Future weather files to support climate resilient building design in Vancouver

M. Ek[a], T. Murdock[b,*], S. Sobie[b], B. Cavka[c], B. Coughlin[a], R. Wells[d]

[a] RDH Building Science Inc., Vancouver, Canada, mek@rdh.com
[b] Pacific Climate Impact Consortium, The University of Victoria, Canada
[c] Department of Civil Engineering, The University of British Columbia, Canada
[d] Sustainability and Engineering, The University of British Columbia, Canada

Abstract:
Since local weather and climate greatly affect the construction and performance of buildings, reliable meteorological data is essential when simulating building performance. It is well understood that climate change will affect future weather and there is a growing interest in generating future weather files to support climate resilient building design. Weather files that account for climate change have not been widely used for the lower mainland region of British Columbia. In this study, hourly weather files for future climate conditions in Vancouver are created for three time periods using a "morphing" methodology. Morphing uses results from global climate models to adjust observed weather data at a specific location. In this study, daily data from climate simulations for the RCP8.5 emission scenario have been used. The weather variables that have been adjusted are dry-bulb temperature, relative humidity, solar radiation, cloud cover, wind speed and atmospheric pressure. The impact of climate change on the energy performance of a multi-unit residential building located on the University of BC campus is analyzed using the energy modelling software EnergyPlus. The simulation results indicate that the changing climate in Vancouver, following RCP8.5, would have a considerable effect on building energy performance and energy demand due to decrease in space heating and increase in cooling requirements.

Keywords:
Weather File, Climate Change, Energy Modelling, Building Simulation, Downscaling

1. Introduction

Dynamic building simulation is an important tool in analyzing the energy performance of building design options. The performance of building envelopes as well as heating and cooling systems are greatly affected by local climate. Therefore, reliable meteorological data is essential when simulating building performance to achieve energy efficient and comfortable buildings. It is well understood that climate change will affect future weather [1]. Since typical building lifetimes can be around 60 years or more, weather files need to cover projected future changes [2]. This has been acknowledged globally and there is a growing interest in using weather files that account for climate change [2-6].

The impact of climate change on energy use patterns in the building sector is poorly understood in the lower mainland region of British Columbia. In this study, hourly weather files for future climate conditions are produced to investigate potential implications for building energy performance in Vancouver.

This project was initiated by the University of British Columbia (UBC) Sustainability and Engineering and was carried out in conjunction with two main project partners: Pacific Climate Impact Consortium (PCIC) and RDH Building Science.

2. Methodology

Several methods can be used to construct weather files for building simulation [1,2]. As a first step, the methodology in this study is based on the work by Belcher et al. [3], referred to as morphing. The concept behind morphing is to generate weather files that account for future climate changes by adjusting historical observations with results from simulations made with global and/or regional climate models.

The morphing methodology has been widely used to predict the impact of climate change on building performance [7-11]. A key reason often cited is because it allows for spatial and temporal downscaling using site-specific weather data so that future projections can be generated that preserve the characteristics of the weather for the specific station. This feature may also have some unintended consequences [12]. In this study, implementation of morphing is considered a first step in producing future weather files, with considerable avenues of further work to investigate (see Conclusions).

The scope of this preliminary investigation was to apply morphing techniques that have been used elsewhere, with only one modification (using daily rather than monthly climate projections). It was beyond the scope of this first step to evaluate the morphing operations used for each parameter and the implications that different choices would have. However, this is an

important aspect to evaluate. Several recommendations for further research are provided in the conclusions.

2.1 Climate Change Correction

The first step in the morphing procedure is to create baselines that represent current and future climate. Baselines consist of climate data for each day of the year and are defined by taking the average of climate simulations over a 30-year period [13].

Daily simulations for the parameters (see Table 2) were available from eight global climate models (GCMs). These GCMs are listed in Table 1.

Table 1: The global climate models used to simulate present-day and future climate baselines.

Global Climate Model
CNRM-CM5
CanESM2
ACCESS1-0
Inmcm4
MIROC5
GFDL-ESM3g
MRI-CGCM3
GFDL-ESM3G

Daily climate projections for the simulation period 1950-2100 were provided by Pacific Climate Impact Consortium (PCIC). For temperature and precipitation PCIC offers statistically downscaled climate data for Canada. Data from GCMs were downscaled to a gridded resolution of roughly 10 km by using Bias-Correction/Constructed Analogues with Quantile mapping reordering (BCCAQ) [14]. For the rest of the weather variables (see Table 2) climate data were provided by PCIC with a gridded resolution of roughly 100 km.

In this study, simulations under the assumption of the RCP8.5 emission scenario are used. In 2014 the IPCC finalized the fifth Assessment Report (AR5) which includes four greenhouse gas concentration pathways, the so called Representative Concentration Pathways (RCPs). These scenarios describe possible climate futures depending on how much greenhouse gases that are emitted in the years to come. The RCP8.5 scenario roughly reflects a 'business as usual' scenario [15].

To define the present-day climate baseline, simulations for the time period 1971-2000 are used. Three future time periods are studied: centred on 2020s, 2050s and 2080s (i.e., 2011-2040, 2041-2070, 2071-2100).

When the present-day and future climate baselines are defined the climate 'correction factors' can be determined. The 'correction factors' represent the change in the daily mean value for each variable.

The remaining section is following the convention of Belcher et al [3]:

The absolute change between the future and present-day baseline for day *d* is called 'shift factor', Δx_d, and is calculated by equation 1.

$$\Delta x_d = \langle x_{future} \rangle_d - \langle x_{present} \rangle_d \quad (1)$$

The fractional change between the future and present-day baseline for day *d* is called 'stretch factor', α_d, and is calculated by equation 2.

$$\alpha_d = \frac{\langle x_{future} \rangle_d}{\langle x_{present} \rangle_d} \quad (2)$$

Unlike the previously mentioned studies [7-11] in which monthly climate projections were used to create future weather files, the climate projections used in this study are daily time series.

2.2 Morphing operation

After the climate correction factors are generated, the next step is to adjust observed data. This is achieved by creating algorithms where a function of the difference between the climate baselines is applied to the existing data. These algorithms are based on three different operations, following Belcher et al., equation 3-5 demonstrate the operations. Note that these methods include an estimation of change in diurnal cycle because they were designed for use with monthly climate projections. The next step in this work is to re-evaluate which variables are shifted, stretched, or both – and if some variables should not be adjusted at all (see conclusions). The choice of which changes were applied to which variables in this initial investigation follows the conventions of Belcher et al. (see section 2.3 and Table 2).

Shift

$$x = x_0 + \Delta x_d \quad (3)$$

x : future hourly weather variable
x_0 : hourly observed weather variable
Δx_d : shift factor, predicted absolute change in the daily mean value of the variable for day *d*

The shift operation adds the projected absolute change obtained from climate model simulations and as a result the observed weather data for a given day is shifted by Δx_d. The daily variance of the variable remains unchanged. The new daily mean value of the variable is $\langle x \rangle_d = \langle x_0 \rangle_d + \Delta x_d$, where $\langle x_0 \rangle_d$ is the observed present-day daily mean value of the variable, x_0, for day *d.*

Stretch

$$x = \alpha_d x_0 \quad (4)$$

α_d : stretch factor, predicted fractional change in the daily value of the variable for day *d*

The stretch operation multiplies the observed weather data by the predicted fractional change obtained from climate model simulations. As a result, the observed weather data is scaled with α_d. This operation changes the daily mean and variance of the future weather variable. The daily mean value becomes $\langle x \rangle_d = \alpha_d \langle x_0 \rangle_d$ and the daily variance becomes $\langle \sigma^2 \rangle_d = {\alpha_d}^2 \langle {\sigma_0}^2 \rangle_d$, where $\langle {\sigma_0}^2 \rangle_d$ is the daily variance of the observed weather data for day *d*.

Combination of shift and stretch

$$x = x_0 + \Delta x_d + \alpha_d \times (x_0 - \langle x_0 \rangle_d) \quad (5)$$

The third operation is a combination of a shift and a stretch. The current hourly weather data is shifted by adding the predicted absolute change and stretched by a predicted diurnal ratio of the variable. This approach is applied when both the mean and variance of the variable is changed. This operation results in a change in the daily mean value and variance of the future weather variable. The new mean value is $\langle x \rangle_d = \langle x_0 \rangle_d + \Delta x_d$ and the new daily variance is $\langle \sigma^2 \rangle_d = {\alpha_d}^2 \langle {\sigma_0}^2 \rangle_d$.

2.3 Current and future weather files for Vancouver

In North America, the most commonly used weather file for building energy performance simulations is called Typical Meteorological Year (TMY) [16]. A TMY file represents the typical long-term weather pattern and is created by analyzing 15-30 years of historical hourly data for the specific site [17].

In this study, the open-source software EnergyPlus is used as the simulation tool. EnergyPlus provides weather files in the TMY format for cities around the world, commonly referred to as 'EnergyPlus/ESP-r Weather' (EPW). The EPW file currently used in EnergyPlus for Vancouver is based on observed data from YVR for the time period 1960-1985 [18]. It was decided that the most suitable approach was to develop climate change adapted TMY files and to provide them as EPW files.

In this study, the EPW file for Vancouver is morphed. Table 2 summarizes the weather variables that are adjusted, together with the required projected climate variables and the algorithm used to generate future data. For each variable, an algorithm has been designed in Matlab to suit the format of the climate data. The choice of morphing algorithm for each variable is presented below, following the work by Belcher et al. [3].

Dry Bulb Temperature (°C)

The methodology proposes to change the mean and the variance of the existing dry bulb temperature (daily mean surface temperature). This is achieved by the third morphing operation, a combination of a shift and a stretch.

Relative humidity (%)

Following Belcher et al. a stretch operation is applied to calculate the morphed relative humidity. The change between the climate baselines is therefore calculated as a fractional change.

Atmospheric Pressure (Pa)

The climate models provide daily values for sea level pressure. The change in the atmospheric pressure is assumed to be the same as the change in sea level pressure. A shift factor calculated based on the change in sea level pressure is applied to the observed atmospheric pressure to compute the future atmospheric pressure.

Global horizontal radiation (Wh/m^2)

The global horizontal radiation is the total amount of direct and diffuse solar radiation received on a horizontal surface. For the global horizontal radiation, it is recommended to stretch the observed data. The stretch operation had to be adopted to avoid the operation resulting in irradiance at night.

Direct normal radiation (Wh/m^2)

The direct normal radiation is the amount of solar radiation received directly from the solar disk on a surface perpendicular to the sun's rays. Climate model simulations for direct normal radiation are not readily available. Therefore, an indirect method is applied. It is assumed that the distribution between direct and diffuse radiation is unchanged. The direct normal radiation can be calculated using the generated future data for global and diffuse horizontal radiation.

Table 2 : Morphed EPW weather variables along with climate projection parameters and an overview of the methodology used to generate future weather data

EPW node	EPW weather variable (unit)	Climate projection parameter (unit)	Methodology for future weather data generation
N6	Dry bulb temperature (ºC)	tasmin: minimum air temperature tasmax: maximum air temperature (all ºC)	Combined shift and stretch using tasmin, tasmax and calculated predicted mean temperature (ºC)
N8	Relative humidity (%)	rhs: relative humidity	Stretch of EPW data using rhs
N9	Atmospheric pressure (Pa)	psl: air pressure at sea level (Pa)	Shift of EPW data using psl
N13	Global horizontal radiation (Wh/m^2)	rsds: surface downwelling shortwave (W/m^2)	Stretch of EPW data using rsds
N14	Direct normal radiation (Wh/m^2)	-	Calculated by assuming that the relationship between N13, N14 and N15 remains the same
N15	Diffuse horizontal radiation (Wh/m^2)	-	Stretch of EPW data using the same stretch factor as for N13
N21	Wind speed (m/s)	uas: eastward wind (m/s) vas: northward wind (m/s)	Stretch of EPW data using the magnitude of the two vectors
N22	Total sky cover (tenths of sky)	clt: cloud area fraction (%)	Shift of EPW data using clt

Diffuse horizontal radiation (Wh/m^2)

As with direct normal radiation, climate data is not available for diffuse horizontal radiation. It is assumed that the change in diffuse horizontal radiation is proportional to the change in global horizontal radiation. The observed data for diffuse horizontal radiation is morphed using the calculated scaling factor for global horizontal radiation.

Wind speed (m/s)

The wind speed data series is calculated by applying a shift operation to the observed data,

Total cloud cover (tenths of sky)

Following Belcher et al. a stretch operation is applied to calculate the morphed cloud cover. The change between the baselines is therefore calculated as a fractional change.

2.4 Impact of climate change on building energy performance in Vancouver

The future hourly weather data for each scenario is compiled and formatted into EPW files using the software tool Elements [19]. To understand the potential impact of climate change on building energy use in Vancouver, the generated weather files are used to carry out an initial energy analysis.

In this study, the energy performance of a typical high-rise under current building code in Vancouver, located on the UBC campus, is simulated. The archetype was designed by RDH Building Science, as part of a project where building designs were explored to support development of UBC's green building strategy. The archetype consists of a 22-storey multi-unit residential building and sixteen 2-storey townhouses. The archetype includes a mechanical cooling system and is connected to UBC's district heating system. The total floor area of the building is approximately 26 600 m^2 [20].

The model was run with the EPW currently provided in EnergyPlus, and with the weather files created using the morphing process. The future building energy performance was simulated under the assumption that no technological advances are going to take place.

3. Results and discussions

Table 3 shows the annual mean value of each morphed weather variable. The results indicate that dry-bulb temperature and relative humidity are the variables that will experience the most change.

Table 3: Annual mean value of the morphed weather data

Weather Variable	Present-day	2020s	2050s	2080s
Dry-bulb temperature (ºC)	9.7	11.1	12.4	14.1
Relative humidity (%)	60.3	79.5	79.2	79.1
Atmospheric pressure (kPa)	101.6	101.6	101.6	101.6
Global horizontal radiation (Wh/m^2)	140.4	140.8	141.7	142.9
Direct normal radiation (Wh/m^2)	147.1	155.4	155.3	154.0
Diffuse horizontal radiation (Wh/m^2)	59.6	59.8	60.2	60.9
Wind speed (m/s)	3.35	3.39	3.46	3.47
Total sky cover (tenths of sky)	6.75	6.75	6.74	6.72

Figure 1 and 2 below demonstrate the morphing process on dry-bulb temperature. Figure 1 shows the simulated shift factors for dry-bulb temperature for each time scenario.

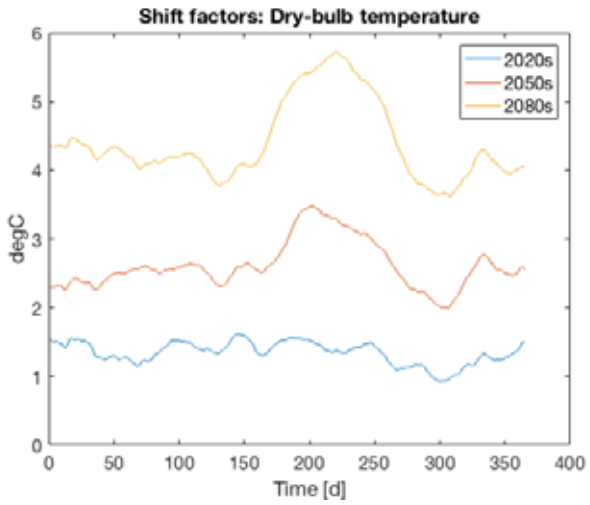

Figure 1: Shift factors for dry-bulb temperature for each time scenario from 8 BCCAQ downscaled GCMs

Figure 2 shows the final climate change adjusted hourly data for dry-bulb temperature under four days in May, together with data from the EPW file for the same time period.

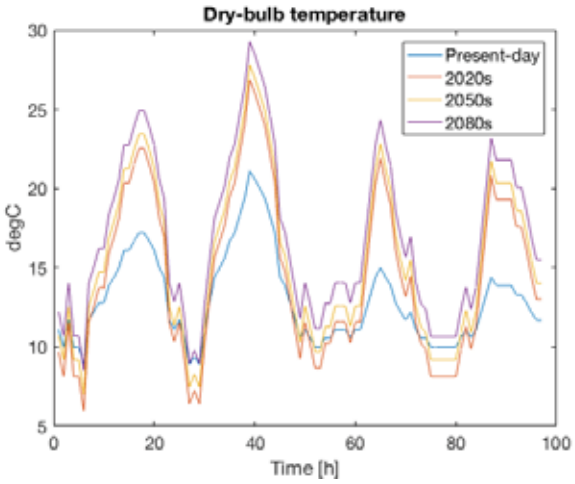

Figure 2: Climate change adjusted hourly data for dry-bulb temperature together with EPW data for four selected days

Figure 3 shows the mean monthly dry-bulb temperature for each weather file.

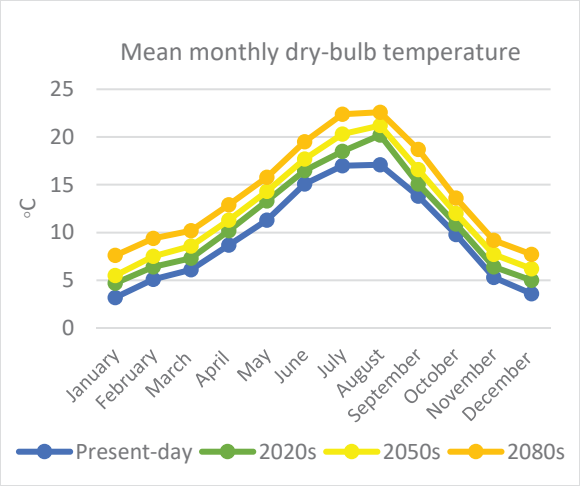

Figure 3: Mean monthly dry-bulb temperature for each weather file

Figure 4 shows the daily standard deviation for dry-bulb temperature, for all four weather files. Note that all sub-daily variability comes from the historical hourly data in the weather files. The standard deviation for dry-bulb temperature is higher for the generated weather files than for the observed weather file. This is due to the use of shift and stretch and indicates that for the predicted future dry-bulb temperature there is a larger variance from the daily mean value. This suggests that application of both a shift and stretch to temperature when using daily climate simulations amplifies the change in diurnal cycle. The effect on the present results is likely an underestimation of the reduction in heating (note in Figure 2 how the stretch causes colder days than present to occur in the coldest hours of the day), and likely an overestimation of the increase in cooling.

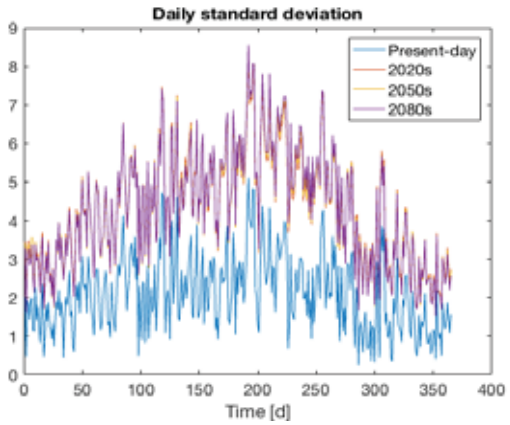

Figure 4: Daily standard deviation for temperature from each weather file

Findings from the building energy analysis are presented below. Figure 5 shows the monthly space heating load for each time scenario.

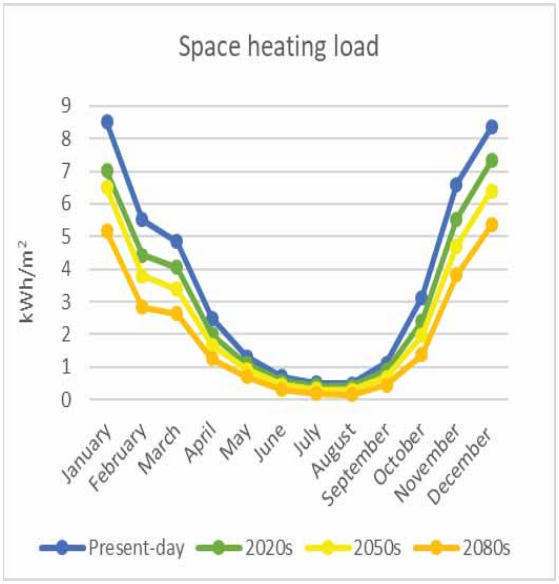

Figure 5: Monthly space heating load for each time scenario

Figure 6 shows the cooling load for each time scenario.

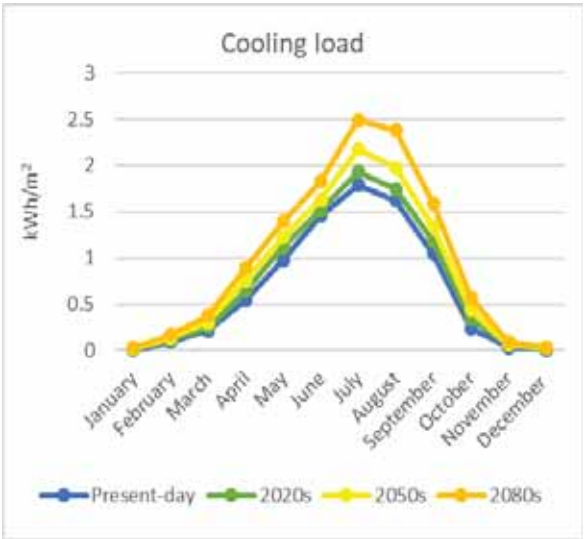

Figure 6: Monthly cooling load for each time scenario

Table 4 shows the percent change in electricity and district heating demand for each time scenario, compared to the results given when using the present-day EPW file.

Table 4: Percent change for electricity and district heating demand for each time scenario

	2020s	2050s	2080s
Electricity			
Cooling	16%	31%	54%
Pumps	5%	10%	17%
Heat Rejection	8%	15%	25%
Total Electricity Demand	2%	4%	6%
District Heating			
Heating	-15%	-27%	-43%
Total District Heating Demand	-10%	-18%	-28%
Total Energy Demand	-3%	-6%	-9%

The findings in this research project indicate that the total energy demand for the studied archetype will slightly decrease with time. The demand for space heating is expected to decline with time and the cooling load to increase with time. For UBC, this means a reduced dependency on district heating (natural gas) and a higher electrical demand. This would have a positive effect on UBC's greenhouse gas (GHG) emissions. However, an increase in electricity load during cooling season is going to exert a greater pressure on the electricity grid. This may result in failure in the power grid and in turn lead to a need to purchase electricity, which may not be GHG neutral.

4. Conclusions and outlook

In this study, weather data in the EPW file currently used in EnergyPlus is adjusted for climate change. The EPW file is in the TMY format, which captures typical weather conditions at a specific site. However, TMY files by design represent "typical" (median) conditions and thus will not include extreme weather events. It is likely that extreme weather events will become more common in the future as a result of climate change. Designing buildings for typical conditions could lead to future vulnerability. To allow designers and engineers to stress test building performance and adapt building design for atypical conditions further research is recommended to focus on creating weather files that represent hotter than average conditions, including extreme events.

Further, a set of raw data for a specific weather station, where each year is different from the previous one could be morphed. This would offer an alternative to the traditionally used TMY file which would allow to assess the impact of climate change on building design options while introducing year-to-year variability.

Morphing is a class of bias corrections which can have unintended effects on results [12]. The next step in using morphing of weather files on a wider basis is to systematically evaluate the consequences of choices of whether to use shift, stretch, or both for each parameter, and indeed whether to make use of morphing for each variable at all (i.e. if for some variables historical values should remain unadjusted).

Alternatively to morphing the weather file, past and future simulated weather could be constructed from a GCM simulation directly with station data only used for hourly information and variables not present in the GCMs.

A simplified method to predict future solar radiation has been used in this study. It is assumed that the distribution between diffuse and direct solar radiation in unchanged. The diffuse solar radiation is affected by cloud cover. In this initial study, the solar radiation and cloud cover are computed independently and the results are not consistent with each other. Since solar radiation has a considerable effect on the energy performance of buildings, these parameters need further work.

In this study, the impact of climate change on a MURB located on UBC campus is analyzed. The building energy simulation is conducted using the software EnergyPlus. The simulation results show that the cooling load can be expected to increase with time, and the heating load to decrease with time. Moreover, the demand for cooling is expected to increase during cooling season. With a warmer climate, there is an increased risk for overheating in buildings. Thermal comfort and risk analysis are not in the scope of this project. To enhance the understanding of overheating risk in the future, further simulations could focus on analysing thermal comfort on zone level under high temperature events. Understanding of overheating during near-extreme weather events is of specific importance.

Further analysis is recommended to understand the impact of climate change on thermal and energy performance of archetypes with different design options such as size and orientation, as well as building design features including window-to-wall ratio, glazing, shadings, thermal insulation, natural ventilation

strategies etc. There is a growing interest in energy-efficient building design with strong envelopes, such as passive-houses and net zero buildings. It is important to understand how these envelopes will perform under a changing climate and if today's targets will be met also in the future.

Buildings that are built today, as well as existing buildings, will experience future climate conditions. The results from this study indicate that analyzing future performance of buildings can be expected to become increasingly important. It is crucial that we consider future vulnerability and understand future design options as well as retrofit pathways to achieve climate resilient buildings.

Weather files that account for climate change are important tools to evaluate future building performance. However, it is important that users are aware of the limitations and the uncertainties when conducting building performance simulations.

Acknowledgements

The authors are grateful for the financial support provided by UBC Sustainability and Engineering, and coordination support provided by David Gill and the UBC SEEDS program.

References

[1] IPCC. Climate Change 2014 – Impact, Adaptation and Vulnerability: Part B: Regional Aspects (2015).

[2] Herrera, M., Natarajan, S., Coley, D.A., Kershaw, T., Ramallo-Gonzalez, A.P., Eames, M., Fosas, D., Wood, M. A review of current and future weather data for building simulation. Building Service Engineering Research and Technology 0 (2017) 1-26
Prev. 9

[3] Belcher SE., Hacker JN., Powell DS. Constructing design weather data for future climates. Building Services Engineering Research and Technology 26 (2005) 46-61.

[4] Guan, L. Preperation of future weather data to study the impact of climate change on buildings. Building and Environment 44 (2009) 793-800.

[5] Jentsch, M.F., Eames, M.E., Levermore, G.J. Generating near-extreme Summer Reference Years for building performance simulation Building Services Engineering Research & Technology 36 (2015) 701-727.

[6] Nik, V.M. Making energy simulation easier for future climate – Synthesizing typical and extreme weather data sets out of regional climate models (RCMs). Applied Energy 177 (2016) 204-226.[7] Jentsch, M.F., Bahaj, A.S., James, P.A.B. Climate change future proofing of buildings – Generation and assessment of building simulation weather files. Energy and Buildings 40 (2008) 2148-2168.

[8] Chan, A.L.S. Developing future hourly weather files for studying the impact of climate change on building energy performance in Hong Kong. Energy and Buildings 43 (2011) 2860-2868.

[9] Robert, A., Kummert, M. Designing net-zero energy buildings for the future climate, not for the past. Building and Energy 55 (2012) 150-158.

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

[11] Shen, P. Impact off climate change on U.S building energy use by using downscaled hourly future weather data. Energy and Buildings 134 (2017) 61-70.

[12] Maraun, D., Stepherd, T.G., Widmann, M., Zappa, G., Walton, D., Gutiérrez, J.M., Hagemann, S., Richter, I., Soares, P.M.M., Hall, A., Mearns, L.O., Towards process-informed bias correction of climate change simulations. Nature Climate Change, vol 7 (2017).

[13] World Meteorological Organization [online]. https://public.wmo.int/en/our-mandate/climate; 2010 [accessed 0.1.08.2017].

[14] Pacific Climate Impact Consortium, University of Victoria. Statistically Downscaled Climate Scenarios [online]https://www.pacificclimate.org/data/statistically-downscaled-climate-scenarios;2016
[accessed 01.08.2017]

[15] Van Vuuren, D.P., Edmonds, J.A., Kainuma, M., Riahi, K., Weyant, J. A special issue on the RCPs. Climate Change (2011) 109:1-4.

[16] Doggett, M.S. Climate Data for Building Simulations [online]. https://builtenv.wordpress.com/2014/02/27/climate-data-for-building-simulations/; 2014 [accessed 01.11.2017].

[17] Chow, T.T., Chan., A.L.S., Fong., K.F., Lin., Z. Some perceptions of typical weather year – from the observations of Hong Kong and Macau. Solar Energy 80 (2006) 459-467.

[18] EnergyPlus, U.S. Department of Energy (DOE). Weather Data [online]. https://energyplus.net/weather; [accessed 01.06.2017].

[19] Big Ladder Software. Elements [online]. http://bigladdersoftware.com/projects/elements/; 2016 [accessed 01.08.2017].

[20] RDH Building Science. UBC Modelling Study: Residential Archetypes. Report prepared for UBC Sustainability and Engineering (2017)

2018

NHICE 01

Conference Proceedings

1st International Conference on New Horizons in Green Civil Engineering

April 25 – 27, 2018, Victoria, British Columbia, Canada

Editor: Phalguni Mukhopadhyaya

University of Victoria

BC HOUSING

Copyright © 2018, Printed by the University of Victoria, British Columbia, Canada

This conference proceeding is released under a Creative Commons Attribution-Non-commercial- Share Alike 4.0 license (CC-BY-NC-SA). See creativecommons.org/ for more information. This proceeding, or parts of it, may be reproduced for non-commercial purposes, provided that proper attribution is given to the original author.

The author grants the publisher a royalty-free worldwide non-exclusive license to publish, reproduce, display, distribute, archive and use the Article as part of the conference proceedings.

ISBN: 978-1-55058-620-6

Foreword

This compilation of papers contains papers from the *1st International Conference on New Horizons in Green Civil Engineering* (http://nhice.engr.uvic.ca), held on April 25 – 27, 2018, Victoria, British Columbia, Canada. The conference was organized by the University of Victoria (www.uvic.ca) and sponsored by BC Housing (www.bchousing.org).

Conference Chair and Editor:

Phalguni Mukhopadhyaya
University of Victoria
Victoria, BC, Canada

Scientific Committee

Andrew Rowe	University of Victoria	Canada
Ashutosh Bagchi	Concordia University	Canada
Atsushi Iwamae	Kindai University	Japan
Bijan Adl-Zarrabi	Chalmers University of Technology	Sweden
Bjørn Petter Jelle	Norwegian University of Science and Technology	Norway
Brahim Benmokrane	University of Sherbrooke	Canada
Caterina Valeo	University of Victoria	Canada
Chris Bachmann	University of Waterloo	Canada
Daisuke Ogura	Kyoto University	Japan
Daniel Hoornweg	University of Ontario Institute of Technology	Canada
Denisa Ionescu	BC Housing	Canada
Dominique Derome	Swiss Federal Laboratories for Mat. Sci. and Tech.	Switzerland
Eugene Mohareb	University of Reading	UK
Ferenc Kalmár	University of Debrecen	Hungary
Fitsum Tariku	British Columbia Institute of Technology	Canada
Harjit Singh	Brunel University London	UK
Jieying Wang	FPInnovations	Canada
Joy Sen	Indian Institute of Technology – Kharagpur	India
Jun-Tae Kim	Kongju National University	Korea
Marco Perino	Politecnico di Torino	Italy
Mario A. Medina	The University of Kansas	USA
Mili Majumdar	Green Business Certification Inc.	India
Nemkumar Banthia	University of British Columbia	Canada
P Marc LaFrance	U. S. Department of Energy	USA
Peter Wild	University of Victoria	Canada
Ping Fan	Hunan University	China
Rajasekar Elangovan	Indian Institute of Technology – Roorkee	India
Ray Ogden	Oxford Brookes University	UK
Samuel Brunner	Swiss Federal Laboratories for Mat. Sci. and Tech.	Switzerland
Samuel V. Glass	Forest Products Laboratory	USA
Sarit Kumar Das	Indian Institute of Technology – Roorkee	India
Sigrid M. Adriaenssens	Princeton University	USA
Sushanta Mitra	York University	Canada
Sybill Derrible	University of Illinois at Chicago	USA
Venkatesh Kodur	Michigan State University	USA
Wilma Leung	BC Housing	Canada
Y. H. Chui	University of Alberta	Canada
Zhaofeng Chen	Nanjing University of Aeronautics and Astronautics	China

Local Advisory Committee

Andrew Pape-Salmon	BC Building Codes & Standards
Cecile Lacombe	BC Ministry of Technology, Innovation & Citizens' Services
Jonathan Reiter	Skyline Engineering
Nolan Beise	Mitacs Canada
Patrick Roppel	Morrison Hershfield
Rob Bernhardt	Passive House Canada
Terry Bergen	Read Jones Christoffersen Ltd.
Graham Finch	RDH Building Science

Organizing Committee (University of Victoria)

David Bristow
Heather Buckley
Christine Doszecki
Caetano Dorea
Ralph Evins
Thomas Froese
Tom Gleeson
Rishi Gupta
Scott Iverson
Chris Kennedy (Co-Chair)
Jennifer Knapp
Cheng Lin
Omayma Motaleb
Phalguni Mukhopadhyaya (Chair)
Min Sun
Armando Tura
Matt Walker
Tracey Woodhouse
Lina Zhou

Contents

Paper ID	Title	Authors	Page #
3	Development of a new multifunctional structural material: high performance aerogel concrete	T. Welsch, M. Schnellenbach-Held, B. Milow	1
5	Mitigation of dangers caused by natural light on museum artefacts in the UAE	K. Al-Sallal, A. AbouElhamd, M. Bin-Dalmouk	9
7	Hygrothermal and structural performance of light wood frame walls with insulated sheathing	Y. Chen, Y. Hei Chui, M. Spasojevic	15
8	Utilizing the knudsen effect in the quest for super insulation materials	B. Petter Jelle, S. A. Mofid and T. Gao	21
9	Condition assessment of bridges using non-contact vibration measurement: A pilot study	H. Rathod, R. Gupta, Y. Kaya, B. Esakki	24
10	Moisture monitoring throughout the construction and occupancy of mass timber buildings	S. L. Zelinka, S. Kordziel, S. Pei, S.V. Glass, P.C. Tabares-Velasco,	32
11	The application of major road infrastructure to support and drive sustainable urban mobility	C. Hood, R. Laing, D. Gray, L. Napier, A. Simpson, E. Tait	36
14	Life cycle coasting and life cycle assessment of wall systems with different insulation	M. Pilehvaran, F. Tariku	45
15	What is Sustainable Infrastructure? A review of sustainable infrastructure rating systems	P. Dimayuga, S. Saxe	56
17	Hygrothermal performance assessment of rain-screen ICF walls in coastal climate	E.D. Iffa, F. Tariku	68
18	Coefficient of permeability of cement-based repair materials	B. Wang, R. Gupta, P. Dias, T. Bergen	76
19	Properties and application of sheep wool thermal and acoustic products	G. Cheng, W. Fang	84
21	A novel single-target selective disassembly sequence planning method for adaptive reuse of buildings	B. Sanchez, C. Haas	88
23	Low portland cement contents concrete with high early age strength and high resistance to sulfate attack	P. Fang, R. D. Hooton	98
25	New and sustainable civil engineering infrastructures from geopolymer concrete and GFRP bars	B. Benmokrane, A. Manalo, G. Maranan	101
26	Recent developments in tall wood buildings	A. Iqbal	111
29	Experimental research on the size effect on the compressive strength of recycled aggregate concrete	J. Su, W. Liu, Y. Mo	117
30	Strength recovery and crack healing of self-healing cement mortar containing cellulose fibers and bacteria	H. Singh, R. Gupta	120
31	Influence of vegetation on pedestrian thermal comfort in a street canyon	L. Manickathan, A. Kubilay, T. Defraeyea, J. Allegrini, D. Derome, J. Carmeliet	130
33	A Bottom up statistical building stock model for the City of Victoria	W. Bowley, R. Evins	134

35	Roadmap to resilient, ultra low energy buildings in the pacific northwest	A. Pape-Salmon, J. Montgomery, E. Henderson, R. Lepage	143
38	Ready mixed concrete production using waste CO_2	S. Monkman	152
39	Parametric study of wetting of urban materials and its impact on the thermal comfort in a street canyon	A. Kubilay, J. Carmeliet, D. Derome	159
40	Monitoring the In-situ freeze-thaw performance and leaching of K-based geopolymer concrete pavers	P. Azarsa, R. Gupta	163
43	Energy harvesting using smart sensors for civil applications	S. Raghavan, R. Gupta	169
45	Understanding risk Vancouver 2017: Pathways to resilience in the Georgia basin	J. McIntyre, J. Shoubridge, M. Heideman, M. Journeay	176
46	VR-based crane operation planning using head-mounted display	M. S. Islam, J. Olearczyk, M. Al-Hussein, A. Bouferguene	186
49	Hygrothermal field testing of multi-functional wood fibre panels for residential buildings	L. Secchi, H. Awad, K M E. Salim, M. Gul, R. Knudson	192
51	Crystalline waterproofing admixtures effects on self-healing and permeability of concrete	P. Azarsa, R. Gupta, A. Biparva	200
52	Exploring the factors affecting home energy retrofit adoption – A Case study of the EcoENERGY retrofit program	E. Mohareb, A. Gillich	210
54	Creating low carbon cities in the UK - The future of civil and building services engineering	A. Gillich, A. Ford	213
55	Turning national retrofit policies into local action: Examples from the US BBNP and the Canadian eco-energy programs	A. Gillich, E. Mohareb	220
56	A framework to assess the performance of indoor swimming pools in Canada	S. Saleem, R. Sadiq, K. Hewage	225
57	A Review on the investigation of impact resistance of rubberized concrete containing recycled concrete aggregate	K. Tamanna, N. Banthia, M. S. Alam	229
58	Thermal performance of double and triple glazed windows: Experimental results from lab and in-situ measurements	A. Rana, M. S. Alam, K. Charles, P. Perera , K. Hewage, R. Sadiq	236
60	Measuring dynamic thermal resistance of building envelope assemblies	G. Mustapha, K. Knight, B. Campbell, J. Wells	243
65	Wood innovation research lab: An all-wood industrial building built to passive house standards	S. Wall, G. Wimmers	252
66	Life cycle assessment supports wood construction and Passive House design in industrial buildings	S. Wall, G. Wimmers	256
67	Recycled aggregate concrete & its application in sustainable development	H. Ahmed, M. S. Alam	260
69	Operational performance management of multi-unit residential buildings	T. Prabatha, R. Ruparathna, K. Hewage, R. Sadiq	264
70	Comparative analysis of environmental product declarations on building materials – Softwood lumbers under different product category rules	H. Feng, K. Hewage, R. Sadiq	274

72	Green building construction practices: Review of environmental management from the contractor perspective in the Canadian industry	S. Saleh, T. M. Froese	282
73	Mitigating risks and overcoming barriers in Canadian renewable energy projects: A partnering approach	H. Karunathilake, K. Hewage, R. Sadiq	290
74	Development of a framework for sustainability management in the construction industry approaching both organizational structure and processes management	S. Carla, N L. Espindola, T. M. Froese	300
76	Installation of charging infrastructure for electric vehicles in multi-unit residential buildings in British Columbia	D. Lopez, T. Froese, M. Tran	310
77	Maximum affluence and lifestyle: Definition and Implications for environmental impact evaluation	J. Mulrow, S. Derrible, A. Kermanshah, D. Lee	315
78	Investigating residential building energy consumption using regression tree approach	D. Lee, S. Derrible, D. Lee, S. Derrible, J. Mulrow	319
79	Evaluation of moisture indices for management of insulated walls in Canada	H. Singh, C. Valeo, P. Mukhopadhyaya	324
80	Structural performance monitoring technology and data visualization tools and techniques – Featured case study: UBC Tallwood House	G. Mustapha, K. Khondoker, J. Higgins	335
82	Civil structural forms and extreme loading	S. Adriaenssens, V. Charpentier, T. Michiels	344
83	A climate change primer for civil engineers	V.K. Arora and A.J. Cannon	348
84	Challenges and potential solutions for the resilience of multi-infrastructure systems	D.N. Bristow	357
87	A new era of energy codes in Canada	C. Cianfronea, L. Westerhoff, R. McClung	361
90	Sustainability through the World's cities	D. Hoornweg	368
91	Cities and energy efficiency: Unravelling the contradictions	L. Sugara, C. Kennedy	372
92	Thermal performance of building frame walls outfitted with encapsulated PCM under full weather conditions	X. Sun, M. A Medina, K. O. Lee, X. Jin	375
93	Impacts of large penetrations of distributed solar PV on Alberta's decarbonization plans	M. Fowler, B. Robertson, J. Donald, J. English, V. Keller, B. Lyseng, T. Niet, K. Palmer-Wilson, A. Rowe, S. Scholtysik, C. Wade, P. Wild	385
97	Entrepreneurship and African urban infrastructure: seeking the intersection	Murray R. Metcalfe	388
98	Evaluation of the long-term performance of vacuum insulation panels installed in real building environments	H. Yamamoto, D. Ogura	392
99	Climate change, mass timber, and biodeterioration – A synthesis	R. Lepage	397

100	Application of fly ash and bottom ash based alkali activated concrete paver blocks for design and construction of rural pavements	M. D. Patel, U. V. Dave, R. Gupta, S. Thakkar	401
101	Future weather files to support climate resilient building design in Vancouver	M. Ek, T. Murdock, S. Sobie, B. Cavka, B. Coughlin, R. Wells	408
102	Canadian Construction Materials Centre guidelines for the evaluation of vacuum insulated panels	C. St-Onge, P. Mukhopadhyaya, G. Torok, T. Moore	417
103	CFD analysis of air flow in buildings with sustainable design	V. Mishra and P. Mukhopadhyaya	421
104	Sustainable- Eco- Buildings Assessment Method for the evaluation of residential buildings in hot dry climate	H. A. K. Osman	428
105	Effect of various surfactant and innovative techniques on dispersion of carbon reinforcement in cement-based materials	R. Vora, R. Gupta, U. Dave	438
106	Carbon footprint of citizen consumption in Canadian metropolitan cities	M. Isman, M. Archambault, C. N. Konga, D. Lin, K. Iha, C. M. Ouellet-Plamondon	446
107	Thermal comfort monitoring in buildings using a BIM-based automated system	M. Valinejadshoubi, A. Bagchi, O. Moselhi	450
108	The potential of natural superhydrophobic hollow milkweed fibers	P. Nguyen-Tri, C.M. Ouellet-Plamondon, P. Carriere	454
109	Principles of Load-Balanced Ground-Source Heat Exchange Systems for Optimization of Energy Efficiency in Building Heating and Cooling	A. Chong, E. Mak	456
110	Passive House Introduction Presentation	S. Hayes	461
111	Passive House Energy Modeling Workshop	S. Hayes, R. Beise, D. Taylor	463
112	Passive House - Leading the Shift to High Performance Buildings	G. Verhulst	465

About the Editor

Phalguni Mukhopadhyaya, Ph.D., P.Eng.
Associate Professor
Department of Civil Engineering, University of Victoria, BC, Canada.
Tel: (250) 472-4546, E-mail: phalguni@uvic.ca

Phalguni is an applied engineering researcher and started his research career in 1997, immediately after finishing his doctoral studies from the University of Sheffield, UK. Initially, his research focused on new construction materials and structural strengthening techniques. Soon thereafter, during his 15+ years tenure at the National Research Council Canada (NRCC), he expanded his research horizon towards the heat-air-moisture responses of exterior building envelope materials and systems. Hence, in a true sense, he is a multidisciplinary building envelopes and structures researcher who brings together the fundamentals of Civil, Mechanical and Materials engineering to address pressing concerns of the construction industry and its stakeholders.