Sustainable Cities and Society 50 (2019) 101688

Contents lists available at ScienceDirect

Sustainable Cities and Society

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

Hourly weather data projection due to climate change for impact assessment on building and infrastructure

Aiyin Jiang[a,*], Xudong Liu[b], Emily Czarnecki[b], Chengyi Zhang[c]

[a] Department of Construction Management, University of North Florida, 1 UNF Drive, Jacksonville, FL 32224, USA
[b] School of Computing, University of North Florida, 1 UNF Drive, Jacksonville, FL 32224, USA
[c] Applied Engineering and Technology, Eastern Kentucky University, 521 Lancaster Ave, Richmond, KY 40475, USA

ARTICLE INFO

Keywords:
Climate change
Building energy simulation
Weather data files
Green-house gas emission scenario

ABSTRACT

The global climate change research has been conducted for a few years in various professional communities. In the building industry, researchers usually investigate the future building energy demands due to the climate change by simulation software. The input files to the simulation software includes projected weather data and building models. Although there exist a few mathematical methods to project the future weather, the morphing method is the most well-known among them. In the meantime, the simulation software and weather data are in a variety of formats depending on country of origin and/or simulation package. In order to provide both the research and the professional communities the possibility to undertake climate change impact assessments on buildings, coastal engineering and construction, land use and other related areas, this study develops the web-based application Weather Morph: Climate Change Weather File Generator accessible to generate the future weather data for more than 2100 locations throughout the world for all four IPCC (Intergovernmental Panel of Climate Change) emission scenarios in the three future time slices of the 2020s, 2050s and 2080s. The output of the application is projected future weather datasets in formats TMY2 and EPW for general use.

1. Introduction

The research of the impact of climate change on the building energy consumption has been conducted for many years world widely. Researchers usually input a projected future weather data file of certain green-house gas emission scenario and a building model into a simulation software to estimate future building energy use. The methods and tools of predicting the future weather, the emission scenarios, and the simulation software and the related weather file formats are developed and used in varieties. In Europe, Frank (2005) used historical hourly weather data from 1981 through 2003 projecting the trend of the future situation for four scenarios – Scenario A: WMO normal, Scenario B: IEA Design Reference Year, C: Average reference year, Scenario D: Warm reference year. He investigated the energy demand change of the multistory residential and office buildings at Zurich-Kloten, Switzerland. Olonscheck, Holsten, and Kropp (2011) investigated the future energy demand of German housing sector due to climate change by applying statistical analysis on the future heating degree days (HDD) and cooling degree days (CDD) under the IPCC green-house gas emission A1B scenario. Asimakopoulos et al. (2012) estimated the future heating and cooling demands of residential, office and educational buildings in Greece for three greenhouse gas emission scenarios: A1B, A2, and B2. The study used regional climate model simulations (RCMs) conducted in the framework of the European ENSEMBLES project (http://ensemblesrt3.dmi.dk/) for a reference period (1961–1990) and for two future periods (2041–2050 and 2091–2100). Further, the study applied a correction factor method to consider the diurnal variability of temperature. Then the projected temperature values on an hourly basis were used by the simulation program TRNSYS. In United Kingdom, Chow and Levermore (2007) developed Q-Sin method to project future weather data while Belcher, Hacker, and Powell (2005) developed a morphing method to produce design weather data for building simulation that accounted for future changes to climate. Jentsch, Bahaj, and James (2008) and Jentsch, James, Bourikas, and Bahaj (2013) developed a climate change weather file generator tool, CCWorldWeatherGen, using Microsoft1 Excel, to allow individual end user to generate future weather data in the widely used Typical Meteorological Year (TMY2) and EnergyPlus/ESP-r Weather (EPW) file formats. The algorithm of projecting future weather data in their study is the morphing method. The tool integrates IPCC green-house gas emission scenario A2 into the future TMY2 and EPW file formats. Thereafter, Sabunas and Kanapickas (2017) used CCWorldWeatherGen Software to

* Corresponding author.
E-mail addresses: a.jiang@unf.edu (A. Jiang), xudong.liu@unf.edu (X. Liu), n01185574@ospreys.unf.edu (E. Czarnecki), chengyi.zhang@eku.edu (C. Zhang).

https://doi.org/10.1016/j.scs.2019.101688
Received 15 February 2019; Received in revised form 7 May 2019; Accepted 25 June 2019
Available online 28 June 2019
2210-6707/ Published by Elsevier Ltd.

Table 1
Research of Future Building Energy Demands due to Climate Change.

Year	Author	Future Weather Scenarios	Building Types	Area	Weather Projection Method	Simulation Software	Journal
2005	Frank, 2005	Scenario A: WMO normal, Scenario B: IEA Design Reference Year, C: Average reference year, Scenario D: Warm reference year	Case study multi-story residential and office building	Zurich–Kloten, Switzerland	Historical hourly weather data were used to define various climate scenarios representing the past, the present and possible future situations.	HELIOS	Energy and Building
2005	Belcher et al., 2005	UKCIP02 climate change scenarios for the UK	N/A	London, Manchester, Edinburgh, UK	Morphing method	N/A	Building Services Engineering Research and Technology
2007	Chow & Levermore, 2007	N/A	N/A	Heathrow, UK	Q-Sin method	N/A	Building Services Engineering Research and Technology
2008	Jentsch et al., 2008	UKCIP02 climate change scenarios for the UK	Case study multi-story office building	UK	Morphing Method	TRNSYS	Energy and Buildings
2009	Radhi, 2009	N/A	Residential buildings	Al-Ain, UAE	Statistical analysis on heating degree days and cooling degree days	Visual DOE	Building and Environment
2010	Lam, Wan, Lam et al., 2010	A1B, B1	Generic office building	Hong Kong of China	Principal component analysis	VisualDOE4.1	Energy
2010	Lam, Wan, Wong et al., 2010	A1B, B1	Buildings in the commercial sector	Hong Kong of China	Principal component analysis	Regression analysis	Applied Energy
2010	Wang et al., 2010	A1B, A1FI, 550 ppm stabilization emission	Residential houses	Sydney, Melbourne, Hobart, Alice Springs, and Darwin of Australia	Morphing method	AccuRate	Building and Environment
2011	Wan et al., 2011	A1B, B1	Generic buildings	Hong Kong of China	Principal component analysis	Regression analysis	Energy
2011	Chan, 2011	A1B, B1	Typical office building and a residential flat	Hong Kong of China	Morphing method	Energy Plus	Energy and Buildings
2011	Olonscheck et al., 2011	A1B	Residential buildings	German	Statistical analysis on heating degree days and cooling degree days	German DIN standard V 4108-6	Energy Policy
2012	Wan et al., 2012	A1B, B1	Office building	Harbin, Beijing, Shanghai, Kunming, and Hong Kong	Regression model	VisualDOE4.1	Applied Energy
2012	Xu et al., 2012	A1FI, A2, B1	Commercial building prototypes	California, USA	Statistical downscaling dynamic procedure	Energy Plus and DOE-2.1E	Energy
2012	Asimakopoulos et al., 2012	A1B, A2, B2	residential, office and educational buildings	Greece	Reginal climate model conducted by European ENSEMBLES project (http://ensemblesrt3.dmi.dk/) and correction factor		Energy and Buildings
2013	Jentsch et al., 2013	A2	Case study multi-story office building	Major cities in UK	Morphing method	TRNSYS	Renewable Energy
2014	Wang & Chen, 2014	A1FI, A2, B1	residential and commercial building prototypes	15 major cities of USA	Morphing method	Energy Plus 8.1	Energy and Buildings
2014	Zhou et al., 2014	A2	One residential building sector and one commercial building sector	State-level of USA	Use downscaled PCM temperature by Intergovernmental Panel on Climate Change (IPCC)	Population-weighted heating degree days and cooling degree days	Applied Energy
2014	Kikumoto et al., 2014	MIROC4h	A detached house	Tokyo, Japan	Dynamical downscaling method	TRNSYS	Sustainable Cities and Society
2015	Dirks et al., 2015	A2 of IPCC	Commercial and residential buildings	Eastern Interconnection located in the United States	Goodness-of-fit procedure across nine different climate variables in a manner similar to the methods used to generate TMY data	BEND, Energy Plus	Energy
2016	Zhu et al., 2016	S1, S2, and S3 of RCP4.5	Office, Hotel, Shopping mall prototypes	Shanghai, China	Morphing method	Energy simulation tool	Energy and Buildings
2016	Arima, Ooka, Kikumoto, & Yamanaka, 2016	MIROC4h	A detached house	Tokyo, Japan	Dynamical downscaling method	TRNSYS	Energy and Buildings

(continued on next page)

Table 1 (*continued*)

Year	Author	Future Weather Scenarios	Building Types	Area	Weather Projection Method	Simulation Software	Journal
2016	Huang & Gurney, 2016	A1B, A2, B1 of IPCC	Residential and commercial building prototypes	Cities in USA	The monthly temperature change of CMIP3 added to the current hourly TMY3 temperature data to generate the future hourly weather conditions in each month and location	Energy Plus	Energy
2017	Sabunas & Kanapickas, 2017	A2 of IPCC and RCP 2.6 and RCP 8.5 of CESM1	Residential buildings	Kaunas, Lithuania	Morphing Method	HEED	Energy Procedia
2017	Shen, 2017	A1FI, A2	Residential and Commercial Buildings	Four cities in USA	Morphing Method	Energy Plus	Energy and Buildings
2017	Wang et al., 2017	A2 of IPCC and RCP2.6, RCP4.5 and RCP8.0 of CESM1	Office buildings	Five cities in USA	Morphing Method	Energy Plus	Energy and Buildings
2018	Jiang & O'Meara, 2018	A2 of IPCC	Commercial Buildings	Florida in USA	Morphing Method	Energy Plus	Energy and Buildings

Table 2
Impact of Climate Change on the Building Energy Demands of Different Areas.

Country/City	Author	Year	Building Types	Energy Types	Change
Swizerland	Frank	2005	Office	Cooling	233-1050%
				Heating	36-58%
Germany	Oloscheck	2011	Residential	Cooling	Remain low
				Heating	Decrease
Greece	Asimakopoulos	2012	Building	Cooling	248%
				Heating	50%
Australia	Wang	2010	Residence	Cooling	350%
				Heating	48%
Hong Kong	Chan	2011	Office	Cooling	2.6–14.3%
			Residence	Cooling	3.7–24%
	Wan	2012	Office	Cooling	11.4–55.7%
China	Zhu	2013	Building	Total Energy	Substantial increase
Saudi Arabia	Radhi	2009	Residence	Cooling	23.5%
Los Angles	Huang	2006	Commercial	Cooling	31%
USA	Wang & Chen	2014	Residence & Commercial	Cooling	30–280%

generate future weather data for the periods of the 2020s, 2050s and 2080s to evaluate residential building energy consumption in Kaunas, Lithuania by Home Energy Efficient Design (HEED) software.

In Asia, Radhi (2009) investigated the potential consequences of global warming on the energy performance of air-conditioned residential buildings in Al-Ain city in the United Arab Emirates. He applied statistical analysis on heating degree days and cooling degree days to predict the future air-temperatures by increasing 1.6 °C and 2.9 °C to reflect the climate in 2050, and by 2.3 °C and 5.9 °C to reflect the climate in 2100. The other climatic parameters were kept unchanged in his study to confine the analysis to one variable. Arima et al. (2016) and Kikumoto, Ooka, Arima, and Yamanaka (2014) assessed the impact of climate change on the energy use of residential houses in Japan. The study applied the dynamical downscaling method to predict future local weather data for the scenario MIROC4h, a Model for Interdisciplinary Research On Climate version 4 presented by Masahide Kimoto of Atmosphere and Ocean Research Institute, the University of Tokyo (Sakamoto et al., 2012). The TRNSYS software, developed by University of Wisconsin, U.S.A., was used to simulate the energy consumption of a detached house in Tokyo. Lam, Wan, Lam, and Wong (2010, 2010) and Wan, Li, and Lam (2011) developed principal component analysis (PCA) to predict the future weather parameters – dry-bulb temperature, wet-bulb temperature, and global solar radiation – and energy uses of commercial buildings in Hong Kong. Wan, Li, Pan, and Lam (2012) applied regression models to project future weather parameters, such as dry bulb temperature, wet bulb temperature, and global solar radiation. Their study investigated the impact of climate change on energy demands in office buildings of the major cities, including Hong Kong, located in the five architectural climates across China for two IPCC emission scenarios A1B and B1. On the other hand, Chan (2011) developed future hourly weather files by applying the morphing method on four weather parameters – dry bulb temperature, wet bulb temperature, solar radiation and rainfall – and simulated a typical office building and a residential flat in Hong Kong under IPCC emission scenarios A1B and B1. Zhu, Pan, Huang, and Xu (2016) also generated the future TMYs in the five time spans (2000–2017, 2018–2035, 2036–2053, 2054–2071 and 2072–2089) by using the morphing method under the three composite scenarios (S1, S2, and S3 of RCP4.5) based on the local existing IWEC-version TMY as the baseline condition. Their study estimated the future energy demands of the prototypical building models in Shanghai.

In Oceania, Wang, Chen, and Ren (2010) combined sensitivity and scenario assessments to investigate the potential impact of climate change on the heating and cooling energy requirements of residential houses in major cities like Sydney in Australia. They applied the

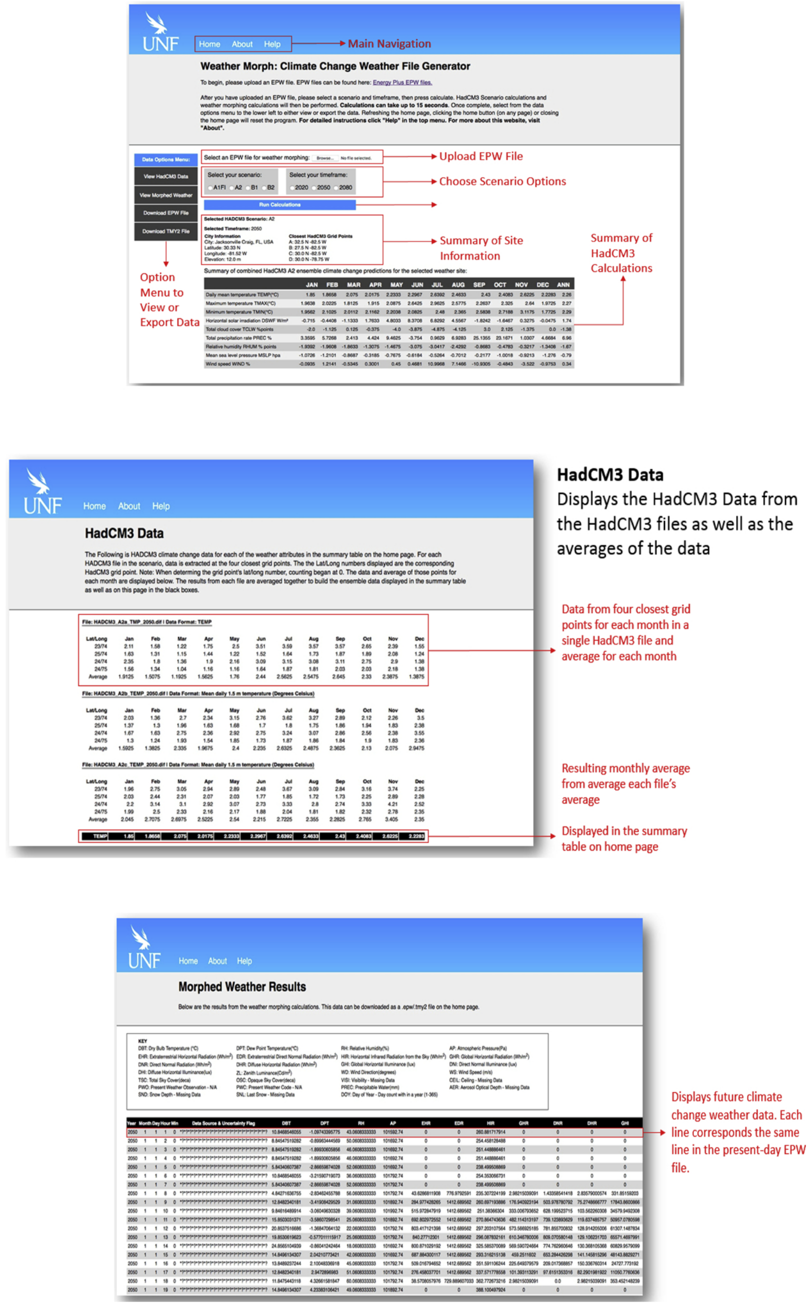

Fig. 1. are the screen shots of the application and corresponding brief illustration of usage.

morphing method to project future ambient temperature, relative humidity, and solar radiation under the three emission scenarios – the A1B, A1FI and 550 ppm stabilization emission scenarios. Sydney was found to be the most sensitive to climate change.

In North America, Xu, Huang, Miller, Schlegel, and Shen (2012) utilized the archived General Circulation Model (GCM) projections and statistically downscaled these data to the site scale for use in building cooling and heating simulations. Their study investigated the impact of climate change on energy demands of commercial building prototypes in major cities of typical California climate zones under three IPCC emission scenarios: A1FI, A2, and B1. Zhou et al. (2014) investigated climate change impact on buildings energy use at the sub-national level. The study integrated the parameters, such as temperature, population, GDP, and floor space, into the residential and commercial building models at the state level. By using the downscaled temperature of Intergovernmental Panel on Climate Change (IPCC) and the population-weighted HDD/CDDs method, the study projected building energy use at state-level under the IPCC emission scenario A2. Dirks et al. (2015) used the Building ENergy Demand (BEND), combining with DOE's Energy Plus, to simulate climate dependent hourly building energy demands. Huang and Gurney (2016) project the future monthly weather from the World Climate Research Programme's (WCRP) Coupled Model Inter-comparison Project phase 3 (CMIP3). Then the monthly temperature change of CMIP3 added to the current hourly TMY3 temperature data to generate the future hourly weather conditions in each month and location. Their study used Energy Plus to investigate the relationship between climate change and building energy consumption variation across a range of building types at different spatiotemporal scales. In the meantime, Wang and Chen (2014) used the morphing method projecting the future dry-bulb temperature, relative humidity, and wind speed in time slices of 2040 and 2080 for the emission scenarios A1FI, A2, and B1. Their study investigated the

Table 3
The selected projected weather variables of the selected cities in 2080 in the four IPCC scenarios.

Year 2080					
Beijing	**IWEC**	**B1**	**B2**	**A2**	**A1FI**
Dry-bulb Temperature (∘ C)	12.81	15.74	15.78	17.48	18.68
Relative Humidity (%)	55.01	55.93	57.40	57.02	56.70
Wind Speed (m/s)	2.31	2.26	2.27	2.27	2.26
Chicago	**TMY**	**B1**	**B2**	**A2**	**A1FI**
Dry-bulb Temperature (∘ C)	9.75	13.53	13.67	15.35	16.83
Relative Humidity (%)	69.12	64.37	63.86	60.51	59.42
Wind Speed (m/s)	4.62	4.62	4.61	4.63	4.65
Hong Kong	**SAR**	**B1**	**B2**	**A2**	**A1FI**
Dry-bulb Temperature (∘ C)	23.10	24.94	25.17	26.11	26.77
Relative Humidity (%)	78.12	78.36	78.36	78.03	78.02
Wind Speed (m/s)	3.08	3.07	3.04	3.01	3.00
London	**IWEC**	**B1**	**B2**	**A2**	**A1FI**
Dry-bulb Temperature (∘ C)	10.24	12.50	12.57	13.71	14.80
Relative Humidity (%)	79.29	75.45	75.85	74.20	72.25
Wind Speed (m/s)	3.24	3.29	3.27	3.28	3.34
Los Angeles	**TMY**	**B1**	**B2**	**A2**	**A1FI**
Dry-bulb Temperature (∘ C)	16.66	19.52	19.77	20.82	21.83
Relative Humidity (%)	69.98	66.40	67.06	66.18	64.84
Wind Speed (m/s)	3.58	3.55	3.52	3.53	3.53
Miami	**TMY**	**B1**	**B2**	**A2**	**A1FI**
Dry-bulb Temperature (∘ C)	24.31	26.46	26.51	27.47	28.17
Relative Humidity (%)	72.54	72.80	72.96	73.13	72.88
Wind Speed (m/s)	4.34	4.25	4.30	4.39	4.43
Rome	**IWEC**	**B1**	**B2**	**A2**	**A1FI**
Dry-bulb Temperature (∘ C)	15.82	18.25	18.68	19.62	20.77
Relative Humidity (%)	77.66	75.66	75.48	74.99	74.23
Wind Speed (m/s)	3.73	3.71	3.73	3.70	3.69
Sydney	**IWEC**	**B1**	**B2**	**A2**	**A1FI**
Dry-bulb Temperature (∘ C)	12.81	15.74	15.78	17.48	18.68
Relative Humidity (%)	68.78	65.69	64.94	64.35	63.02
Wind Speed (m/s)	3.32	3.38	3.39	3.39	3.39

impact of climate change on the cooling and heating demands for two types of residential buildings and seven types of commercial buildings in U.S.A. by Energy Plus simulation program. Shen (2017) input the "morphed" future hourly weather data to Energy Plus program to predict future energy use pattern for residential and office buildings in four representative cities in the U.S.A. Wang, Liu, and Brown (2017) also applied the morphing method to generate the future weather data files for 2020s, 2050s and 2080s from HadCM3 A2 scenario, and the future weather data files for years 2020–2089 from NCAR Community Earth System Model version 1 (CESM1) for RCP2.6, RCP4.5 and RCP8.0 scenarios. The study then applied Energy Plus program to simulate the energy use and explored the sustainable design of office building by emphasizing the importance of efficiently operating mechanical systems. Jiang, Zhu, Elsafty, and Tumeo (2018) used CCWorldWeatherGen Software to generate future weather data for the periods of the 2020s, 2050s and 2080s to assess electricity and gas consumption of nine types of commercial buildings in eight major cities, representing the climate zones in Florida. Their studies also investigated the mitigation measures on energy consumption of commercial buildings in Florida due to climate change. Table 1 lists the research mentioned above in terms of year, author, future weather scenarios, weather projection method, as well as energy simulation software.

Through the literature review, it shows that there are various future weather projection methods, energy simulation software, green-house gas emission scenarios, and the impact of climate change on the building energy demands are at various rate in different areas (Table 2). The morphing method is the most often used algorithm to project future weather variables. And the IPCC green-house gas emission scenarios are widely used in the analysis on future building energy demands. Although Jentsch et al. developed *CCWorldWeatherGen* program in 2008 by applying the morphing method, the program generates future weather data only under the IPCC emission scenario A2. The primary objective of this project is to develop an application to generate future climate change weather files for building energy simulation programs (e.g. Energy Plus, Visual DOE, TRNSYS) under all four experimented emission scenarios reported by Intergovernmental Panel on Climate Change (IPCC). The application would assist research and professional communities to conduct further research and sensitivity analysis on climate change impact on not only the building energy demands but also infrastructure, coastal engineering and construction, sustainability analysis of buildings and infrastructure, and land use.

2. Methodology

2.1. Climate change models and scenarios

Climate change is considered as the changes in the state of the climate that persists for an extended period, typically in decades or centuries either due to natural driving forces and/or as a result of human activities (Wang et al., 2010). A few global climate models (GCM) for simulating the effects of climate change have been developed. A GCM is a mathematical model of the general circulation of a planetary atmosphere or ocean and based on the Navier–Stokes equations on a rotating sphere with thermodynamic terms for various energy sources (NOAA, 2007). It was originally created by Syukuro Manabe and Kirk Bryan at the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey (Shen, 2017). There are groups of GCM based on the country of origin, grid resolution, and carbon emission scenarios. For example, the Swiss Federal Office of Meteorology and Climatology creates the CH2018 Climate Change Scenarios (https://www.meteoswiss.admin.ch/home/climate/climate-change-in-switzerland/climate-change-scenarios.html). Japan developed MIROC4h (Takashi et al., 2012). UK Climate Impacts Programme (UKCIP02) quantifies the potential impacts of climate change on the UK (Hulme et al., 2002). Among these GCMs, HadCM3 is the most well-known developed by the Hadley Center in the United Kingdom. Like other GCMs, it is a grid point model in which the spatial resolution of each grid cell is 2.5° in latitude and 3.75° in longitude. In the meantime, the model provides the monthly change in dry-bulb temperature, diurnal temperature variation, relative humidity, wind speed, and solar radiation, which have a major impact on the building heating and cooling load and can be found on Intergovernmental Panel on Climate Change (IPCC) website (http://www.ipcc-data.org/sres/hadcm3_download.html) (Wang & Chen, 2014). The monthly changes of the weather variables represent the climate changes of the grid points in time slices 2020, 2050, and 2080 under four future green-house gas emission scenarios assigned by IPCC. Based on social trends, economic growth, technology development, and population and demographic factors, IPCC described four scenario families to account for the implications of future green-house gas emissions on global climate – B1 (low), B2 (medium-low), A2 (medium-high), and A1FI (high) – in 3 time-slices: the 2020s, 2050s and 2080s. The B1 scenario is of a world more integrated, and more ecologically friendly. The economic growth of B1 scenario is characterized by the reduction in material intensity and the introduction of clean and resource efficient technologies. The rapid economic growth changes towards a service and information economy. It emphasizes on global solutions to economic, social and environmental sustainability while the B2 scenario focuses on local rather than global solutions to economic, social and environmental stability. The underlying theme of the A2 scenario is self-reliance and preservation of local identity. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in the other scenario families. A1FI is the worst carbon scenario which is characterized by rapid economic growth and an emphasis on fossil fuels (IPCC, 2000). Due to the well-known developed IPCC assessment reports, this study would project the future climate weather data accounting for the four IPCC scenarios B1, B2, A2, and A1F in 3 time-slices: the 2020s, 2050s and 2080s. Since the grid point of HadCM3 might not coincide exactly with the locations selected by professional

Fig. 2. The projected dry bulb temperatures of four scenarios in three time slices.

and research communities due to the active responses of governments of many countries, states, and counties to the climate change, this study retrieves the longitude and latitude of the selected location and calculates the four closest grid points to the selected location using Euclidean distance. The average of monthly changes of each weather variable at four closest grid points becomes the monthly change of a weather variable of the selected location. However, assessing the impact of climate change on various commercial and residential buildings by running simulation tools, like EnergyPlus, Visual DOE, DOE 2, BEND, HEED, AccuRate or TRNSYS, requires hourly datasets of weather variables. Therefore, downscaling the monthly changes of weather variables to selected location weather at hourly datasets of weather variables becomes urgent. Therefore, a mathematical method is necessity in downscaling procedures.

2.2. Downscaling of global climate change model by the morphing method

Chow and Levermore (2007) proposed Q-Sin method. Wan, Li, and Lam (2011) developed principal component method. Xu et al. (2012) applied statistical downscaling dynamic procedure. Belcher et al. (2005) summarized these downscaling methods as dynamical downscaling, stochastic weather generation and interpolation weather generation, then they proposed the well-known morphing method. After their proposition, a few research projects used the morphing concept to conduct the investigation of impact of climate change on building industry. Jentsch et al. (2008, 2013) applied the morphing concept to investigate the generation of climate change adapted simulation weather data for locations worldwide from readily available data sets. Wang et al. (2010) assessed the impact of climate change on the residential houses in Australia. Jiang and O’Meara (2018), Jiang et al. (2018), Shen (2017) and Wang and Chen (2014) estimated the energy demands of residential and commercial buildings of some typical cities in U.S.A. and in Florida. Their work demonstrated that, until more detailed regional climate model data becomes available globally, “morphing” with GCM data can be considered a viable and practical interim approach due to its computing efficiency.

The morphing method has several practical advantages. First, the “baseline climate” is reliable, because it is the climate of the present-day weather series. Second, the resulting weather sequence is likely to be meteorologically consistent. Third, spatial downscaling is achieved because the present day weather series is obtained from observations at a real location. The basic underlying methodology for “morphing” weather data consists of three different algorithms depending on the weather parameter to be changed (Belcher et al., 2005; Jentsch et al.,

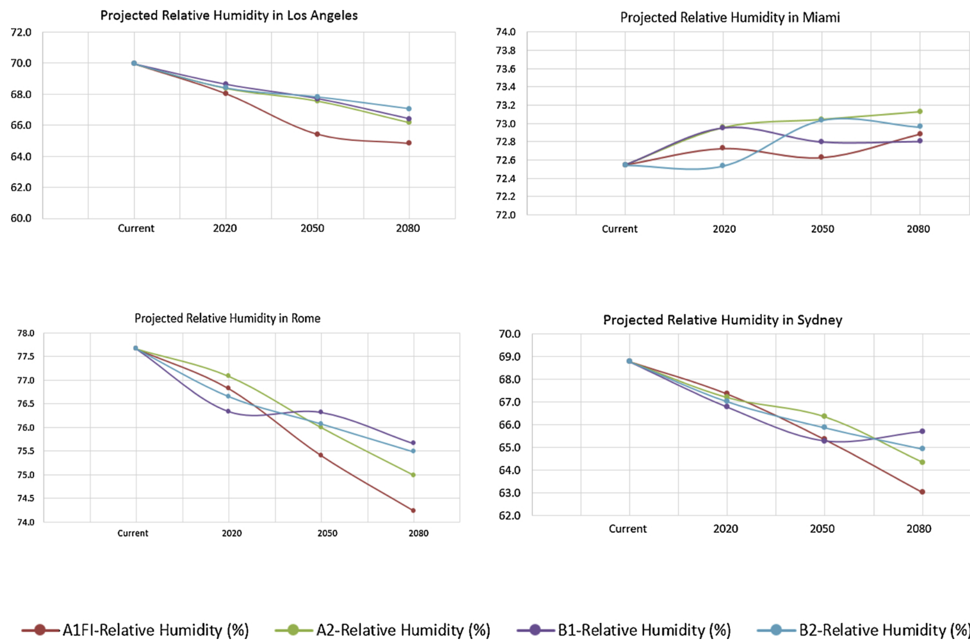

Fig. 3. The projected relative humidity of four scenarios in three time slices.

2008, 2013; Jiang et al., 2018; Shen, 2017; Wang & Chen, 2014; Wang et al., 2010):

(1) a "shift" of a current hourly weather data parameter by adding the predicted absolute monthly mean change:

$$x = x_0 + \Delta x_m$$

where x is the future climate variable, x_0 the original present day variable and Δx_m the absolute monthly change;

(2) a "stretch" of a current hourly weather data parameter by scaling it with the predicted relative monthly mean change:

$$x = a_m x_0$$

where a_m is the fractional monthly change;

(3) a combination of a "shift" and a "stretch" for current hourly weather data. In this method a current hourly weather data parameter is" shifted" by adding the predicted absolute monthly mean change and "stretched" by the monthly diurnal variation of this parameter:

$$x = x_0 + \Delta x_m + a_m (x_0 - (x_0)_m)$$

where $(x_0)_m$ is the monthly mean related to the variable x_0, and a_m is the ratio of the monthly variances of Δx_m and x_0. This method is applied for adjusting the present-day dry bulb temperature.

This study would apply the morphing method to generate the future weather files in that the existing weather data used for the 'morphing' calculations delivers regional and temporal downscaling on the basis of the measured weather station data captured in it (Jentsch et al., 2013)

2.3. Weather files

The weather files used for building energy consumption simulation at a specific location are hourly datasets in a variety of formats depending on country of origin and/or simulation package (Jentsch et al., 2008). For example, RMY is Australia Representative Meteorological Year climate files developed for the Australia Greenhouse Office for use in complying with Building Code of Australia. Chinese Standard Weather Data (CSWD), developed by Tsinghua University and China Meteorological Bureau, includes 270 typical hourly weather data files. The typical year hourly data of Solar and Wind Energy Resource Assessment (SWERA), funded by the United Nations Environment Program, is available for 156 locations in 14 developing countries. International Weather for Energy Calculations (IWEC) data files are typical weather files for 227 locations outside the USA and Canada. City University of Hong Kong (CityUHK) weather data is typical year weather file for Hong Kong, which is originally in IWEC format spreadsheet. (https://energyplus.net/weather/). Among all these weather data formats, the Typical Meteorological Year (TMY2) format, which was developed by the U.S. National Renewable Energy Laboratory (NREL) in the beginning of the 1990s (Marion & Urban, 1995) is the most widely available hourly data format file type. Therefore, this study would input present TMY2 as a baseline weather file format for general use.

In order to give both the research and the professional communities the possibility to undertake climate change impact assessments on buildings, infrastructure, coastal engineering and construction, sustainability analysis, and land use, this study develops the application *Weather Morph: Climate Change Weather File Generator* which can be accessible at http://139.62.210.131/weatherGen/ to generate the future weather data of all four IPCC emission scenarios by using the morphing method. The output of the application is projected future weather datasets in formats TMY2 for general use and EPW (for simulation program Energy Plus which is most widely used in building energy analysis). Due to licensing and copyright issues with both US Department of Energy, Office of Building Technologies and International Panel of Climate Change, Data Distribution Center, the user of this program takes full responsibility for the risk pertaining to the quality, accuracy and performance of the calculated climate change weather data. Under no circumstance will the authors/creators of this tool be liable to any person or entity for any damages, including without limitation any lost profits, lost savings, or other incidental or consequential damages arising out of the use or inability to use the data generated by this website.

3. Results

This study adopts the morphing method to generate future weather data for the carbon emission scenarios B1 (low), B2 (medium-low), A2 (medium-high), and A1FI (high) – in 3 time-slices: the 2020s, 2050s and 2080s. In order to make the results of this work accessible to a wider group of users, a web-based application, has been developed using Djangos which enables end users to generate climate change adapted

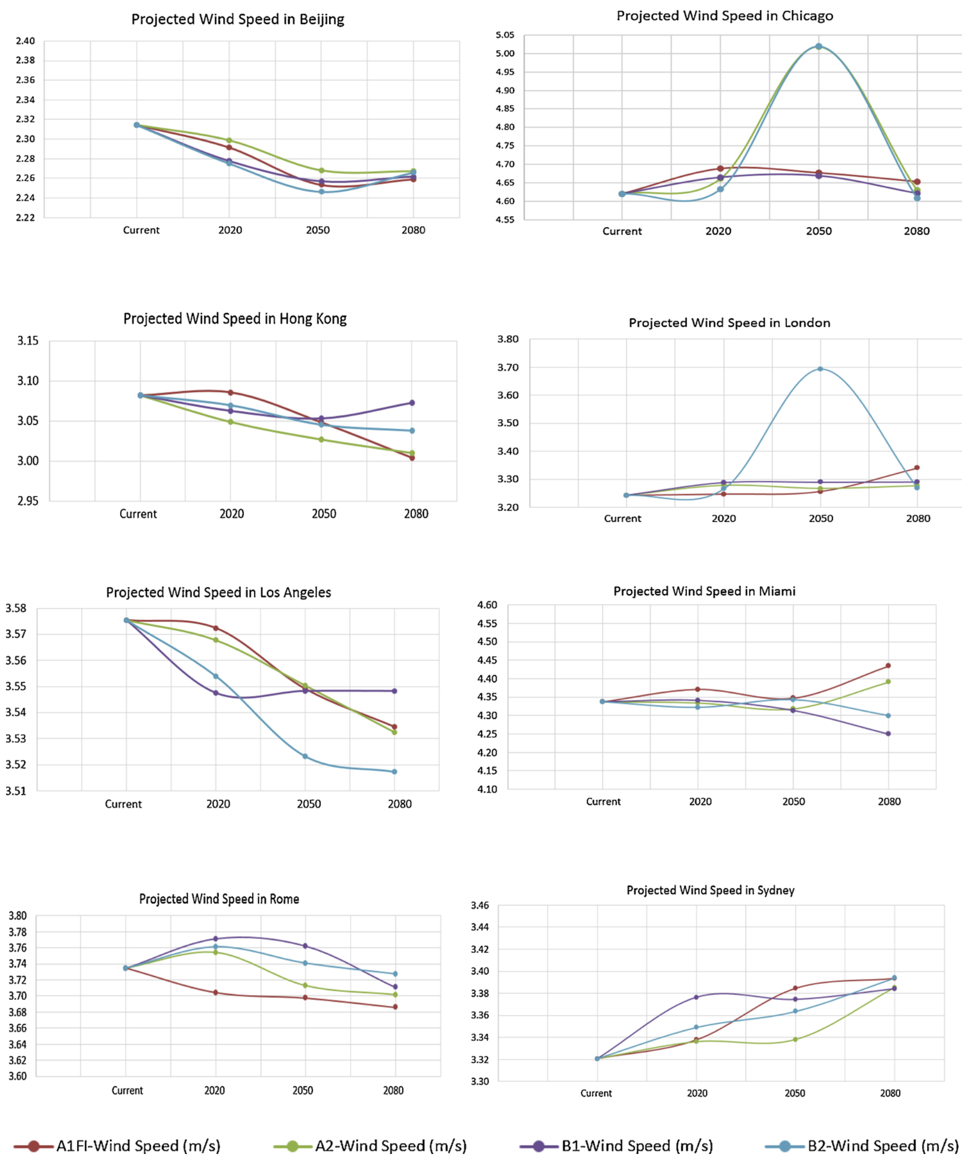

Fig. 4. The projected wind speeds of four scenarios in three time slices.

EPW and TMY2 weather files for any location (more than 2100 locations, 1042 locations in the USA, 71 locations in Canada, and more than 1000 locations in 100 other countries throughout the world) in the world for all four emission scenarios and the three future time slices of the 2020s, 2050s and 2080s. This tool, named *Weather Morph: Climate Change Weather File Generator*, is freely available to the public at http://139.62.210.131/weatherGen/. Comparing to the *CCWorldWeatherGen*, *Weather Morph: Climate Change Weather File Generator* includes the B1, B2, and A1FI carbon emission scenarios except the A2 scenario. This application runs more efficiently in multiple platforms such as Microsoft Windows, Mac OS X, andLinux meanwhile the IPCC HadCM3 files are pre-loaded. This application is visually simplified for ease of use. Further details on obtaining the required data and a description of the tool's function are given in the about and help page of the application. Fig. 1 are the screen shots of the application and corresponding brief illustration of usage.

This study select a few typical cities world-wide to show the results of this study: Beijing, Chicago, Hong Kong, London, Los Angeles, Miami, Rome, and Sydney. The present weather data or baseline weather data of these cities are in various data formats such as IWEC, RMY, CityUHK, as well as TMY. All these baseline weather data at various formats run on this web-based application as input files. The outputs are the projected weather files at either TMY2 or EPW format. Table 3, Figs. 2–4 show the selected values of weather variables of the typical cities for four emission scenarios in three time slices.

4. Conclusion

The global climate change has impact on the communities and people in many perspectives. In order to give both the research and the professional communities the possibility to undertake climate change impact assessments on buildings, coastal engineering and construction, land use and other related areas, this study develops the application *Weather Morph: Climate Change Weather File Generator* to generate the future weather data by using the morphing method. This tool is a web-based application which enables end users to generate future weather variables, such as dry-bulb temperature, solar radiation, wind speed and direction, precipitation, etc. in widely recognized file formats – EPW and TMY2 – for more than 2100 locations throughout the world for all four emission scenarios – B1 (low), B2 (medium-low), A2 (medium-high), and A1FI (high) – in the three future time slices of the 2020s, 2050s and 2080s.

Furthermore, National Renewable Energy Lab (NREL) also provides the latest TMY3 weather files, although TMY2 is the most widely recognized weather file format. The TMY3 files are based on data for 1020 locations in the US derived from a 1976–2005, and a 1991–2005 period of record for all other locations, while the TMY2 weather files are data between 1961 and 1990 based on 239 stations in the US. Because TMY3 are based on more recent and accurate data, the TMY3 weather files are recommended for use in place of earlier TMY2 data in some simulation software. Under this situation, the end users of this web-based future weather generator could reformat TMY3 data to TMY2 and EPW data by using a conversion program provided by NREL. Then end users could use the *Weather Morph: Climate Change Weather File Generator* to project the future weather files in EPW and TMY2 formats.

Acknowledgement

The authors are grateful to the Academic Affairs Office of the University, where the authors work, sponsoring this project.

References

Arima, Y., Ooka, R., Kikumoto, H., & Yamanaka, T. (2016). Effect of climate change on building cooling loads in Tokyo in the summers of the 2030s using dynamically downscaled GCM data. *Energy and Buildings, 114*, 123–129.

Asimakopoulos, D. A., Santamouris, M., Farrou, I., Laskari, M., Saliari, M., Zanis, G., et al. (2012). Modelling the energy demand projection of the building sector in Greece in the 21st century. *Energy and Building, 49*, 488–498.

Belcher, S. E., Hacker, J. N., & Powell, D. S. (2005). Constructing design weather data for future climates. *Building Services Engineering Research and Technology, 26*(1), 49–61.

Chan, A. L. S. (2011). Developing future hourly weather files for studying the impact of climate change on building energy performance in Hong Kong. *Energy and Building, 43*(10), 2860–2868.

Chow, D. H. C., & Levermore, G. (2007). New algorithm for generating hourly temperature values using daily maximum, minimum and average values from climate models. *Building Services Engineering Research and Technology, 28*(3), 237–248.

Frank, T. H. (2005). Climate change impacts on building heating and cooling energy demand in Switzerland. *Energy and Buildings, 37*, 1175–1185.

Huang, J., & Gurney, K. R. (2016). The variation of climate change impact on building energy consumption to building type and spatiotemporal scale. *Energy, 111*, 137–153.

Hulme, M., Jenkins, G. J., Lu, X., Turnpenny, J. R., Mitchell, T. D., Jones, R. G., Lowe, J., Murphy, J. M., Hassell, D., Boorman, P., McDonald, R., & Hill, S. (2002). *Climate change scenarios for the United Kingdom: The UKCIP02 scientific report*Norwich, UK: Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia.

IPCC (2000). *IPCC Special Report on Emissions Scenarios (SRES): Summary for policymakers—A special report of IPCC working group III intergovernmental panel on climate change*Geneva, Switzerland: IPCC.

Dirks, J. A., Gorrissen, W. J., Hathaway, J. H., Skorski, D. C., Scott, M. J., Pulsipher, T. C., et al. (2015). Impacts of climate change on energy consumption and peak demand in buildings: A detailed regional approach. *Energy, 79*, 20–32.

Jentsch, M. F., Bahaj, A. S., & James, P. A. B. (2008). Climate change future proofing of buildings—Generation and assessment of building simulation weather files. *Energy and Buildings, 40*(12), 2148–2168.

Jentsch, M. F., James, P. A. B., Bourikas, L., & Bahaj, A. S. (2013). Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates. *Renewable Energy, 55*, 514–524.

Jiang, A., Zhu, Y., Elsafty, A., & Tumeo, M. (2018). Effects of global climate change on building energy consumption and its implications in Florida. *International Journal of Construction Education and Research, 14*(1), 22–45.

Jiang, A., & O'Meara, A. (2018). Accommodating thermal features of commercial building systems to mitigate energy consumption in Florida due to global climate change. *Energy and Buildings, 179*, 86–98.

Kikumoto, H., Ooka, R., Arima, Y., & Yamanaka, T. (2014). Study on the future weather data considering the global and local climate change for building energy simulation. *Sustainable Cities and Society, 14*, 404–413.

Lam, J. C., Wan, K. W., Lam, T. N. T., & Wong, S. L. (2010). An analysis of future building energy use in subtropical Hong Kong. *Energy, 35*, 1482–1490.

Lam, T. N. T., Wan, K. K. W., Wong, S. L., & Lam, J. C. (2010). Impact of climate change on commercial sector air conditioning energy consumption in subtropical Hong Kong. *Applied Energy, 87*(7), 2321–2327.

Marion, W., & Urban, K. (1995). *User's manual for TMY2s—Typical meteorological years.* Golden, Colorado, USA: National Renewable Energy Laboratory.

NOAA (2007). *The first climate model.* National Oceanic and Atmospheric Administration.

Olonscheck, M., Holsten, A., & Kropp, J. P. (2011). Heating and cooling energy demand and related emissions of the German residential building stock under climate change. *Energy Policy, 39*, 4795–4806.

Radhi, H. (2009). Evaluating the potential impact of global warming on the UAE residential buildings—A contribution to reduce the CO2 emissions. *Building and Environment, 44*, 2451–2462.

Sabunas, A., & Kanapickas, A. (2017). Estimation of climate change impact on energy consumption in a residential building in Kaunas, Lithuania, using HEED software. *Energy Procedia, 128*, 92–99.

Sakamoto, T., Tatebe, H., Shiogama, H., Hasegawa, A., Toyoda, T., Mori, M., et al. (2012). MIROC4h—A new high-resolution atmosphere-ocean coupled general circulation model. *Journal of the Meteorological Society of Japan, 90*(3), 325–359.

Shen, P. (2017). Impacts of climate change on U.S. building energy use by using downscaled hourly future weather data. *Energy and Building, 134*, 61–70.

Takashi, T. S., Yoshiki, K., Teruyuki, N., Masayoshi, I., Hiroaki, T., Hideo, S., et al. (2012). MIROC4h—A new high-resolution atmosphere-ocean coupled general circulation model. *Journal of the Meteorological Society of Japan, 90*(3), 325–359.

The World Climate Research Programme (2019). *The World Climate Research Programme's (WCRP's) coupled model intercomparison project phase 3 (CMIP3) multi-model dataset.* Available athttp://gdo-dcp.ucllnl.org/downscaledcmip_projections/n.d.

Wan, K. K. W., Li, D. H. W., & Lam, J. C. (2011). Assessment of climate change impact on building energy use and mitigation measures in subtropical climates. *Energy, 36*, 1404–1414.

Wan, K. K. W., Li, D. H. W., Pan, W., & Lam, J. C. (2012). Impact of climate change on building energy use in different climate zones and mitigation and adaptation implications. *Applied Energy, 97*, 274–282.

Wang, H., & Chen, O. (2014). Impact of climate change heating and cooling energy use in buildings in the United States. *Energy and Buildings, 82*, 428–436.

Wang, L., Liu, X., & Brown, H. (2017). Prediction of the impacts of climate change on energy consumption for a medium-size office building with two climate models. *Energy and Buildings, 157*, 218–226.

Wang, X., Chen, W. X. D., & Ren, Z. (2010). Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. *Building and Environment, 45*, 1663–1682.

Xu, P., Huang, Y. J., Miller, N., Schlegel, N., & Shen, P. (2012). Impacts of climate change on building heating and cooling energy patterns in California. *Energy, 44*(1), 792–804.

Zhou, Y., Clarke, L., Eom, J., Kyle, P., Patel, P., Kim, S. H., et al. (2014). Modeling the effect of climate change on U. S. state-level buildings energy demands in an integrated assessment framework. *Applied Energy, 113*, 1077–1088.

Zhu, M., Pan, Y., Huang, Z., & Xu, P. (2016). An alternative method to predict future weather data for building energy demand simulation under global climate change. *Energy and Buildings, 113*, 74–86.