# Identifying suitable general circulation model for future building cooling energy analysis

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**Abstract.** These future building energy studies mainly stem from hourly based dynamic building simulation results with the future weather data. The reliability of the future building energy forecast heavily relies on the accuracy of these future weather data. The global circulation models (GCMs) provided by IPCC are the major sources for constructing future weather data. However, there are uncertainties existed among them even with the same climate change scenarios. There is a need to develop a method on how to select the suitable GCM for local application. This research firstly adopted principal component analysis (PCA) method in choosing the suitable GCM for application in Taiwan, and secondly the Taiwanese hourly future meteorological data sets were constructed based on the selected GCM by morphing method. Thirdly, the future cooling energy consumption of an actual office building in the near (2011-2040), the mid (2041-2070), and the far future (2071~2100), were analysed. The results show that NorESM1-M GCM has the lowest root mean square error (RMSE) as opposed to the other GCMs, and was identified as the suitable GCM for further future climate generation processing. The building simulation against the future weather datasets revealed that the average cooling energy use intensity (EUIc) in Taipei will be increased by 12%, 17%, and 34% in the 2020s, 2050s, and 2080s, respectively, as compared to the current climate.

# **1** Introduction

The constant changing climate due to global warming in recent years brings great attentions on the studies not only on the future building energy consumption trends, but also desire to seek potential adaptation measures in order to minimize the excessive building energy usage impacted by the climate change. A literature review done by Santamouris [1] revealed that the building cooling energy may increase by 34% and 61% in 2050 and 2100, respectively, as compared to that in 2010. Numerous researches has emerged in recent years to study the effect of future climatic influences on the building energy in order to formulate adaptive measures to cope with the rising building energy issue.

In the study of projecting future building energy use, the hourly future meteorology data is required to study the effect by the changing climate. These future climate data is generally prepared and downscaled from the GCMs, in which the monthly meteorological data are usually provided. In 2005, Belcher [2] suggested a method on how to construct an hourly future climate data set for building simulation application based on the morphing method. However, as there are several GCMs provided by the Intergovernmental Panel on Climate Change (IPCC) and readily available, each provides monthly averaged projections of meteorological variables till the end of the 21st century with four climate change scenarios in the fifth assessment report (AR5), it is necessary to identify which GCM is suitable for application in Taiwan. The objective of this study is to establish a method to identify suitable GCM for local use exclusively for building energy simulation. Furthermore, we further constructed the future hourly climate data based on the identified GCM and studied the potential cooling energy variation of an actual office building.

# 2 Methodology

## 2.1 General circulation models (GCMs)

This study used the GCM data obtained from the IPCC data distribution centre as bases to construct the regional future climate. Each GCM database comprises historical data (1968-2100) together with three future scenarios (RCP2.6, RCP4.5, and RCP8.5). By firstly screening the weather elements provision and the data robustness among the available GCMs, six GCMs were selected as candidates, which are BCC-CSM1.1 (China), CanESM2 (Canada), GISS-E2-H (USA), IPSL-CM5A-LR (France), and MRI-CGCM3 (Japan). Furthermore, a statistical method, the Principal Component Analysis (PCA), is adopted to analyze the projected historical climate conditions of those GCMs against the observed local meteorology data to identify the most suitable GCM with its predicted climate is best corresponds to the long-term

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meteorological trend in Taiwan in order to produce the regional future weather data.

#### 2.2 PCA as a means for suitable GCM selection

Previous researches [3, 4] adopted the PCA technique to subtract the climatic feature from the multivariable weather database to discuss the relationship between the climate change and the building energy usage. In these study, the PCA was used considering weather variables, including the dry bulb temperature (DBT), the specific humidity (HUSS), the global solar radiation (GSR), and the wind velocity (WV), to analyze the composition characteristics among the GCM candidates and the observed weather. Afterwards, we use the first principal component score as a criterion to determine how the climatic features of each GCM fits the local weather variation in Taipei and Kaohsiung.

# 2.3 Generating downscaled hourly future weather data

The identified GCM was further temporally and spatially downscaled to meet the temporal resolution required by the dynamic building simulation tools, *i.e.* EnergyPlus herein. Therefore, the morphing method [2] is introduced to generate the hourly future weather data based on the existing local typical meteorological year (TMY) and the predicted future weather variations provided in the identified GCM. As there are two distinct climatic zones in Taiwan, Taipei's TMY and Kaohsiung's TMY were used in this study to represent the subtropical northern and tropical southern Taiwan, respectively.

The morphing method is one of the statistical downscaling methods, since it predicts the future climate trend based on the locally TMY by the monthly climatic anomalies of GCM scenarios. Considering the differences of the fluctuation characteristics among the weather variables, the morphing method suggests the following three modification methods, which are (1) the shifting, (2) the stretching, and (3) the combination of shifting and stretching, to alter the hourly local data in TMY with the future monthly changes given in the identified GCM data. The mathematical expressions of the three methods are given below from equation (1) to (3), respectively. By means of the morphing method, the downscaled weather data can not only match the resolution for building energy simulation but also involve both the features of local data and the GCM prediction.

$$x = x_0 + \Delta x_m \tag{1}$$

$$x = \alpha_m \cdot x_0 \tag{2}$$

$$x = x_0 + \Delta x_m + \alpha_m \cdot \left(x_0 - \overline{x_0}_m\right) \tag{3}$$

where x is the morphed future weather data;  $x_0$  denotes to the local historical observed meteorological data; subscript m denotes to the month,  $\Delta x_m$  is the monthly difference between the future weather and the historical weather;  $a_m$  is the ratio of the fluctuation amplitude between the future and the historical weather data;  $\overline{x_0}_m$  is the monthly averaged values of the historical observed weather data. One should note that the historical data herein is the hourly data obtained from the local TMY.

#### 2.4 Building model for simulation

To quantify the effect of the changing climate on the building cooling energy variation, EnergyPlus is implemented in this study as a tool for building energy simulation under future climate change scenarios using the constructed hourly future meteorological data. A five-story existing office building is considered, the physical appearance of the building is as **Fig. 1**.

The total floor area of this reinforced concrete building is 4728.9 m<sup>2</sup>, and the building orientation is 30 degree west to the south. The U-value of the exterior wall, the fenestration, and the roof constructions are 3.49, 6.16, and 0.75 W/m<sup>2</sup>K respectively. The widow-to-wall ratio is 40%. The amount of the indoor heat gain is defined by the area density of the occupants, the lighting power, the equipment nominal power, and are 0.2 person/m<sup>2</sup>, 15 W/m<sup>2</sup>, and 10 W/m<sup>2</sup>, respectively. The airconditioning system is a 150 USRT water-cooled centrifugal chiller with the COP value being 6.5. The airside system is a constant air flow volume air handling unit (AHU) system. The indoor temperature set points are 26°C in summer and 22°C in winter. The building is operated as a typical office building, the operation hours of the air-conditioning system is between 08:00 to 17:00 on weekdays and is not in operation on weekends and holidays.



**Fig. 1.** A typical office building is used for studying the future climate impact on its annual cooling energy consumption.

## 3 Results and discussions

#### 3.1 The identified GCM and its PCA results

The features of historical weather data in both Taipei and Kaohsiung are revealed by PCA, and the first principal

component (PC) score is used as the criterion for GCM selection because of the eigenvalue of the first principal component is above 80% of the cumulative variance explained.

The specific humidity (HUSS), the global solar radiation (GSR), the dry bulb temperature (DBT), and the wind velocity (WV) were chosen as four main weather variables for PCA. Before the PCA process, the weather variables were firstly standardized in order to compare with each to reveal their relative importance. The variable standardization is done by using the variation ranges of each weather variable terms given in the equation (4). The PC score (Z) is therefore calculated via equation (4) with the coefficients a to d, which are statistically calculated by PCA. The subscript *min* and *max* are the monthly minimum and maximum values of the corresponding variables.

$$Z = a \cdot \left[ \frac{2(HUSS - HUSS_{\min})}{HUSS_{\max} - HUSS_{\min}} - 1 \right] + b \cdot \left[ \frac{2(GSR - GSR_{\min})}{GSR_{\max} - GSR_{\min}} - 1 \right] + c \cdot \left[ \frac{2(DBT - DBT_{\min})}{DBT_{\max} - DBT_{\min}} - 1 \right] + d \cdot \left[ \frac{2(WV - WV_{\min})}{WV_{\max} - WV_{\min}} - 1 \right]$$
(4)

The coefficients from *a* to *d* of the first to the fourth principal component scores (Z) are summarized in Table 1. The eigenvalue of the first principal component is far larger than the second component either for Taipei or Kaohsiung case. The explanation capability of the first principal component is 80.48% and 75.72%, respectively for Taipei and Kaohsiung. The additional explanation by adding the second principal component is only increased by 13.5% to 18.0%. It suggests that in order to simplify the process of identifying the suitable GCMs against the local TMY, using the first component for the meteorological suitability evaluation is suffice enough. In the first principal component, the coefficients of the specific humidity and the dry bulb temperature are the top two higher than those of the other meteorological variables either for Taipei or Kaohsiung case. It indicates that the weighting of the specific humidity and the dry bulb temperature are higher during the identification process of the suitable GCM and are considered the dominant variables.

According to the equation (1), the principal component score of each GCM of both cities in Taiwan are calculated and are used for error analysis. The suitable GCM for Taiwan is determined by the one who has the smallest total RMSD in Taipei and Kaohsiung. Each GCM's RMSD results are listed in Table 2. By observing the smallest RMSD for each places, the most suitable GCM for Taipei is the BCC-CSM1.1m and the NorESM1-M is suitable for Kaohsiung. However, the total RMSD of the NorESM1-M is 0.5295, which is the smallest among all the six GCM candidates while two places' RMSD is considered, and is identified as the most suitable model to further used as a base for the future hourly weather data generation. Consequently, the hourly future meteorological years are generated by the morphing method based on NorESM1-M for the further usage in the building energy simulation.

Table 1. T	The PCA	analysis	results of	of the	historical	observed
		wea	ther dat	a		

	Principal component score (Z)					Eigen-	Cumulative
Location	No.	HUSS	GSR	DBT	WV	value	explanation (%)
	1st	0.662	0.394	0.617	-0.161	0.698	80.48
Tainai	2nd	0.071	0.040	0.155	0.985	0.117	13.51
Taipei	3rd	-0.391	0.907	-0.156	0.016	0.047	5.42
	4th	-0.636	-0.142	0.756	-0.068	0.005	0.59
	1st	0.712	0.251	0.656	0.017	0.682	75.72
Kaohsiung	2nd	-0.037	0.432	-0.149	0.889	0.163	18.04
	3rd	-0.288	0.856	-0.005	-0.429	0.050	5.59
	4th	-0.640	-0.130	0.740	0.161	0.006	0.65

 Table 2. The RMSD results of the GCM candidates against the local TMY of Taipei and Kaohsiung.

Model	Taipei	Kaohsiung	Total error
BCC-CSM1.1m	0.2693	02660	0.5353
CanESM2	0.3277	0.3002	0.6279
GISS-E2-H	0.3250	0.3280	0.6529
IPSL-CM5A-LR	0.2605	0.3194	0.5799
MRI-CGCM3	0.3658	0.2882	0.6540
NorESM1-M	0.2785	0.2510	0.5295

#### 3.2 Building performance in the future

The weather data bank based on NorESM1-M is produced and is applied to building simulation through EnergyPlus. The results are classified into four time slices, which are the 2000s (1998-2012), the 2020s (2013-2040), the 2050s (2041-2070), and the 2080s (2071-2100). The average annual total cooling energy under three scenarios and in these three time slices are illustrated in **Fig. 2** and **Fig. 3**. In the figures,  $\Delta$ DBT is the difference between the certain future time slices to that in the year of 2000, while the annual total cooling energy in the future is expressed as cooling energy usage intensity (EUIc) with the absolute values.

The  $\Delta DBT$  in Taiwan varies with different scenarios. In 2080s, the  $\Delta DBT$  under RCP2.6, RCP4.5, and RCP8.5 are 2.20, 2.68, and 4.22°C in Taipei and are 1.61, 2.66, and 3.84°C in Kaohsiung. The cooling energy consumption in 2000s is 122.78 and 149.97 kWh/m<sup>2</sup>•yr in Taipei and Kaohsiung, respectively. However, it will increase much higher in Kaohsiung than in Taipei under either future scenarios. Before 2040, there is no significance difference among three scenarios in the cooling energy increase. It only increases by 7-9% in Taipei and 12-13% in Kaohsiung. In contrast, the cooling energy consumption is rapidly rising after 2040. Take RCP8.5, which is the severest climate change scenario, as an example, the cooling energy in Taipei and Kaohsiung will rise 26.66 and 36.03 kWh/m<sup>2</sup>•yr in 2050s as compared to 2000, while it will increase by 42.22 and 52.57 kWh/m<sup>2</sup>•yr in the 2080s, which are equivalent to a 34% and 35% increase as compared to the level in the year of 2000.

It seems that northern and southern Taiwan may obviously be impacted by the future climate. According to the future variation trend of the temperature and cooling energy, there is an apparent climate change impact on the cooling energy consumption of office buildings in Taiwanese cities. Therefore, it's urgent that Taiwan's government should take initiatives to formulate adaptive strategies of the building sector in response to the future climate change in order to neutralize the drastic rising of the future cooling energy demand.



Fig. 2. The future annual cooling energy and the average temperature variations in Taipei.



Fig. 3. The future annual cooling energy and the average temperature variations in Kaohsiung.

# 4 Conclusion

In this study, we identified the Norwegian NorESM1-M is the best suitable GCM for application in Taiwan by the PCA approach. The hourly future weather dataset with three climate change scenarios till 2100 for both northern Taipei and southern Kaohsiung were accordingly constructed. An actual office building with typical layout were further simulated with the constructed future weather years. The results showed that although the average temperature will increase by 2.20°C, 2.68°C, and 4.62°C in 2080s as compared to that

in 2000s for RCP2.6, RCP4.5, and RCP8.5 scenarios in Taipei, respectively. For the worst scenario RCP8.5, the office building's annual cooling energy will be increased by 34% and 35%, respectively, in Taipei and Kaohsiung. It indicates how vulnerable of the buildings are in facing with future climate change. The research results make possible of the building energy forecast in response to the future climate, and by that it may facilitate formulating adaptation or countermeasures to neutralize the building energy consumption affected by the changing climate.

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 Table 2. Climatic and the cooling energy variations in the three future climate change scenarios in 2080s.

Location	(Nortl	Taipei nern Taiwan)	Kaohsiung (Southern Taiwan)		
Climate change scenarios	ΔT (°C)	Annual cooling energy increasing ratio	ΔT (°C)	Annual cooling energy increasing ratio	
RCP2.6	2.20	12%	1.61	15%	
RCP4.5	2.68	17%	2.66	21%	
RCP8.5	4.62	34%	3.84	35%	

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