Energy and Buildings 157 (2017) 218–226

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Prediction of the impacts of climate change on energy consumption for a medium-size office building with two climate models

Liping Wang[a,*], Xiaohong Liu[b], Hunter Brown[b]

[a] Civil and Architectural Engineering, University of Wyoming, 1000 E University Ave, Laramie, WY 82071, United States
[b] Atmospheric Science, University of Wyoming, 1000 E University Ave, Laramie, WY, 82071, United States

ARTICLE INFO

Article history:
Received 8 October 2016
Received in revised form
12 November 2016
Accepted 4 January 2017
Available online 7 January 2017

Keywords:
Building energy simulation
Climate change
Mixed-mode ventilation

ABSTRACT

The paper presents an energy simulation-based study to investigate the impacts of climate change on energy consumptions of an office building located in five different cities, United States. Annual energy consumption of a medium-size office building was predicted by building energy simulation software—EnergyPlus using TMY3 weather data and future climate data. In this study, we have used two sets of further climate data with different climate models including (1) Hadley Centre Coupled Model, version 3 (HadCM3), and (2) NCAR Community Earth System Model version 1 (CESM1) with the Community Atmosphere Model version 5 (CAM5). A morphing method was applied to downscale the monthly weather forecast to hourly forecast for use in building energy simulation for the two General Circulation Models (GCMs): HadCM3 and CESM1. Using the generated future weather files, HVAC operation related mitigation measures including adjustment of thermostat setpoints, reduced HVAC operation hours, reduced VAV box minimum flow setting, and mixed-mode ventilation were simulated to compare with ASHRAE Standard 90.1 baseline simulated using TMY3 weather data. Simulation results on predicted whole building, heating and cooling energy consumptions were examined. The paper highlighted the importance of efficiently operating mechanical systems in buildings to ensure a more sustainable future.

1. Introduction

Global warming, one important aspect of climate change, refers to a gradual increase in average surface temperatures near the Earth's surface. The major cause of global warming or climate change is the increased greenhouse gas emission in the atmosphere associated with human activities. Researches were conducted to understand the impacts of climate changes on building energy use and building design and to investigate mitigation measures to climate changes. Kikumoto et al. [1] constructed weather files based on future climate data via a dynamical downscaling method, predicted from version 4 of the Model for Interdisciplinary Research on Climate (MIROC) and the Weather Research and Forecasting (WRF). The energy simulation software TRNSYS was used to predict the energy performance of a detached house in Tokyo, Japan for the present (2007) and the future (2034). The simulation results indicated that the cooling demand was increased by 15% from the present to the future. van Hooff et al. [2] evaluated the effectiveness of six passive climate change adaptation measures using energy simulation software—EnergyPlus—for three generic residential buildings in the Netherlands. The six passive climate change adaptation measures are (1) increased thermal resistance; (2) changed thermal capacity; (3) increased short-wave reflectivity (albedo); (4) vegetation roofs; (5) solar shading; and (6) additional natural ventilation. Wang and Chen [3] generated weather files for three future typical meteorological years: 2020, 2050, and 2080 using the HadCM3 General Circulation Model (GCM) for 15 cities in the U.S. based on three CO_2 emission scenarios. A morphing method was used to scale the weather data predicted by HadCM3 to hourly data for building energy simulation. EnergyPlus was used to simulate two types of residential buildings and seven types of commercial buildings in the 15 cities for past, current and future climates and to evaluate the impacts of climate change on building heating and cooling energy uses. The study concluded that a net increase in source energy uses would probably occur by the 2080 s for climate zones1-4 and a net decrease would probably occur by the 2080s for climate zones 6–7 based on future climate projections.

* Corresponding author.
E-mail address: lwang12@uwyo.edu (L. Wang).

http://dx.doi.org/10.1016/j.enbuild.2017.01.007
0378-7788/

A few important researches to investigate the impacts of urban heat island and climate changes on building energy use have been conducted. Santamouris et al. [4] reviewed existing studies on the impacts of urban heat island and global warming on the peak electricity demand in a comparative way. The analysis of existing studies showed that for each degree of ambient temperature increase, the increase in peak electricity load varies between 0.45% and 4.6%, and the increase in electricity consumption per degree of temperature increase varies between 0.5% and 8.5%. Kolokotroni et al. [5] created twenty weather files through London, which represent specific locations within the London urban heat island effect based on measurements and predictions and were subsequently constructed using the morphing method according to 2050s UKCIP02 climate change medium-high emission scenario. The authors used the CCWeatherGen tool [6] to carry out the morphing process. A typical office building in London was simulated with an energy simulation program (IESVE) using the developed weather files. They concluded that buildings in London were likely to have an increasing demand of cooling in buildings due to climate change and the urban heat island effect, and heating demands decrease in 2050s due to increased outdoor air temperature. Chan et al. [7] proposed an approach to modify typical meteorological year 3 (TMY3) weather file taking into account the urban heat island effect in summer. They determined the urban heat island intensities by field measurement in summer. A morphing method is applied to modify the existing TMY3 weather files for energy plus. An increase of 10% cooling demands for an office building and a typical residential flat in Hong Kong was identified through building energy simulations.

In this paper, we investigated the impacts of climate change on building energy use of a medium-size office building using an energy simulation program—EnergyPlus. First, we created weather files in the format of '.epw' representing future climates using two different climate models: (1) Hadley Centre Coupled Model, version 3 (HadCM3) with A2 scenario, which represents higher emissions and results in high levels of climate change and (2) NCAR Community Earth System Model version 1 (CESM1) with the Community Atmosphere Model version 5 (CAM5) considering the Representative Concentration Pathway (RCP) 2.6, RCP4.5, and RCP8.5, which represent low greenhouse gas emission, intermediate emission and high emission. Second, we simulated the medium-size office building using the TMY3 weather files as our baseline and future weather files. Third, building energy simulations were further conducted with various mitigation scenarios of HVAC operations to climate changes. Fourth, we analysed the simulation results on whole building energy consumption, cooling and heating energy consumption and compared the results among the two climate models. Finally, we drew the conclusion and highlighted the importance of energy efficient building operations to counteract climate change.

2. Methodology

2.1. Weather files for future climate

We selected five cities: Miami, Florida; Phoenix, Arizona; Los Angeles, California; Washington DC; and Akron, Colorado for our study representing ASHRAE climate zones 1A, 2B, 3B, 4A, and 5B, respectively. We employed the future climate data from two different climate models (HadCM3 and CESM1) in this study to evaluate the impact of climate change on building energy consumption. Both HadCM3 and CESM1 are General Circulation Models (GCM).

The emission scenarios used in HadCM3 are Special Report on Emissions Scenario (SRES) A1, A2, B1, and B2 scenarios. The SRES A2 scenario follows a storyline that describes less trade and more self-reliance, slow technological change and consolidated economic regions [8]. The emission scenarios used in CESM1 (CAM5) are RCPs 2.6, 4.5, 6.0, 8.5. These RCPs, taking into account patterns of economic growth, population change, technology development, and other factors, superseded SRES. RCPs describe different mitigation scenario implementations that affect the ongoing emission and time evolution of GHGs, while being selected to represent stabilization, mitigation, and reference emission scenarios in current scientific research [9]. Their titles assume a rough estimate of the radiative forcing, following the given mitigation scenario, in the year 2100 (e.g. RCP2.6 corresponds to a radiative forcing of 2.6 $W\,m^{-2}$) [10,11]. Compared to the RCP scenarios, SRES A2 has slightly larger carbon emissions than RCP6.0 in the early 2000s, which increase to values more similar to RCP8.5 by 2100 [12].

We have generated future weather data files for 2020s, 2050s and 2080s from HadCM3 A2 scenario, and future weather data files for years 2020–2089 from CESM1 for RCP2.6, RCP4.5 and RCP8.0. In total, we have 213 future weather files for each city.

The future climate data obtained from climate models are usually in monthly interval. Morphing method [13] is commonly be applied to down-scale the monthly changes to hourly changes for weather data. There are three typical functions, which can be applied for the down-scale process, as written in Eqs. (1)–(3) for shift, linear stretch, and a combination of shift and linear stretch, respectively. Shift function can be applied to the parameter such as atmospheric pressure when creating future hourly weather data. Linear stretch function can be applied to the parameters such as relative humidity, wind speed and total sky cover. A combination of shift and linear stretch function can be applied to the parameter such as dry bulb temperature.

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

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

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

Where x_0 is the hourly weather data for a variable from an existing reference weather file (e.g. TMY3 weather file), Δx_m is the predicted monthly mean change for a variable obtained from future climate models, α_m is a stretching/scaling factor calculated based on changes of monthly mean value of a specific variable from future weather files relative to the existing reference weather file, and $(x_0)_m$ is the monthly mean value of a specific variable in the existing reference weather data.

2.1.1. Weather files generated from HadCM3 future climate data

HadCM3 (Hadley Centre Coupled Model, version 3) was developed at the Hadley Centre in the United Kingdom. HadCM3 includes the atmospheric model HadAM3 and the ocean model HadOM3. It has a spatial resolution of 2.5° x 3.75° (latitude by longitude). We chose Special Report on Emission Scenario (SERS) A2, which represents higher emissions and results in high levels of climate change. The key parameters in HadCM3 for constructing future weather files include dry bulb temperature, maximum and minimum dry bulb temperatures, horizontal solar radiation, total sky cover, total precipitation rate, relative humidity, mean see level pressure and wind speed.

We used the future weather data tool CCWorldWeatherGen [14], developed by University of Southampton. CCWorldWeatherGen can directly generate hourly weather files in '.epw' format for EnergyPlus based on the future climate monthly data predicted by HadCM3 for A2 scenario. CCWorldWeatherGen applies the morphing method to down-scale the monthly weather data to hourly weather data.

2.1.2. Weather files generated from CESM1 future climate data

This set of climate data are from the NCAR Community Earth System Model version 1 (CESM1) with the Community Atmosphere Model version 5 (CAM5), participating in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) multi-model ensembles. The purpose of CMIP5 is to provide a way of comparing the performance of many different models in both long term (century scale) and short term (10–30 years) climate modelling experiments. These models consist of coupled atmosphere-ocean global climate models (AOGCMs), Earth system models of intermediate complexity (EMICs), and Earth system models (ESMs). AOGCMs and EMICs work with specified, time-varying concentrations of greenhouse gases (GHGs) over a responsive representation of the atmosphere, ocean, land, and sea ice. ESMs (such as CESM1(CAM5)) are AOGCMs that also take into account important fluxes of carbon between ocean, terrestrial, and atmospheric biosphere carbon reservoirs [10].

The CESM1(CAM5) model is run at 1° resolution (0.9° × 1.25°) with 30 vertical levels for the time period of 2006–2300 [11]. The model simulations also consist of three ensemble members (r1i1p1, r2i1p1, and r3i1p1) and four mitigation scenarios, or representative concentration pathways (RCPs). The ensemble members are identical model runs with different initializations. These ensembles can be averaged to reduce the noise in the model run [10].

The key parameters in CESM1 for generating future weather files include dry bulb temperature, relative humidity, atmospheric pressure, extraterrestrial horizontal radiation, wind speed, wind direction and total sky cover. Meridional and zonal surface winds are used to calculate wind direction and wind speed at each site since surface winds are not available in the model output. The model output variables used in our study are averaged over the three ensembles for RCP2.6, RCP4.5, and RCP8.5, over years 2020–2089. We developed Matlab codes for applying the morphing method to downscale monthly data to hourly data and for generating the future weather data files for years 2020–2089. Hourly dewpoint temperature was calculated based on relative humidity and dry bulb temperature using psychrometric functions.

2.2. Building energy simulation for future climate

EnergyPlus (DOE) [15] is used as the simulation program in this study for modelling future climate with the consideration of UHI effect. EnergyPlus, developed by the U.S. Department of Energy, is an open-source whole-building energy simulation program built upon sub-hourly zone heat balance and integrated solutions of building loads, HVAC systems, and central plant equipment. In this study, a commercial building reference model (DOE) [16] in compliance with ASHRAE 90.1 [17] for a medium-size office building is used as the baseline of the study to investigate the impacts of window operation on energy use and thermal environment. The total building area is 4982.19 m^2. There are three stories and 15 thermal zones in the medium-size office reference model. The shape of the office building is rectangle with an aspect ratio of 1.5. The geometry of the building is shown in Fig. 1. There are four perimeter zones and one core zone for each floor. The window to wall ratio (WWR) is 0.48 for all four orientations. The lighting-power density and electric plug-load density are 8.87 W/m^2 and 8.07 W/m^2, respectively. The occupant density for each thermal zone is 18.6 m^2/person. A multi-zone variable air volume (VAV) system, with a two-speed direct-expansion (DX) cooling coil and a gas burner, is used to provide the conditioned environment for each floor. There are three multi-zone VAV systems in total. An electric reheating coil is available for each thermal zone. In this study, the mechanical equipment were autosized based on TMY3 weather data. The mechanical equipment sizes were kept the same for future climate runs.

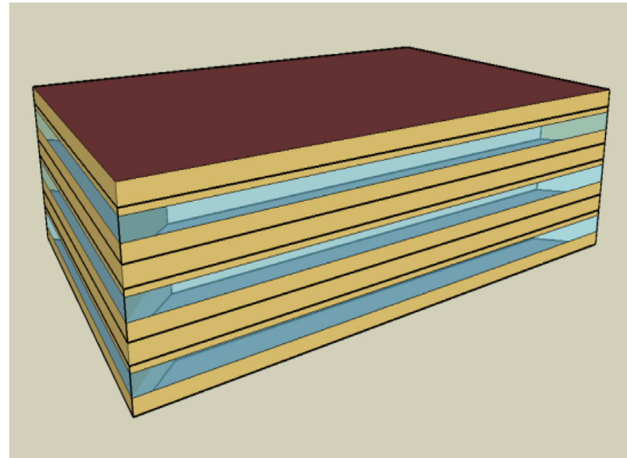

Fig. 1. Geometry of the DOE Benchmark Mid-size Commercial Office Building.

2.3. Mitigation measures to climate change

Mitigation measures for climate change are intended to slow or counteract the increases in building energy consumption for future climate, and therefore alleviate the increases in CO_2 emission. Mitigation of the effects from climate change requires the efforts on improving building energy efficiency in both design and operation for building envelope and mechanical systems. Previous studies [18,2] have mostly focused on mitigation measures on building design or retrofits. However, few studies has looked into how building operations can mitigate climate change. Mitigation measures on building operations for climate change could have significant effects on existing buildings.

In this study, we considered the five mitigation measures from building HVAC system operations to climate change. The five mitigation measures include: (1) room temperature setpoints, (2) HVAC operation hours, (3) VAV box minimum flow setting, (4) combination of all three measures above, and (5) mixed-mode ventilation strategies.

2.3.1. Room temperature setpoints

In the baseline model, room temperature heating and cooling setpoints were 21 °C and 24 °C for occupied hours, respectively, and were 15.6 °C and 26.7 °C for night setback, respectively. As one of the mitigation measures, we changed the room temperature heating and cooling setpoints during occupied hour to 20 °C and 25 °C for occupied hours, respectively; the night setback temperature setpoints were 12.7 °C and 30 °C for heating and cooling, respectively.

2.3.2. HVAC operation hours

In the baseline model, the HVAC system operated between 6:00 am to 10:00 pm during weekdays. As one of the mitigation measures, we reduced the HVAC operation hours to the period from 6:00 am to 8:00 pm during weekdays.

2.3.3. VAV box minimum flow setting

In the baseline model, the VAV box minimum flow setting was 30% of the maximum airflow rate. A higher minimum airflow fraction can provide better ventilation to thermal zones during HVAC operation, but it comes at the expense of high fan power as well as extra heating and cooling usage. As one of the mitigation measures, we adjusted the VAV box minimum flow setting to be 15%.

2.3.4. Combination of previous three measures

This measure combines all the three measures above with adjusted room temperature setpoint, reduced HVAC operation hours and reduced VAV box minimum flow setting.

2.3.5. Mixed-mode ventilation

In the baseline model, only mechanical system provides conditioned air to thermal zones for the medium-size office building. Mixed-mode ventilation [19] is considered another important strategy to mitigate climate change in this study. For mixed-mode ventilation, mechanical HVAC systems served the core zones, and cooling and heating setpoints remained the same as the baseline. We modified the perimeter zones by adding natural ventilation capability for each perimeter zone and adjusting ventilation controls for concurrent mixed-mode ventilation [20]. For concurrent mixed-mode ventilation, natural ventilation is taken as the priority to provide cooling for perimeter zones, and mechanical systems provide supplementary cooling when natural ventilation alone is not enough to meet cooling setpoints. The control type of this mixed-mode ventilation is classified as 'Concurrent'.

In addition, adaptive thermal comfort [21] were applied for all the perimeter zones with mixed-mode ventilation. Cooling and heating setpoints for mixed-mode ventilated zones were set by Eqs. (4) and (5) respectively based on mean monthly outdoor air temperature according to 80% acceptability for naturally conditioned spaces in ASHRAE Standard 55 [22].

$$T_{NVCooling} = T_a \times 0.31 + 21.3 \tag{4}$$

$$T_{NVHeating} = T_a \times 0.31 + 14.3 \tag{5}$$

where $T_{NVCooling}$—upper 80% acceptability limit for natural ventilation (°C), $T_{NVHeating}$—lower 80% acceptability limit for natural ventilation (°C), T_a —mean outdoor monthly air temperature (°C).

3. Weather data analysis

We compared the future weather data generated by the two climate models (HadCM3 and CESM1) to the baseline—the latest Typical Meteorological Year (TMY3) data and identified the changes in future weather data. We also compared the future weather data generated by two climate models.

3.1. HadCM3

We observed the changes of future weather data generated by HadCM3 A2 in comparison with TMY3 weather data as follows:

1) Extremely hot weather conditions were increased for all the cities. For example, the number of days in which dry bulb temperature exceeds 32 °C was increased from 28 (TMY3) to 101 (2080s) in Washington DC.
2) There were slight variations for solar radiations in TMY3 and future weather files. But the trends of these variations were not consistent for the three cities.
3) Daily average dry bulb temperature, maximum dry bulb temperature and minimum dry bulb temperature experienced a large increase from TMY3 to years 2080s. Fig. 2 shows daily average dry bulb temperature in a year for TMY3, the 2020s, 2050s and 2080s in Los Angeles. The increases in daily average dry bulb temperature from TMY3 to 2080s is in the range of 3.3 °C and 5.6 °C for Los Angeles.

3.2. CESM1

Annual average dry bulb temperature of future weather files through years 2020–2089 predicted by CESM1 in comparison to TMY3 showed similar trends for all the cities in this study: (1) $\Delta T_{dbRCP8.5} > \Delta T_{dbRCP4.6} > \Delta T_{dbRCP2.6}$, where $\Delta T_{dbRCPxx}$ represents the increases in annual average dry bulb temperature for a particular Relative Concentration Pathways (RCP); (2) $\Delta T_{dbRCPxx}$ increased through years 2020–2089 with fluctuations. However, the increased values in annual average dry bulb temperature for each RCP varies with cities.

The increases in annual average dry bulb temperature were illustrated in Figs. 3 and 4 for Los Angeles, CA and Akron, CO, respectively. Among all the five cities, Los Angeles, CA shows the most temperature increase in future weather forecast and Akron, CO shows the least temperature increase in future weather forecast. The maximum increases in annual average dry bulb temperature for Los Angeles, CA are 5.5 °C for RCP8.5, 3.8 °C for RCP4.6 and 3.0 °C for RCP2.6. The maximum increases in annual average dry bulb temperature for Akron, CO are 3.6 °C for RCP8.5, 1.4 °C for RCP4.6

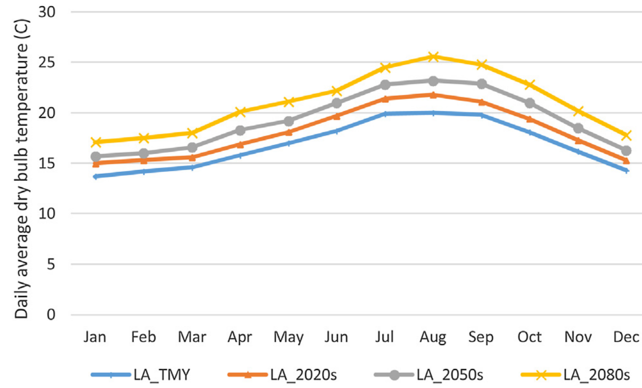

Fig. 2. Daily average dry bulb temperature for TMY3 and future climate for Los Angeles.

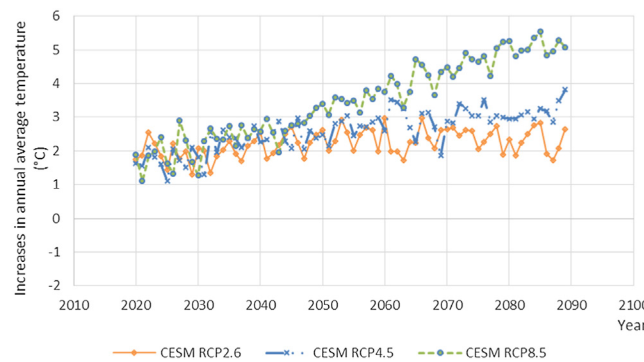

Fig. 3. Changes of annual average dry bulb temperature compared to TMY3 in Los Angeles, California (3B).

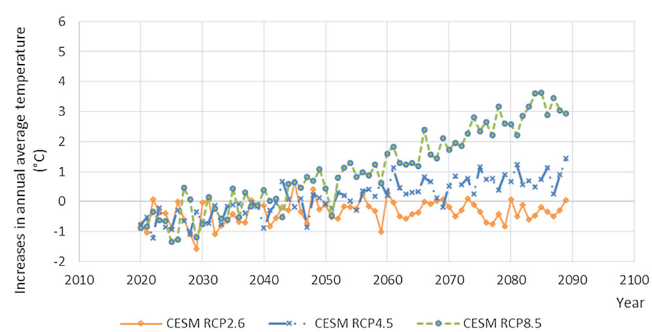

Fig. 4. Changes of annual average dry bulb temperature compared to TMY3 in Akron, Colorado (5B).

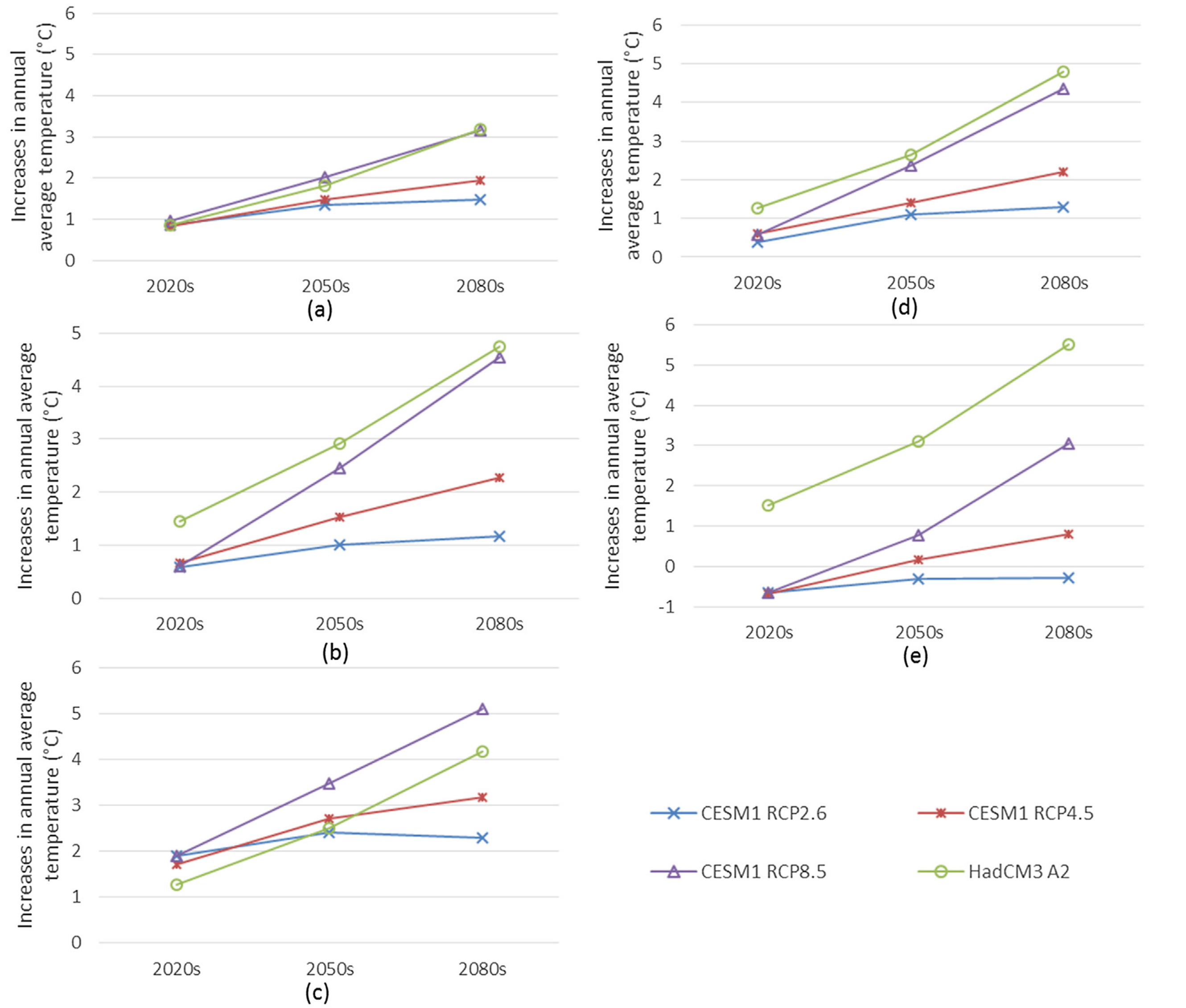

Fig. 5. Comparison of changes of annual average temperature for 2020s, 2050s and 2080s between weather data predicted by HadCM3 and weather data predicted by CESM1. (a) Miami, FL (b) Phoenix, AZ (c) Los Angeles, CA (d) Washington DC (e) Akron, CO.

and 0.7 °C for RCP2.6. It is also interesting to find that for many years within the period of years 2020–2089, the annual average dry bulb temperature for future climates predicted by CESM1 RCP 2.6 is lower than the annual average of TMY3 weather data. For example, in 2020s, an average decrease of 0.6 °C in annual dry bulb temperature for RCP2.6 in comparison to TMY3 were observed for Akron, CO.

3.3. *Comparison between future weather data predicted by HadCM3 and predicted by CESM1*

In this section, we made comparison of the increases in annual average temperature between future weather data predicted by HadCM3 and future weather data predicted by CESM1. We calculated the average increases in annual average temperature in 2020s, 2050s and 2080s predicted by CESM1 to compare with the average increases predicted by HadCM3 in the same periods.

Fig. 5 shows the comparison on the increases of annual average dry bulb temperature. Annual average dry bulb temperature increases from years 2020s to years 2080s for all future weather data scenarios. Based on weather data predicted by CESM1 RCP8.5, increase in annual average temperature ranges from 3.0 °C to 4.5 °C for the five cities.

However, the results did not show a consistent relationship between the increases in annual average dry bulb temperature predicted by HadCM3 and the increases predicted by CESM1 among the five cities as shown in Fig. 5. Among the five cities in this study, the predictions of the increases in annual average dry bulb temperature for future weather from HadCM3 A2 and from CESM1 RCP8.5 for Miami, as shown in Fig. 5a, are very close and the differences are within 0.2 °C. For the two cities: Phoenix and Washington DC, as shown in Fig. 5b and d, the increases in annual average dry bulb temperature predicted by HadCM3 are slight higher than those predicted by CESM1 RCP8.5 in 2020s, 2050s and 2080s; the discrepancies are large (0.7–0.9 °C) in 2020 s and become small (0.2–0.4 °C) in 2080s. It is also interested to find that for Los Angeles, as shown in Fig. 5c, the increases in annual average dry bulb temperature predicted by HadCM3 is 0.6 °C lower than those predicted by CESM1 RCP2.6 in 2020 s and is 0.9 °C lower than those predicted by CESM1 RCP8.5 in 2080s. For Akron, as shown in Fig. 4e, the increases in annual average dry bulb temperature predicted by HadCM3 is much higher (2.2–2.5 °C) than those predicted by CESM1 RCP8.5 for all the years.

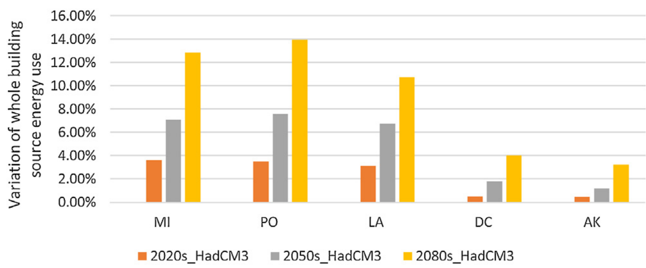

Fig. 6. Variation of annual whole building source energy use for future climate in the five cities: Miami (MI), Phoenix(PH), Los Angeles(LA), Washington DC (DC) and Akron(AK).

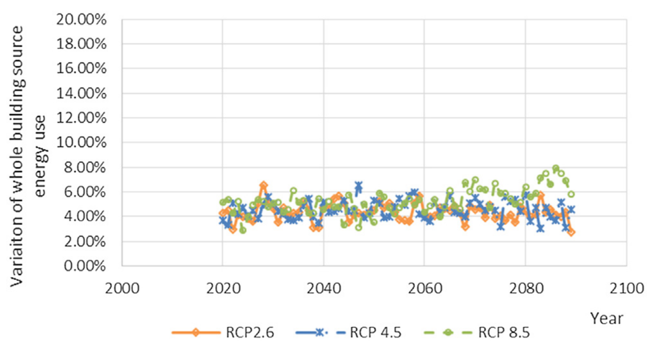

Fig. 7. Variation of annual whole building source energy use for future climate in Akron (AK) with future weather data predicted by CESM1.

4. Results and discussion

4.1. Impacts of climate change without mitigation measures

In this section, we conducted building energy simulations of the medium-size office building for both TMY3 and future weather files predicted by HadCM3 and CESM1 without mitigation measures. Throughout our analysis, we used the building annual source energy predicted with the TMY3 weather data as the baseline for each city.

Fig. 6 shows the variation of whole building source energy use in the five cities for future climates predicted by HadCM3 A2. A positive value of variation represents the percentage of increased whole building source energy consumption in comparison to the baseline, while a negative value of variation represents the percentage of decreased whole building source energy consumption in comparison to the baseline. Based on the simulation results as shown in Fig. 6, Miami, Phoenix and Los Angeles will experience higher percentages of increases in whole building energy use than the percentages of increases in Washington DC and Akron. With weather data predicted by HadCM3 A2, the percentages of increases in whole building source energy use are 12.8%, 14.0% and 10.7% in 2080s for Miami, Phoenix and Los Angeles, respectively, and the increases in whole building source energy use are 1222.5 GJ, 1266.0 GJ and 762.4 GJ in 2080s for Miami, Phoenix and Los Angeles, respectively. We observed continuous increases in whole building energy use predicted by HadCM3 A2 through years 2020s, 2050s and 2080s for all five cities.

With the weather data predicted by CESM1 RCP8.5, the percentages of increases are 11.2%, 15.4% and 14.4% in 2080s for Miami, Phoenix and Los Angeles, respectively, and the absolute increases in whole building source energy use are 1069.7 GJ, 1392.6 GJ and 1026.0 GJ in 2080s for Miami, Phoenix and Los Angeles, respectively. Figs. 7 and 8 show the variation of whole building energy use predicted by CESM1 for Akron (AK), CO and Phoenix (PO), AZ. The percentages of variation in whole building energy use for AK

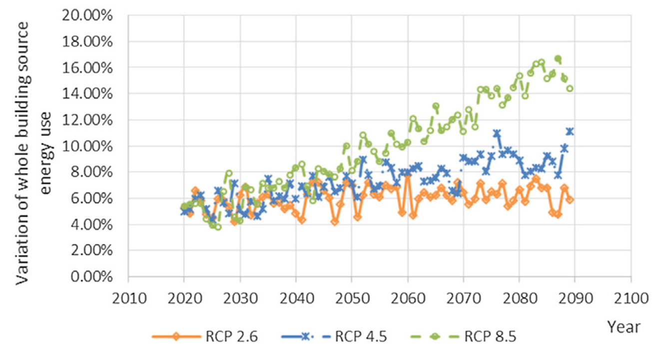

Fig. 8. Variation of annual whole building source energy use for future climate in Phoenix (PO) with future weather data predicted by CESM1.

are nearly constant through years 2020–2089 with the weather data predicted by CESM1 RCP2.6 and RCP4.5 but the percentages of variation have increased slightly for years 2060–2089 with weather data predicted by CESM1 RCP8.5, while the percentages of increases in whole building energy use for PO keep increasing through years 2020–2089 with weather data predicted by CESM1 RCPs 4.5 and 8.5 except that the percentage of the increases stays nearly unchanged through the years 2020–2089 with weather data predicted by CESM1 RCP2.6.

Fig. 9 shows the variation of annual whole building source energy use for future climate in the five cities: Miami (MI), Phoenix(PH), Los Angeles(LA), Washington DC (DC) and Akron(AK) for HadCM3 A2 and CESM1 RCPs. The percentages of increases in whole building source energy use for HadCM3 A2 are higher than those for CESM1 RCP8.5 in Miami, while the predicted percentages of increases in whole building source energy use for CESM1 RCP8.5 are higher than those for HadCM3 A2 in the other four cities.

During the periods of the 2020s to the 2080s, our simulation results showed that PO and LA will experience substantial increases (15.4% and 14.4% respectively from CESM1 RCP8.5) in source energy use among the five cities, and that AK will experience the least increase (6.7% from CESM1 RCP8.5) in source energy use among the five cities. The differences in variations of source energy use among the five cities were determined by two factors: (1) climate zones, and (2) the increases in dry bulb temperature in future climate. For tropical climate or subtropical climate including the cities such as Miami, Phoenix and Los Angeles, cooling loads was substantially increased. The percentage of increases in annual source energy use was determined mainly by the key parameter −the increase in dry bulb temperature. As shown in Fig. 5, relatively higher temperature increases in Phoenix and Los Angeles than the temperature increases in Miami was observed based on future weather predictions. The climates for Washington DC and Akron has high annual demands in both heating and cooling. We observed substantial increase in cooling energy use for both cities. For example, an increase of 86% cooling energy use for Washington DC in 2080s was predicted by CESM RCP 8.5. However, compared to the cooling energy uses in tropical or subtropical climates, the increases in annual cooling energy use is relatively low. For Washington DC climate, heating energy use keeps decreasing for future climates with the scenarios HadCM3 A2, CESM1 RCPs4.5 and 8.5 through years 2020s-2080s. Interestingly, we found that heating energy consumption in DC for 2020s predicted by CESM1 RCP2.6 was increased by up to 16% of heating energy use of DC baseline, and heating energy consumption in AK for future climates predicted by CESM1 RCPs2.6, 4.5 and 8.5 was increased by up to 32% of heating energy use of AK baseline.

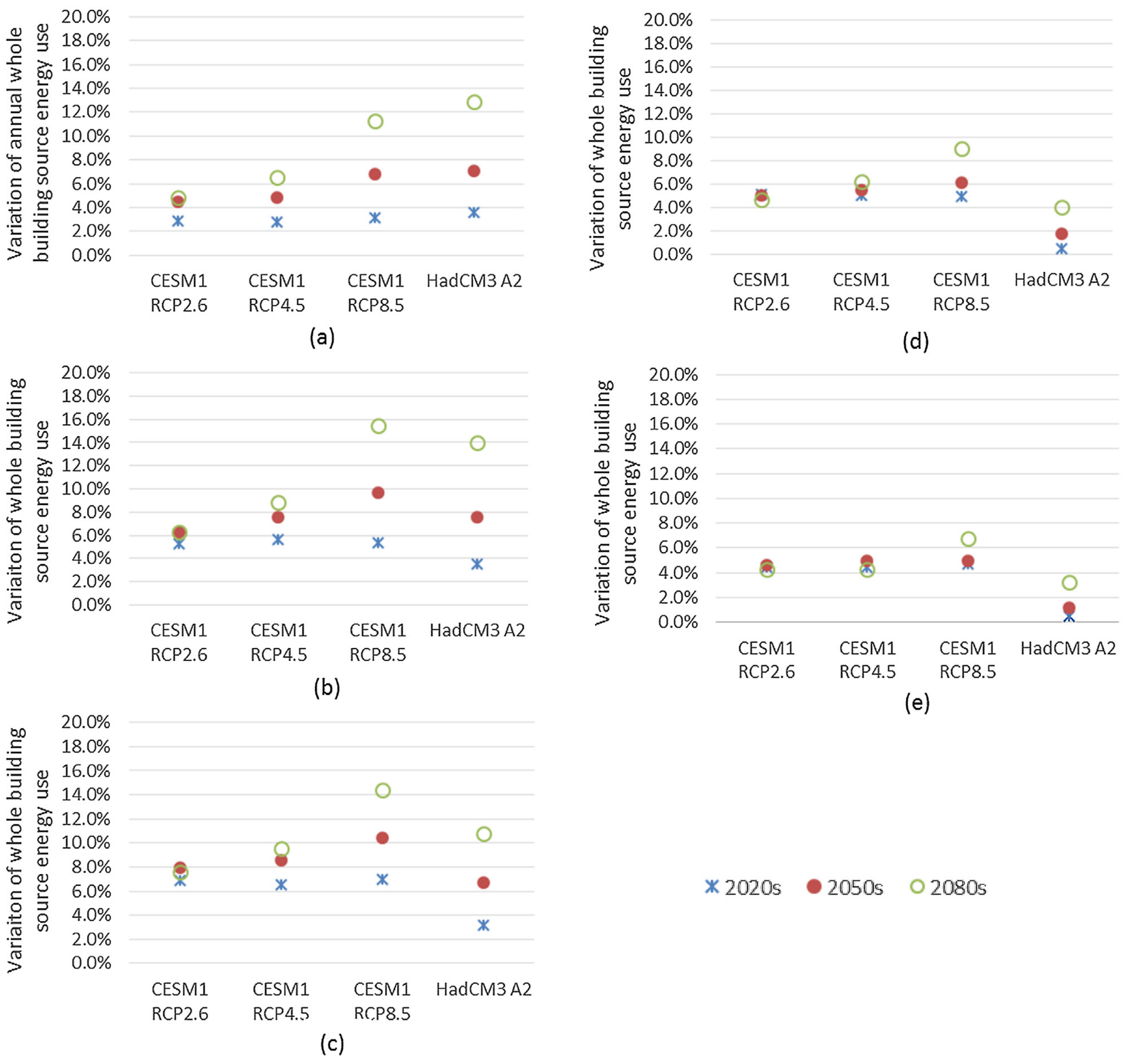

Fig. 9. Variation of annual whole building source energy use for future climate in the five cities: a. Miami (MI), b. Phoenix(PH), c. Los Angeles(LA), d. Washington DC (DC) and e. Akron(AK).

4.2. Impacts of climate change with mitigation measures

In this section, we implemented the five measures discussed in Section 2.3 into the medium-size office building model and created five modified EnergyPlus models with mitigation measures. These five measures are (1) adjustment of room temperature setpoint, (2) adjustment of HVAC operation hour, (3) adjustment of minimum airflow fraction in VAV boxes, 4) combined measure with measures 1–3, and (5) implementation of mixed-mode ventilation for perimeter zones. We simulated the five models with future climate weather data predicted by HadCM3 and CESM1 to evaluate the effects of each measurement on mitigating climate change. For each city, we compared source energy use of the modified model with the five measures to that of the baseline with TMY3 weather file.

Figs. 10–12 illustrated the impacts of the five measures on whole building source energy use for three cities: Phoenix, Los Angeles, and Washington DC, respectively. The simulation results

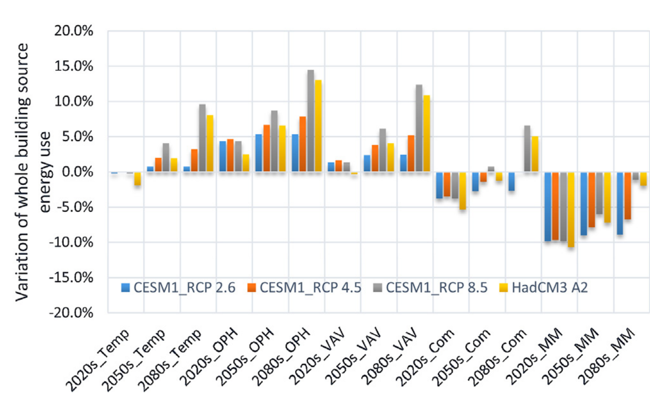

Fig. 10. Variation of annual whole building source energy use with the implementation of mitigation measures for future climate in Phoenix. (“XX_TEMP” — adjustment of room temperature setpoint, “XX_OPH” — adjustment of HVAC operation hour, “XX_VAV” — adjustment of minimum airflow fraction in VAV boxes, “XX_Com” —combined scenario, “XX_MM” — mixed-mode ventilation).

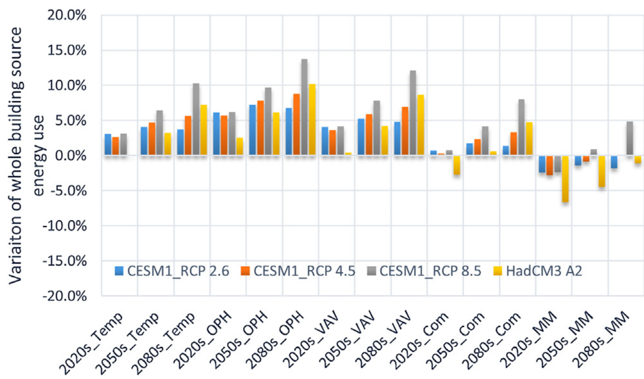

Fig. 11. Variation of annual whole building source energy use with the implementation of mitigation measures for future climate in Los Angeles. ("XX_TEMP" — adjustment of room temperature setpoint, "XX_OPH" — adjustment of HVAC operation hour, "XX_VAV" — adjustment of minimum airflow fraction in VAV boxes, "XX_Com" —combined scenario, "XX_MM" — mixed-mode ventilation).

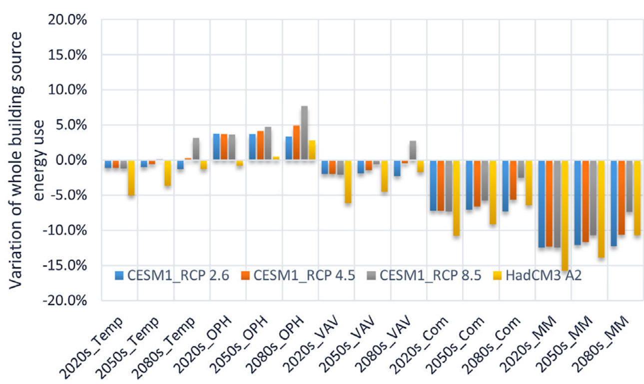

Fig. 12. Variation of annual whole building source energy use with the implementation of mitigation measures for future climate in Washington DC. ("XX_TEMP" — adjustment of room temperature setpoint, "XX_OPH" — adjustment of HVAC operation hour, "XX_VAV" — adjustment of minimum airflow fraction in VAV boxes, "XX_Com" —combined scenario, "XX_MM" — mixed-mode ventilation).

showed that the five mitigation measures were effective in reducing building annual source energy use and therefore greenhouse gas emission, but may not be sufficient to counteract climate change. Mixed-mode ventilation is the most effective mitigation measure for all the cities. The results indicated that mixed-mode ventilation measure can counteract climate change effects for the five cities through years 2020s–2080s except Los Angeles in 2080s with weather data predicted by CESM1 RCP8.5 and HadCM3 A2.

In Phoenix, as shown in Fig. 10, adjustment of temperature setpoitns ("XX_Temp") can effectively deal with the impacts of climate change in 2020s but was insufficient to counteract climate change in 2050s and 2080s. Adjustment of HVAC operation hours ("XX_OPH") or minimum airflow fraction of VAV boxes ("XX_VAV") only was not able to counteract climate changes through years 2020s-2080s. The combination of all three measures ("XX_Com") was insufficient to counteract the overall impacts of climate change on building energy use in 2050s and 2080s with weather data predicted by CESM1 RCP8.5. Mixed ventilation strategy was demonstrated as an effective measure to substantially reduce HVAC energy consumption and to reduce the impacts from climate change on buildings.

The variation of annual whole building source energy use in Los Angele (LA) with mitigation measures for future climates is shown in Fig. 11. Adjustment of room temperature setpoint, HVAC operation hours or minimum airflow fractions of VAV boxes only cannot counteract the overall impacts of climate changes on building energy use in LA. The combination of the three measures can reach a reduction of 2.7% (192.4 GJ) in whole building source energy use in 2020s predicted by HadCM3 A2, but was insufficient to counteract the overall effects of climate changes with other future weather data predicted by CESM1. The mixed-mode ventilation strategy can reach a reduction of 4.5% (320.6 GJ) and 1.1% (78.4 GJ) in whole building source energy use in 2050s and 2080s predicted by HadCM3 A2. However, it was insufficient to counteract climate change in 2050s and 2080s predicted by CESM1 RCP8.5.

For the climates which have high demands in both heating and cooling such as Washington DC and Akron, CO, adjustment of room temperature setpoint and minimum airflow fractions of VAV boxes can counteract climate change in 2020s–2080s except in 2080s predict by CESM1 RCP8.5. The combination of adjustment of room temperature setpoint, HVAC operation hours and minimum airflow fractions of VAV boxes can reach a reduction of 2.5% (246.1 GJ) in whole building source energy use in 2080s predicted by CESM1 RCP8.5 in DC. The mixed-mode ventilation strategy can reach a reduction of 7.4% (728.4 GJ) in whole building source energy use in 2080s predicted by CESM1 RCP8.5 in DC.

5. Conclusions

This study investigated the impacts of climate change on annual building energy use using two climate change models (HadCM3 and CESM). We considered the representative concentration pathways (RCP)2.6, RCP4.5, and RCP8.5, which represents low greenhouse gas emission, intermediate emission and high emission based on IPCC AR5 (the fifth assessment report). We observed discrepancies in the increases of annual average dry bulb temperature from future weather data predicted by the two models. The discrepancies vary with cities. In Akron,CO, the increases in annual average dry bulb temperature predicted by HadCM3 A2 is much higher than those predicted by CESM1 RCP8.5. In Los Angeles, the increases predicted by HadCM3 A2 was 0.6–1.0 °C lower than those predicted by CESM1 RCP8.5. Both HadCM3 and CESM are general circulation models with relative coarse resolutions. The differences in model resolution could result in the discrepancies in future weather data. It would be interesting to compare the results of this study with future weather files predicted with regional climate model (RCM) for refined resolution.

Energy simulation tool—EnergyPlus was used to simulate future climate conditions and mitigation measures for five U.S. cities. The overall impacts of climate change on buildings varied with climate zones. Our simulation results indicated that there is high potential that Miami, Phoenix, Los Angeles will experience substantial increases in building energy use due to climate change with the weather data predicted by both HadCM3 and CESM1. The five mitigation measures related to HVAC operations investigated in this study were effective in mitigating climate changes. The mixed-mode ventilation measure was found as the most effective to counteract climate changes among the five mitigation measures to ensure a sustainable future.

References

[1] H. Kikumoto, R. Ooka, et al., Study on the future weather data considering the global and local climate change for building energy simulation, Sustain. Cities Soc. 14 (2015) 404–413.
[2] T. van Hooff, B. Blocken, et al., On the predicted effectiveness of climate adaptation measures for residential buildings, Build. Environ. 82 (2014) 300–316.
[3] H. Wang, Q. Chen, Impact of climate change heating and cooling energy use in buildings in the United States, Energy Build. 82 (2014) 428–436.
[4] M. Santamouris, C. Cartalis, et al., On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—a review, Energy Build. 98 (2015) 119–124.

[5] M. Kolokotroni, X. Ren, et al., London's urban heat island: impact on current and future energy consumption in office buildings, Energy Build. 47 (2012) 302–311.
[6] SERG, Climate Change World Weather File Generator- CCWorldWeatherGen, 2016, Retrieved 10/1, 2016, from http://www.energy.soton.ac.uk/ccworldweathergen/.
[7] R.K.L. Chan, E.W.M. Lee, et al., An integrated model for the design of air-cooled chiller plants for commercial buildings, Build. Environ. 46 (1) (2011) 196–209.
[8] Nakicenovic, et al., Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2000.
[9] Richard H. Richard, Jae A. Edmonds, et al., The next generation of scenarios for climate change research and assessment, Nature 463 (7282) (2010) 747–756.
[10] K.E. Taylor, R.J. Stouffer, G.A. Meehl, An overview of CMIP5 and the experiment design, Bull. Am. Meteorol. Soc. 93 (2012) 485–498.
[11] Gerald A. Meehl, M. Warren, et al., Climate change projections in CESM1(CAM5) compared to CCSM4, J. Clim. 26 (1) (2013) 6287–6308.
[12] Katharine Hayhoe, Emissions, Concentrations, and Temperature Projections (CMIP3, CMIP5), 2013, Retrieved 10/1/2016, from https://data.globalchange.gov/report/nca3/chapter/appendix-climate-science-supplement/figure/emissions-concentrations-and-temperature-projections.
[13] S. Belcher, J. Hacker, et al., Constructing design weather data for future climates, Build. Serv. Eng. Res. Technol. 26 (1) (2005) 49–61.
[14] SERG, Climate Change World Weather File Generator Manual, University of Southampton, 2013.
[15] DOE, EnergyPlus, 2015, Retrieved 11/01, 2015, from https://energyplus.net/.
[16] DOE, Commerical Reference Buildings, 2014, Retrieved 12/02, 2014, from http://energy.gov/eere/buildings/commercial-reference-buildings.
[17] ASHRAE, ANSI/ASHRAE/IES Standard 90. 1–2010 Energy Standard for Buildings Except Low-Rise Residential Buildings, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, Georgia, 2010.
[18] S. Wong, K. Wan, et al., Impact of climate change on residential building envelope cooling loads in subtropical climates, Energy Build. 42 (11) (2010) 2098–2103.
[19] G. Brager, Mixed-mode cooling, ASHRAE J. 48 (2006) 30–37.
[20] L. Wang, S. Greenberg, Window operation and impacts on building energy consumption, Energy Build. 92 (2015) 313–321.
[21] G.S. Brager, R.J. de Dear, Thermal adaptation in the built environment: a literature review, Energy Build. 27 (1) (1998) 83–96.
[22] ASHRAE, ANSI/ASHRAE Standard 55–2013, Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, Atlanta, 2013.