# IMPACT OF CLIMATE CHANGE ON INDOOR THERMAL COMFORT OF NATURALLY VENTILATED PUBLIC RESIDENTIAL BUILDINGS IN SINGAPORE

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## 1 ABSTRACT

Public residential buildings in Singapore are designed as naturally ventilated. As climate changes, the indoor thermal comfort becomes critical as it depends greatly on the outdoor weather condition. The Predicted Mean Vote (PMV) model developed for Singapore (Givoni, et al., 2006) which depends on indoor air temperature and air speed is used to predict the indoor thermal comfort. The objectives are to determine the current level of PMV and the future level of PMV due to climate change, and to simulate whether proposed mitigation method on the building envelope can bring back the future PMV level back to current level.

The paper discusses the changes in the indoor air temperature, the indoor air movement and the subsequent thermal comfort due to the climate change by simulating two main typologies of typical public housing, i.e. point block (model Point) and slab block (model Slab), at three different heights of the building (level 2, mid-level and top-level), and under current (reference) and projected weather conditions (future). The 24-hour indoor air temperature is simulated in IES-VE, while the indoor air movement is simulated in CFD Fluent under four external wind scenarios, i.e. Northeast (NE) and Southwest monsoon (SW), ambient prevailing wind (Generic set) and a simulated wind in an estate (Local set).

The changes in indoor air temperature, indoor air speed and the compilation of PMV results are presented in the paper.

The simulation study shows that there is increase of the indoor air temperature, but no significant difference of the indoor air speed due to the climate change. The resulting PMV index shows that climate change causes longer duration of warm thermal discomfort throughout the day. Implementing a mitigation method proposed from other study on cooling load e.g. a combination of lower solar absorption for wall and roof surface, lower u-value of wall and lower shading coefficient of glass, the thermal comfort level on the Top level in each model in the future can be brought back to current level.

## 2 KEYWORDS

Climate change, public residential buildings, natural ventilation, thermal comfort, Singapore

## 3 INTRODUCTION

Public residential buildings in Singapore are designed as naturally ventilated. As climate changes, the indoor thermal comfort becomes critical as it depends greatly on the outdoor weather condition. This paper discusses the impact of climate change on the indoor thermal comfort in the public residential buildings in Singapore. Predicted Mean Vote (PMV) index can be used to predict the mean value of the subjective ratings of a group of people in a given environment. Using the PMV model developed for Singapore which depends on indoor air temperature and air speed, the current level of PMV can be determined, and the future level of PMV due to climate change can be predicted. Mitigation methods on the building envelope to reduce the heat gain are proposed to bring back the future PMV level back to current level.

## 4 METHODOLOGY

### 4.1 The approach of study

The study is based on the PMV model developed for Singapore (Givoni, et al., 2006) as shown below.

$$\text{PMV} = 1.2*((0.4257*\text{Temperature}-12.04) + (0.26-1.231*\text{Wind})) \quad (1)$$

The perception of the PMV value is shown in Table 1.

Table 1: PMV value

| PMV value | Perception |
|---|---|
| 3 to 2 | Hot |
| 2 to 1 | Warm |
| 1 to 0 | Neutral |
| 0 to -1 | Neutral |
| -1 to -2 | Cool |
| -2 to -3 | Cold |

The study found that higher wind speed allows a person to tolerate higher air temperatures and yet still achieve thermal comfort (Givoni, et al., 2006).

The indoor air temperature data were gathered from simulations using Integrated Environmental Solution <Virtual Environment> software. The models were simulated using the historical weather data of year 1990 as Reference Case and then simulated using the projected weather data (Future Case) to predict the increase of indoor air temperature from year 1990. Average indoor air temperature for each room in each unit is used for the analysis. The indoor air speed data were from simulations using CFD Fluent. The models were simulated using historical wind data of year 1990 as Reference Case and projected wind data in the future due to climate change (Future Case), based on Northeast (NE) and Southwest monsoon (SW) for two scenarios, i.e. ambient/ prevailing wind condition (Generic set) and localized wind condition in an estate in Singapore (Local set). Average air speed at 1.20m above the floor for each room in each unit is used for the analysis.

The paper then discusses the changes in the indoor air temperature, the indoor air movement and the subsequent thermal comfort due to the climate change.

## 4.2 The models

There are two models of public residential buildings used in the study, i.e. model for point block (model Point) and model for slab block (model Slab). Model Point is a 40-storey high building with overall window-to-wall ratio (WWR) of 0.108 and east-west orientation WWR of 0.023, while model Slab is a 16-storey high building with overall WWR of 0.114 and east-west orientation WWR of 0.04. The east-west openings are mainly from the bathrooms. Model Point and model Slab are shown in Figure 1 and Figure 2 respectively.

The properties of the models are as follows: the thermal transmittance (u-value) of opaque wall is 2.6087 W/m$^2$K, the u-value of roof is 0.5363 W/m$^2$K, the u-value of ceiling is 2.4275 W/m$^2$K, the solar absorptance of wall and roof surface is 0.70, the u-value of fenestration is 6.9326 W/m$^2$K, and the shading coefficient of glass is 0.7016. Each window has 300mm wide horizontal shading.

Naming of the rooms in each unit of model Point and model Slab can be referred to Figure 1 and Figure 2 respectively. MBR is Master Bedroom, BR1 is Bedroom 1, BR2 is Bedroom 2, K is Kitchen, and LR is Living Room.

The models were simulated as naturally ventilated all the time. The analysis was conducted for low level (Level 2), middle level (Mid level) and top level (Top level) of the block.

## 4.3 The boundary conditions

For the indoor air temperature simulation, the Reference Case is based on historical weather data of 20-year observation. The projected weather data used shows an average increase of 1.3°C.

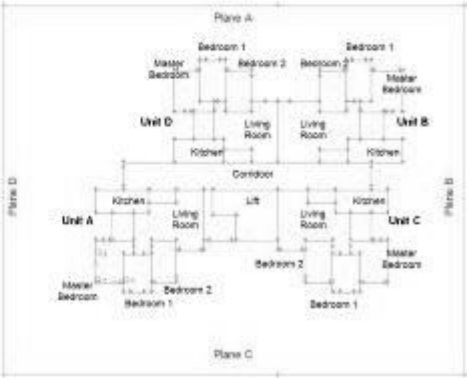
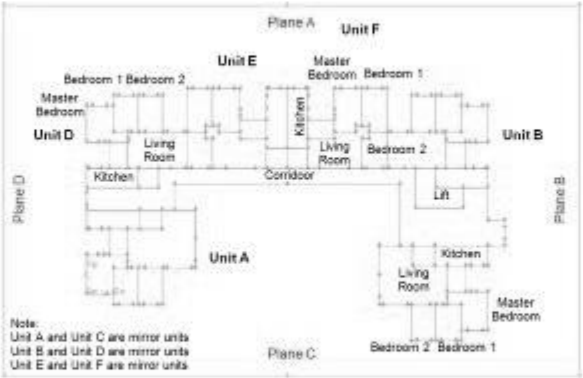


Figure 1: Model Point



Note:
Unit A and Unit C are mirror units
Unit B and Unit D are mirror units
Unit E and Unit F are mirror units

Figure 2: Model Slab

For the air movement simulation, the simulations were performed under turbulence k-ε realizable model with standard wall function. Uniform meshes were used with length of 0.10m. For the Level 2, the plane containing the ceiling of the second level was defined as symmetrical plane. Similarly, for the Top level, the plane containing the floor of the top level was defined as symmetrical plane. For the Mid level, both the planes containing the floor and ceiling of the mid-level were defined as symmetrical planes.

For the Generic set, the external environment is typically a residential unit length away from the block; while for the Kallang set, the external environment is 10m and 8m away from the model Point and model Slab respectively.

## 4.4 The mitigation method

From other study on cooling load using the same models and boundary conditions, a mitigation method was implemented in this study. The mitigation method (Mitigation Case) uses 1.03 W/m$^2$K for u-value of wall, 0.45 for shading coefficient of glass and 0.25 for solar absorptance of both wall and roof. This case uses the projected weather data.

# 5 RESULT ANALYSIS AND DISCUSSION

In average, the impact of climate change is predicted to increase the indoor air temperature of around 1.2°C for all levels in model Point. The mitigation method can reduce the indoor air temperature at Mid and Top levels back to the current level. It only can reduce 0.9°C for Level 2.

Table 2: Range of air temperature across the units for model Point in Reference Case

| | **Level 2** | | **Mid level** | | **Top level** | |
|---|---|---|---|---|---|---|
| **Unit** | **Min (°C)** | **Max (°C)** | **Min (°C)** | **Max (°C)** | **Min (°C)** | **Max (°C)** |
| A | 28.5 | 30.3 | 28.9 | 30.7 | 28.7 | 31.6 |
| B | 28.6 | 30.4 | 29.1 | 30.8 | 28.7 | 31.7 |
| C | 28.6 | 30.3 | 28.7 | 30.7 | 28.7 | 31.7 |
| D | 28.6 | 30.2 | 29.1 | 30.6 | 29.1 | 31.5 |

Table 3: Range of air temperature across the units for model Point in Future Case

| | **Level 2** | | **Mid level** | | **Top level** | |
|---|---|---|---|---|---|---|
| **Unit** | **Min (°C)** | **Max (°C)** | **Min (°C)** | **Max (°C)** | **Min (°C)** | **Max (°C)** |
| A | 29.8 | 31.5 | 30.1 | 31.9 | 29.8 | 32.8 |
| B | 29.8 | 31.6 | 30.3 | 32.0 | 30.3 | 32.9 |
| C | 29.8 | 31.5 | 30.2 | 31.9 | 29.8 | 32.8 |
| D | 29.8 | 31.4 | 30.2 | 31.8 | 30.3 | 32.7 |

Table 4: Range of air temperature across the units for model Point in Mitigation Case

| | **Level 2** | | **Mid level** | | **Top level** | |
|---|---|---|---|---|---|---|
| **Unit** | **Min (°C)** | **Max (°C)** | **Min (°C)** | **Max (°C)** | **Min (°C)** | **Max (°C)** |
| A | 29.5 | 30.6 | 29.6 | 30.6 | 29.4 | 30.8 |
| B | 29.6 | 30.6 | 29.7 | 30.7 | 29.5 | 30.9 |
| C | 29.6 | 30.6 | 29.6 | 30.6 | 29.4 | 30.8 |
| D | 29.6 | 30.6 | 29.6 | 30.6 | 29.5 | 30.9 |

In model Slab, the increase of indoor air temperature is predicted to be around 1.2°C, 0.9°C and 1.1°C for Level 2, Mid level and Top level respectively. The mitigation method can reduce the indoor air temperature at Mid and Top level back to the current level. It only can reduce 0.8°C for Level 2.

Table 5: Range of air temperature across the units for model Slab in Reference Case

| | **Level 2** | | **Mid level** | | **Top level** | |
|---|---|---|---|---|---|---|
| **Unit** | **Min (°C)** | **Max (°C)** | **Min (°C)** | **Max (°C)** | **Min (°C)** | **Max (°C)** |
| A | 28.5 | 30.4 | 28.4 | 30.8 | 28.5 | 32.2 |
| B | 28.5 | 30.4 | 28.4 | 30.8 | 28.5 | 32.2 |
| C | 28.5 | 30.4 | 28.5 | 30.9 | 28.5 | 32.2 |
| D | 28.5 | 30.1 | 28.9 | 30.5 | 28.7 | 31.5 |
| E | 28.7 | 30.2 | 29.1 | 30.7 | 29.2 | 31.6 |
| F | 28.7 | 30.3 | 29.1 | 30.7 | 29.2 | 31.7 |

Table 6: Range of air temperature across the units for model Slab in Future Case

| | **Level 2** | | **Mid level** | | **Top level** | |
|---|---|---|---|---|---|---|
| **Unit** | **Min (°C)** | **Max (°C)** | **Min (°C)** | **Max (°C)** | **Min (°C)** | **Max (°C)** |
| A | 29.7 | 31.6 | 30.0 | 31.9 | 29.7 | 33.3 |
| B | 29.8 | 31.4 | 30.2 | 31.8 | 29.8 | 32.8 |
| C | 29.7 | 31.7 | 29.4 | 30.3 | 29.6 | 33.3 |
| D | 29.8 | 31.4 | 30.1 | 31.7 | 30.2 | 32.7 |
| E | 29.9 | 31.5 | 30.3 | 31.9 | 30.4 | 32.8 |
| F | 29.9 | 31.5 | 30.3 | 31.9 | 30.4 | 32.8 |

Table 7: Range of air temperature across the units for model Slab in Mitigation Case

| | **Level 2** | | **Mid level** | | **Top level** | |
|---|---|---|---|---|---|---|
| **Unit** | **Min (°C)** | **Max (°C)** | **Min (°C)** | **Max (°C)** | **Min (°C)** | **Max (°C)** |
| A | 29.6 | 30.7 | 29.7 | 30.8 | 29.5 | 31.3 |
| B | 29.5 | 30.5 | 29.6 | 30.5 | 29.4 | 30.8 |
| C | 29.6 | 30.8 | 29.7 | 30.9 | 29.5 | 31.3 |
| D | 29.5 | 30.5 | 29.5 | 30.5 | 29.4 | 30.8 |
| E | 29.6 | 30.6 | 29.7 | 30.7 | 29.5 | 30.9 |
| F | 29.6 | 30.6 | 29.7 | 30.7 | 29.5 | 30.9 |

For Generic set, as the ambient wind speeds are fairly high, ranging from a magnitude of 2.52 m/s to 2.87 m/s, the indoor air speeds are correspondingly higher. The maximum air speeds for model Point and model Slab are 1.97 m/s (NE monsoon for Future Case in the kitchen of Unit B on the Mid level) and 2.90 m/s (SW monsoon for Future Case in the living room of Unit F on the Top level) respectively. Comparing between Reference Case and Future Case, no significant difference in indoor air speeds are observed among the units and all three levels for both models.

For Local set, the ambient wind speeds are lower, ranging from a magnitude of 0.07 m/s to 2.35 m/s, and the indoor air speeds are correspondingly lower. The maximum air speeds for model Point and model Slab are 4.21 m/s (SW monsoon for Future Case in the master bedroom of Unit C on the Top level) and 1.44 m/s (NE monsoon for Future Case in the bedroom 2 of Unit C on the Top level) respectively. Comparing between Reference Case and Future Case, the difference in indoor air speeds for model Point are greater, although not very significantly. For model Slab, significant difference is observed during the SE monsoons, where an order of magnitude decrease in indoor air speed across all units is found in the Future Case. Furthermore, the Top level experiences a twofold increase in indoor air speeds for both NE and SW monsoons.

Figure 3 and Figure 4 show the compilation of all hourly PMV results for model Point based on Generic set and Local set wind conditions respectively for different cases. Figure 5 and Figure 6 show the compilation of all hourly PMV results for model Slab based on Generic set and Local set wind conditions respectively for different cases. The compilation is a 24-hour hourly PMV results for all units in the three different levels in a residential model.

In all figures, the left column shows the Reference Case, the middle column shows the Future Case, and the right column shows the Mitigation Case. The rows show different levels of the building and different wind directions. From top to bottom, in Figure 3 and Figure 4, the rows represent Level 2 with NE wind, Level 2 with SW wind, Mid level with NE wind, Mid level with SW wind, Top level with NE wind and Top level with SW wind. In Figure 5 and Figure 6, the rows represent Mid level with NE wind, Mid level with SW wind, Top level with NE wind and Top level with SW wind. In each row, the vertical axis shows the 24-hour of a day, while the horizontal axis shows the different rooms in all units in a building level. Green color represents neutral PMV of between -1 to 1, red color represents warm to hot PMV of between 1 to 3, and blue color represents cool to cold PMV of between -1 to -3.

Figure 3 shows that based on NE wind on Level 2, climate change increases the percentage of warm discomfort from 20% in Reference Case to 55% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 33%.

Based on SW wind on Level 2, climate change increases the percentage of warm discomfort from 21% in Reference Case to 56% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 37%.

Based on NE wind on Mid level, climate change increases the percentage of warm discomfort from 12% in Reference Case to 47% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 30%.

Based on SW wind on Mid level, climate change increases the percentage of warm discomfort from 19% in Reference Case to 49% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 28%.

Based on NE wind on Top level, climate change increases the percentage of warm discomfort from 23% in Reference Case to 51% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 24%.

Based on SW wind on Top level, climate change increases the percentage of warm discomfort from 21% in Reference Case to 56% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 24%.

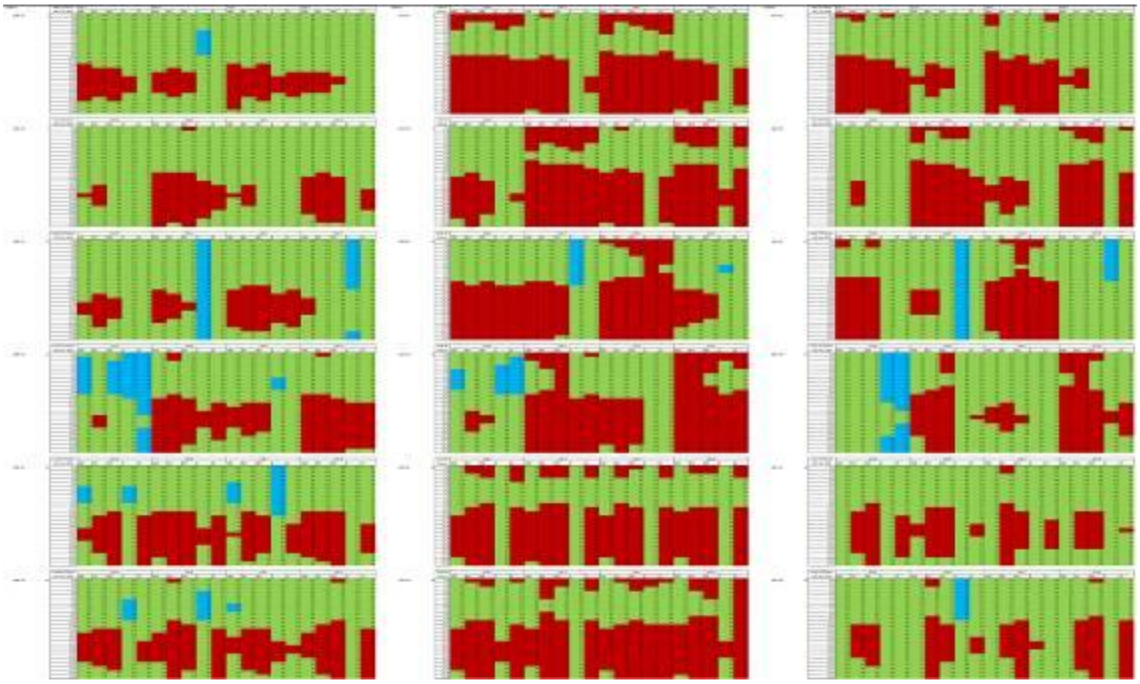


Figure 3: Compilation of PMV results for model Point Generic set: Reference Case (left), Future Case (middle), and Mitigation Case (right)

Figure 4 shows that based on NE wind on Mid level, climate change increases the percentage of warm discomfort from 44% in Reference Case to 75% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future is reduced to 68%.

Based on SW wind on Mid level, climate change increases the percentage of warm discomfort from 33% in Reference Case to 84% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future is reduced to 72%.

Based on NE wind on Top level, climate change increases the percentage of warm discomfort from 14% in Reference Case to 25% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 6%.

Based on SW wind on Top level, climate change increases the percentage of warm discomfort from 12% in Reference Case to 31% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 10%.

Figure 5 shows that based on NE wind on Level 2, climate change increases the percentage of warm discomfort from 7% in Reference Case to 26% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 13%.

Based on SW wind on Level 2, climate change increases the percentage of warm discomfort from 8% in Reference Case to 31% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 14%.

Based on NE wind on Mid level, climate change increases the percentage of warm discomfort from 12% in Reference Case to 8% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 11%.

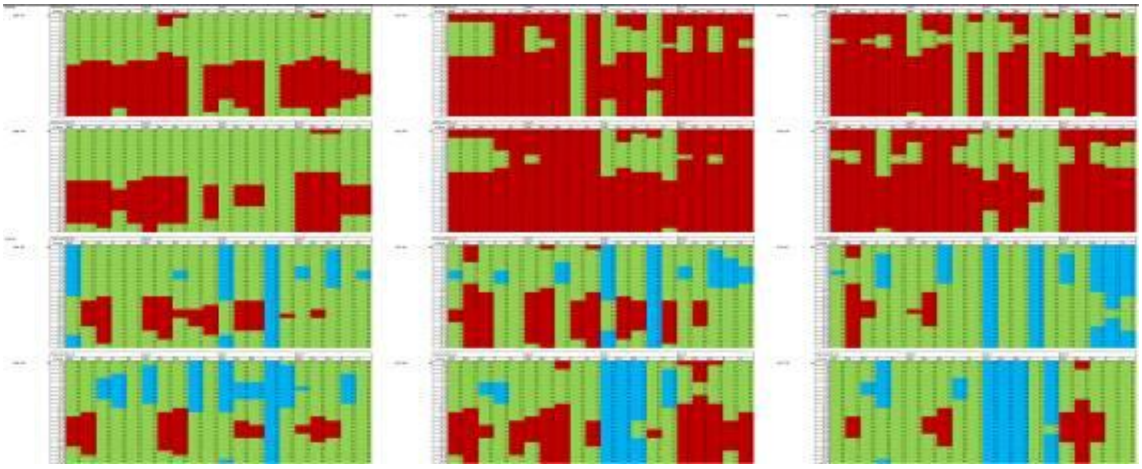


Figure 4: Compilation of PMV results for model Point Local set: Reference Case (left), Future Case (middle), and Mitigation Case (right)

Based on SW wind on Mid level, climate change increases the percentage of warm discomfort from 10% in Reference Case to 28% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 14%.

Based on NE wind on Top level, climate change increases the percentage of warm discomfort from 3% in Reference Case to 9% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 0%.

Based on SW wind on Top level, climate change increases the percentage of warm discomfort from 1% in Reference Case to 13% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 0.3%.

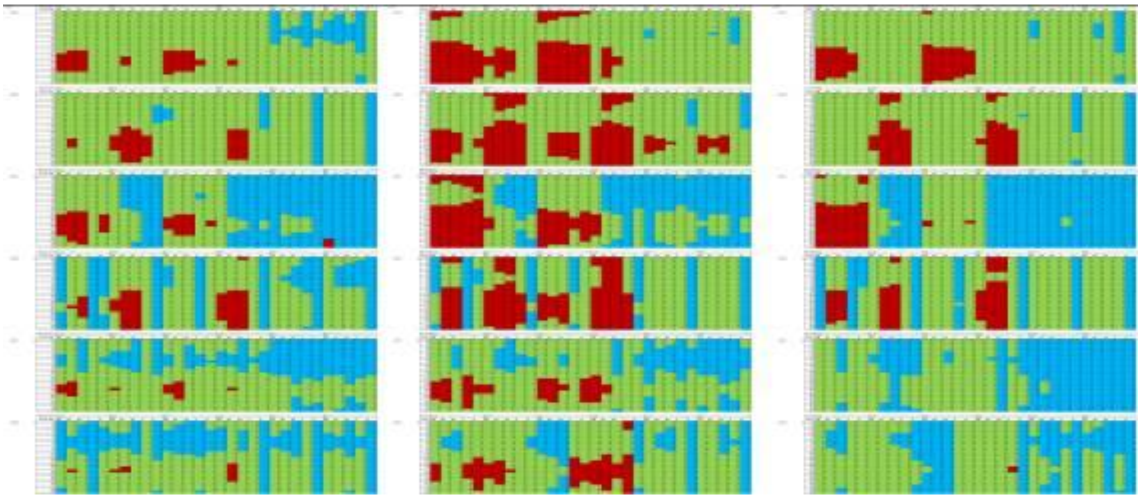


Figure 5: Compilation of PMV results for model Slab Generic set: Reference Case (left), Future Case (middle), and Mitigation Case (right)

Figure 6 shows that based on NE wind on Mid level, climate change increases the percentage of warm discomfort from 56% in Reference Case to 95% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future is still at 92%.

Based on SW wind on Mid level, climate change increases the percentage of warm discomfort from 36% in Reference Case to 99% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future is still at almost 100%.

Based on NE wind on Top level, climate change increases the percentage of warm discomfort from 50% in Reference Case to 70% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 34%.

Based on SW wind on Top level, climate change increases the percentage of warm discomfort from 57% in Reference Case to 71% in Future Case, but by implementing Mitigation Case, the percentage of warm discomfort in the future can be reduced back to 36%.

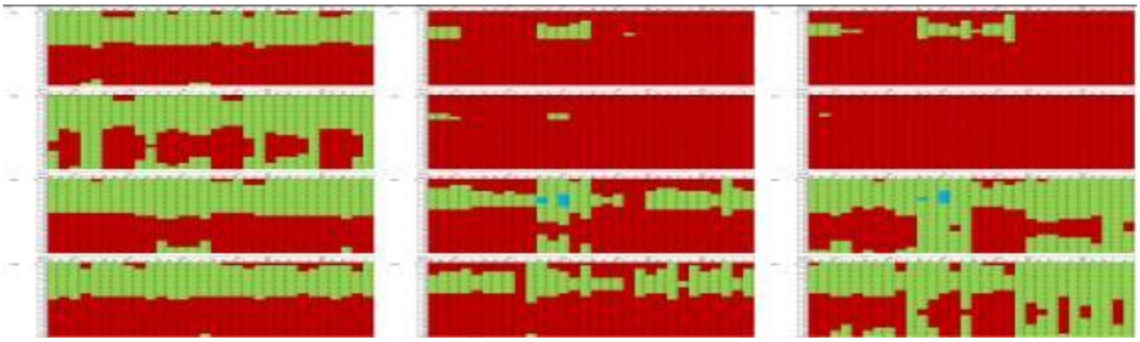


Figure 6: Compilation of PMV results for model Slab Local set: Reference Case (left), Future Case (middle), and Mitigation Case (right)

In overall, the thermal comfort becomes warmer more frequently for all the units in a particular floor in Future Case due to climate change, but with implementing mitigation methods in Mitigation Case, the thermal comfort condition in the future, except for Local set at Mid level, can be brought back to current level.

The thermal comfort condition on the Top level is better than the Mid level as the mitigation method which provides insulation works on both roof and wall for the Top level, compared with only on wall for the Mid level.

## 6 CONCLUSION

Using PMV model for Singapore, the impact of climate change on the indoor thermal comfort of naturally ventilated public residential buildings in Singapore has been analysed. The main variables are the indoor air temperature and indoor air movement. Using historical weather data as Reference Case and projected weather data and wind condition as Future Case, the changes in the indoor thermal comfort have been analysed. Mitigation Case analysis which combines a lower solar absorption for wall and roof surface, lower u-value of wall and lower shading coefficient of glass has also been done to see whether the mitigation method can improve the indoor thermal comfort on the Top level in the future back to the current level.

Air temperature simulations were conducted. The results show that there is increase in indoor air temperature due to climate change. Due to the insulation provided by the mitigation method, the Mitigation Case reduces the maximum air temperature in the Future Case.

Air movement or wind speed simulations were conducted based on two wind conditions, i.e. prevailing wind condition (Generic set) and localized wind condition (Local set) as a representative of residential area. The unit arrangements of each model are found to significantly affect the average indoor air speed, and cross ventilation is found to have increased the indoor air speed.

The calculation of PMV shows the there is increase of percentage dissatisfaction towards warm or hot sensations due to climate change. Implementing the Mitigation Case can only help to bring down the discomfort level on the Top level back to the current level. The mitigation method is less effective on the Mid level due to the lower wind speed and the less insulation effect. Further study can be carried out to assess if mitigation methods such as introducing a “void deck” or sky garden at the Mid level will improve ventilation for Mid level units.

From the study, besides improving the insulation of the opaque walls to reduce solar heat gain, it is recommended to optimize cross ventilation as it helps to increase wind speed through the units and improve thermal comfort. It is to be reminded that all the simulations were conducted based on ideal situation on which all windows are fully opened during natural ventilation period, and did not consider occupants’ behavior to close the windows.

## 7 ACKNOWLEDGEMENTS

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## 8 REFERENCES

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