 clo which corresponds to being fully covered, and an activity level of 0.7 met was used. For the upper floor bedroom space an MRT sensor was placed where one might expect the head of someone sleeping in bed to be slightly above the pillow of a bed placed in the model. The temperatures registered for this sensor were used in the calculation of the PMV for a sleeping person. The ground floor spaces were considered to be occupied for a short period in the morning on weekdays and during the daytime for weekends and holidays. The upper floor occupation was considered to be during the evening and night times. PMV was calculated for the occupied hours only. Given that most of the occupancy would occur at night in upper floor it was thought that this would be the space with conditions most likely drive a decision to acquire an air conditioner.

Equation 3

$$PMV = 0.0998 \left\{ 40 \ \frac{1}{R_t} \left[\left(34.6 \ \frac{4.7 \bar{t}_r + h_c t_a}{4.7 + h_c} \right) + 0.3762 (5.52 \ p_a) \right] \right\} \ 0.0998 [0.056 (34 \ t_a) + 0.692 (5.87 \ p_a)]$$

5. Results

Ffigures 2, 3, 4 and 5 show the PMV percentage frequency for the main bedroom using the simple temperature based window opening control strategy. Although the results show that cool temperature sensations would be obtained under the modelling scenario it can be assumed that in practice occupants experiencing cool conditions will compensate by using more bedding and warmer bedclothes. When the thermal sensation is uncomfortably hot with 1.8 clo it would be difficult to reduce the bedclothes and bedding much further. It can be assumed that the use of fans and air conditioning would come under consideration if these conditions are more frequent and/or prolonged.

There is a clear tendency for hotter temperature sensations becoming more common in the latter part of the century. The climate model predicts a respite in rising temperatures in the next decade but after this period the frequency of warm to hot conditions increases significantly. Towards the end of the century there are some occasions with much higher thermal comfort sensations particularly for housing with unfavourable orientations.

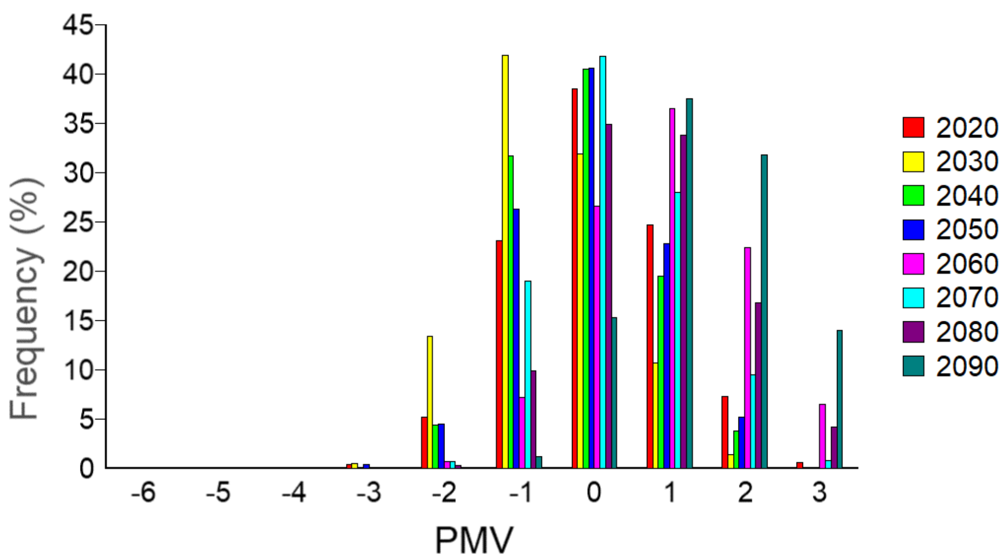

Fig. 2 PMV frequency between 10pm and 6am for a North facing bedroom from February 15th to June 15th. The mean radiant temperature virtual sensor was placed just above the pillow on the bed with a 1.8 clo body clothing insulation level.

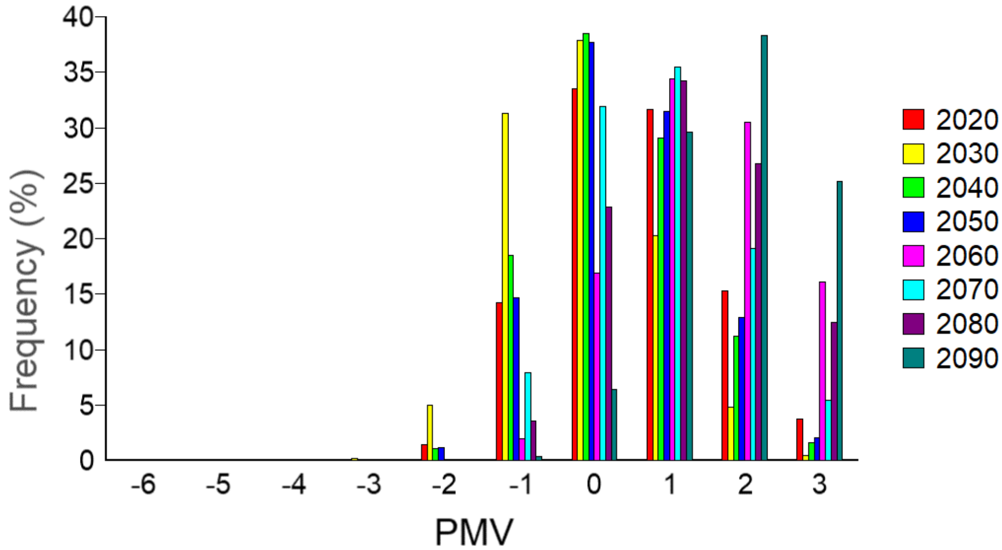

Fig. 3 PMV frequency between 10pm and 6am for an East facing bedroom from February 15th to June 15th. The mean radiant temperature virtual sensor was placed just above the pillow on the bed with a 1.8 clo body clothing insulation level.

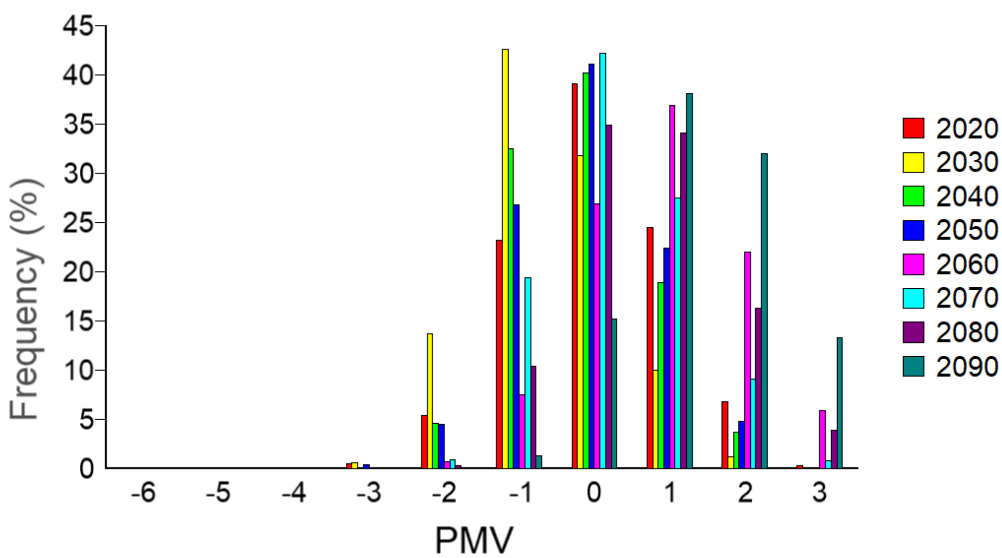

Fig. 4 PMV frequency between 10pm and 6am for a South facing bedroom from February 15th to June 15th.

The mean radiant temperature virtual sensor was placed just above the pillow on the bed with a 1.8 clo body clothing insulation level.

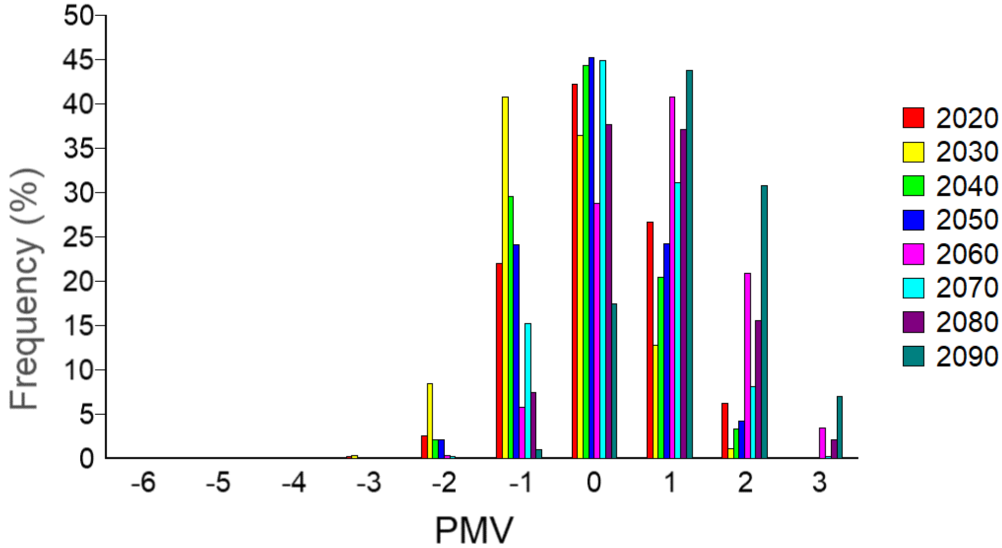

Fig. 5 PMV frequency between 10pm and 6am for a West facing bedroom from February 15th to June 15th. The mean radiant temperature virtual sensor was placed just above the pillow on the bed with a 1.8 clo body clothing insulation level.

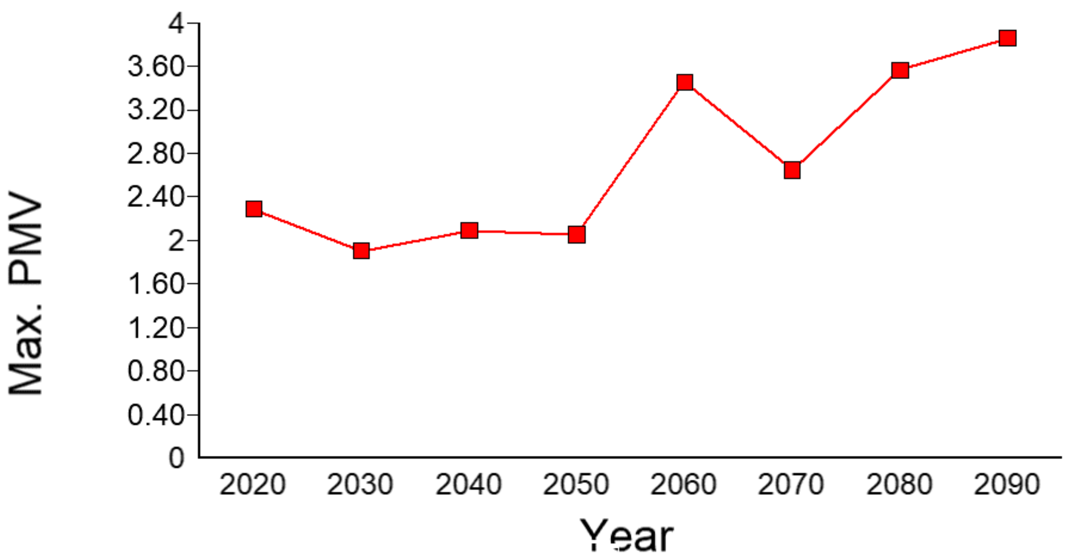

Fig. 6 Maximum PMV during hottest part of the year for a North facing bedroom between 10pm and 6am from February 15th to June 15th. The mean radiant temperature virtual sensor was placed just above the pillow on the bed with a 1.8 clo body clothing insulation level.

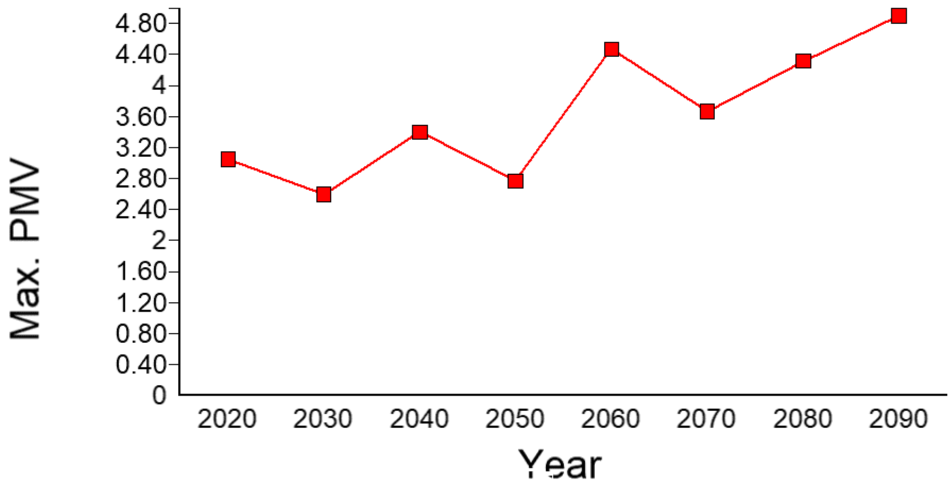

Fig. 7 Maximum PMV during hottest part of the year for an East facing bedroom between 10pm and 6am from February 15th to June 15th. The mean radiant temperature virtual sensor was placed just above the pillow on the bed with a 1.8 clo body clothing insulation level.

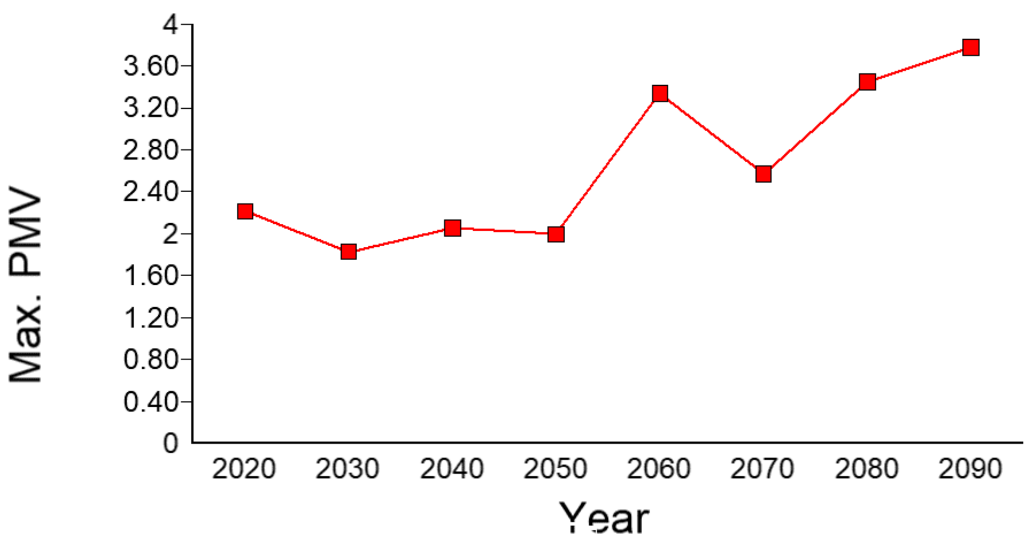

Fig. 8 Maximum PMV during hottest part of the year for a South facing bedroom between 10pm and 6am from February 15th to June 15th. The mean radiant temperature virtual sensor was placed just above the pillow on the bed with a 1.8 clo body clothing insulation level.

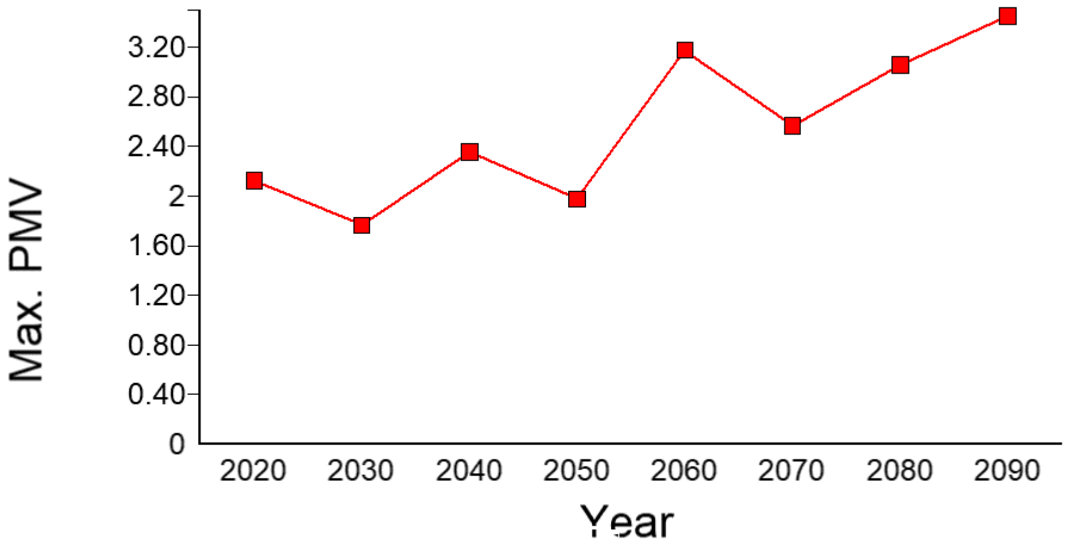

Fig. 9 Maximum PMV during hottest part of the year for a South facing bedroom between 10pm and 6am from February 15th to June 15th. The mean radiant temperature virtual sensor was placed just above the pillow on the bed with a 1.8 clo body clothing insulation level.

The orientation of the modelled house does have an impact on the frequency of higher PMV conditions in the bedroom, but this is a characteristic that is specific to the design of the house. In this case the latitude (19.43° N) means that an unshaded East facing window in June will receive significant direct solar radiation falling on the floor of the bedroom before mid-day and thus store heat to be released later. During June the rainy season has usually started and afternoons are frequently overcast reducing the direct sunshine entering a West facing window. The differences in the PMV frequencies for the four building orientations do show the need for designers to simulate their specific projects with detailed predicted future climate data to gain an insight into the resilience or otherwise of their proposals. However, the changes in the distribution of frequencies of PMV are similar for all four modelled orientations.

In absolute terms the indicated PMV are in the comfortable range but taking into consideration that the control strategy is optimistic in the use of window opening, the clothing assumptions are rational and the modelled house is not particularly prone to overheating, the increase in potentially extreme temperature events would in practice lead to purchase and use of air conditioning units. Once these have been installed, their use would become habitual.

Figures 6, 7, 8 and 9 show the maximum PMV for the main bedroom for the years modelled for the period: 15th February to 15th June which is the usual period of high temperatures for Mexico City. The increase in the maximum values of PMV are indicative of extreme conditions becoming more extreme as the present century progresses. As in other urban areas worldwide more intense heatwaves can cause challenges for local government and health services particularly if the housing design is thermally unsuitable.

6. Conclusions

The combination of weather adjustment and building simulation with a simple window opening control strategy has shown the potential impact of climate change on indoor comfort conditions in housing in Mexico City. Since night time thermal comfort is most important for quality sleep and this is the time of day of most occupancy, the bedroom thermal comfort was thought to be most important in the propensity to use air conditioning. The specific PMV for any given house and occupants will necessarily differ from the results presented here. However, the objective of gaining an insight into the potential changes over the course of this century was achieved. It is clear, that further modelling of a range of housing, clothing and activity levels would be useful.

The conclusions following from the results presented above, are:

- There is reason to be concerned with respect to the potential motivators for the uptake of domestic air conditioning in this extensive urban area.

- When a tipping point on the uptake of domestic air conditioning is reached this will have significant knock-on effects with respect to investments in electric power transmission and distribution in this large urban area.

- Extreme temperatures will cause worse and more frequent overheating events with consequences for public health and local government responses.

- Programmes are necessary to forestall these climate change impacts on housing habitability in Mexico City and the consequences for electric energy consumption, thermal comfort and health.

- A caveat to the results from the present study is that these are based on one regional climate model which has been judged to be the best performer for this region based on the precision of its hindcasting. There is a very high degree of certainty that changes will occur in the way this model predicts: however, the magnitude and speed of these changes will not be exactly as predicted. Whilst carrying out further studies using a range of regional climate models would be desirable, the present results are sufficient to indicate that changes are necessary in building design for Mexico City.

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