Topic: Urban Microclimate and Energy, Wind Engineering, Aerodynamics and Urban Physics

High Resolution Urban Climate Map Generator Using a Geographical Information System: The Vertical City Weather Generator (VCWG v.2.1.0)

Mohsen Moradi[1*], Amir A. Aliabadi[1]

[1]School of Engineering, University of Guelph, Guelph, Canada

[*]*Corresponding email: moradim@uoguelph.ca*

Keywords: Micro-climate Modeling, Urban Canopy Model (UCM), Urban Climate, Urban Hydrology

SUMMARY

Urban climate models can predict the environmental impacts of urban development by simulating the exchange processes between the atmosphere and urban surfaces. A comprehensive simulation of urban climate requires adequate representation of the exchanges of momentum, heat, and water between the atmosphere and urban elements. Urban areas are characterized by high spatial variability of surface properties, land coverage, and population density. Hence, scientists, engineers, and urban planners require accurate estimation of urban climate and weather variables with reasonable spatial resolution. This study presents inclusion of a pre-processor function in the Vertical City Weather Generator (VCWG) to automate the Geographic Information System (GIS) processes. This tool can simulate the urban climate using a raster file, which describes the spatial distribution of urban morphometric, thermal, aerodynamic, and vegetative parameters. The capability of VCWG to generate the climate map at the scale of a city is assessed by conducting simulations for an area in Vancouver in July 2007. The simulation results reveal notable spatial variation of building energy, latent, and sensible heat fluxes.

INTRODUCTION

Urban expansion and conversion of the Earth's surface to urban uses have brought numerous environmental issues at various scales. Cities and industrial areas disturb the natural water cycle and thermal energy exchange between the earth's surface and the atmosphere. In urban climatology, the scale of analysis specifies the key parameters that contribute to climate modifications. At the microscale, individual building and surrounding area properties influence the microclimate [1].

From the energy balance perspective, built-up areas are mainly characterized by the reduction in loss of longwave radiation, increased heat storage, anthropogenic heat release, inter-reflections of radiation between the urban elements, and loss of evaporation from surfaces, all of which contribute to the Urban Heat Island (UHI) [2]. UHI is recognized as one of the clearest examples of climate modification. This phenomenon causes a greater temperature in cities compared with their surroundings. Replacing green spaces with impervious surfaces (e.g., roads and buildings) disrupts the watershed's drainage and hydrology. In general, the assessment of meteorological processes involved in the hydrologic cycle requires a water balance analysis at the surface and its interaction with the groundwater. Depending on the type of the surface, the fraction of precipitation reaching the ground can be stored in the soil and reaches the deeper soil layers [3].

The numerical models used to simulate urban climate typically contain equations that conserve momentum, mass, and energy. These equations determine the relationships between meteorological quantities and surface conditions under different large scale meteorological forcing conditions. Urban climate models are generally designed for certain spatial and temporal scales that cover the atmospheric processes of interest. For example, if the model aims to determine the exchange processes between an entire city and the atmosphere, the computational domain should be extended far beyond the horizontal and vertical size of the city. Depending on the scale of analysis, the surface representation can vary from a simple one-dimensional slab in a mesoscale model to more realistic forms that include vertical and horizontal surfaces. In the latter case, simplifying the urban canopy layer into a street canyon with representative dimensions and orientation is a common practice. These Urban Canopy Models (UCMs) are either used stand-alone to obtain the exchanges in an urban area or coupled with the mesoscale models that provide more realistic boundary conditions for them. As an alternative to the computationally expensive models (e.g. CFD), UCMs require an understanding of the interaction between the atmosphere and urban elements to parameterize various exchange processes of radiation, momentum, heat, and moisture within and just above the canopy. UCMs have been developed based on experimental data [4], three-dimensional simulations, or simplified urban configurations [5,6].

An overview of the literature reveals a lack of an independent urban micro-climate model that accounts for unique features of the built-up environment including building energy, urban energy exchange, urban hydrology, low and high vegetation, and most importantly the dynamic interactions between these elements. To address this need, the Vertical City Weather Generator (VCWG v1.3.2) was developed [7]. VCWG v1.3.2 intends to integrate various sub-models to create a comprehensive simulation platform capable of predicting urban climate and building energy performance variables. This version does not include the hydrologic model, cannot be forced from the top of the urban domain using mesoscale data products, and does not offer the opportunity to investigate simulation output variables on a spatial grid of the urban environment. In the next version, VCWG v1.4.5 includes renewable and alternative energy systems and account for full two-way interaction between the building system and outdoor environment [8]. The latest version of the model, VCWG v2.0.0 accounts for not only the interaction between indoor and outdoor environments through parameterizations including building energy, surface energy balance, radiation, and vertical diffusion models, but also the biophysical and ecophysiological behaviour of urban vegetation via an advanced hydrology model [9].

In this study, the VCWG v2.0.0 is equipped with a GIS pre-processor function, which allows the user to generate a climate map at the scale of a city. This feature offers the opportunity to investigate spatial variation of urban climate, weather, and building energy performance variables with reasonable spatial and temporal resolution. This newest version of VCWG is v2.1.0.

METHODS

Vertical City Weather Generator (VCWG v2.0.0):

VCWG v2.0.0 preserves most features of VCWG v1.3.2, but it adds extra physical models and functionalities to predict urban climate and building energy performance variables. This version includes a hydrologic model, can be forced from the top of the urban domain using mesoscale data products, and offers the opportunity to investigate simulation output variables on a spatial grid of the urban environment (see Figure 1). A brief description of VCWG v2.0.0 is provided below. For further details, readers are referred to Moradi et al. (2022) [9].

A rural model forces meteorological boundary conditions based on a surface energy balance model and Monin-Obukhov Similarity Theory (MOST). Alternatively, the Penman-Monteith (PM) method can be used to solve the surface energy balance model in the rural area. An urban one-dimensional vertical diffusion model is used to calculate the vertical profiles of cross- and along-canyon wind speed, potential temperature, specific humidity, and turbulence kinetic energy in the urban area considering the effects of trees, buildings, and building energy systems. The model can be forced at the top of the domain, either by the rural model or a top forcing dataset, and at the bottom by surface and water balance models. A building energy model is used to calculate the building energy fluxes and waste heat of buildings imposed on the urban environment. A radiation model with trees is used to compute the longwave and shortwave radiation fluxes between the urban canyon, trees, and the sky. An urban surface energy balance model is used to calculate surface heat fluxes, including sensible, latent, and conductive heat fluxes. The moisture sources include not only evaporation from tree foliage but also the wet surfaces and soil columns, which contribute to the urban energy balance. An urban hydrology model is used to obtain ecophysiological behaviour of urban trees and low vegetation at the ground and roof levels and calculate urban hydrological exchanges and soil water content profile in the presence of precipitation.

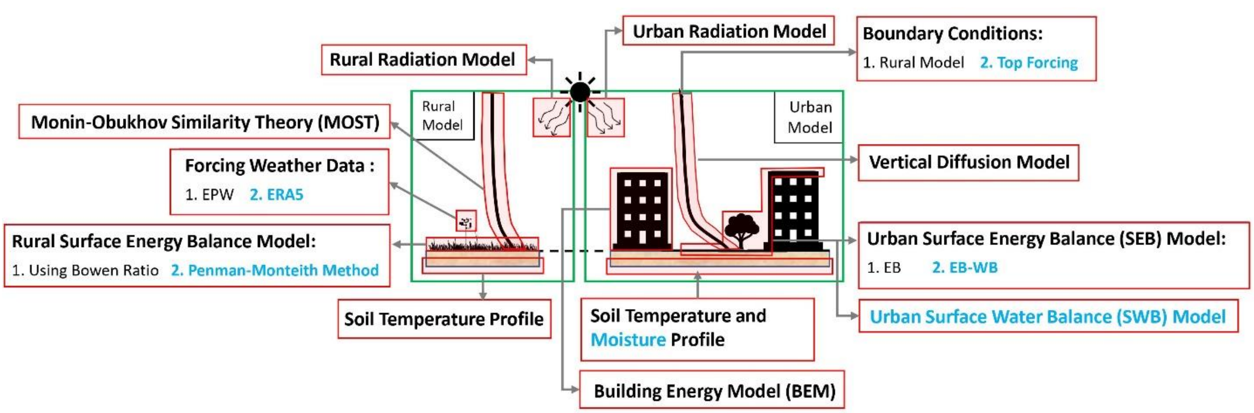

Figure 1. Overview of the Vertical City Weather Generator (VCWG v2.0.0). The new additions in VCWG v2.0.0 (over VCWG v1.3.2) are highlighted in blue.

Vertical City Weather Generator Empowered by a Geographical Information System (VCWG v2.1.0):

Urban areas are characterized by high spatial variability of surface properties, land coverage, and population density. Hence, scientists, engineers, and urban planners require accurate estimation of urban climate and weather variables with reasonable spatial resolution.

VCWG is equipped with a pre-processor function to automate the Geographic Information System (GIS) processes. At the first step, if a rural dataset is required to force the model, the pre-processor finds the nearest rural area in the upwind of the urban site. If the model is set to run using the top forcing approach, the appropriate ERA5 dataset above the urban area can be retrieved. ERA5 data products are real-time reanalysis datasets that provide hourly atmospheric variables [10]. Urban morphology can be obtained from the geographic file provided by the user or other sources of land cover datasets including OpenStreetMap [11], OSMnx [12], and World Urban Database and Access Portal Tools (WUDAPT) [13]. OSMnx is a tool that can analyze street networks, retrieve building footprints, elevations, and download data from the OpenStreetMap repository. WUDAPT characterizes the built-up areas using the Local Climate Zone (LCZ) classification approach [14]. Figure 2 shows the VCWG v2.1.0 model schematic.

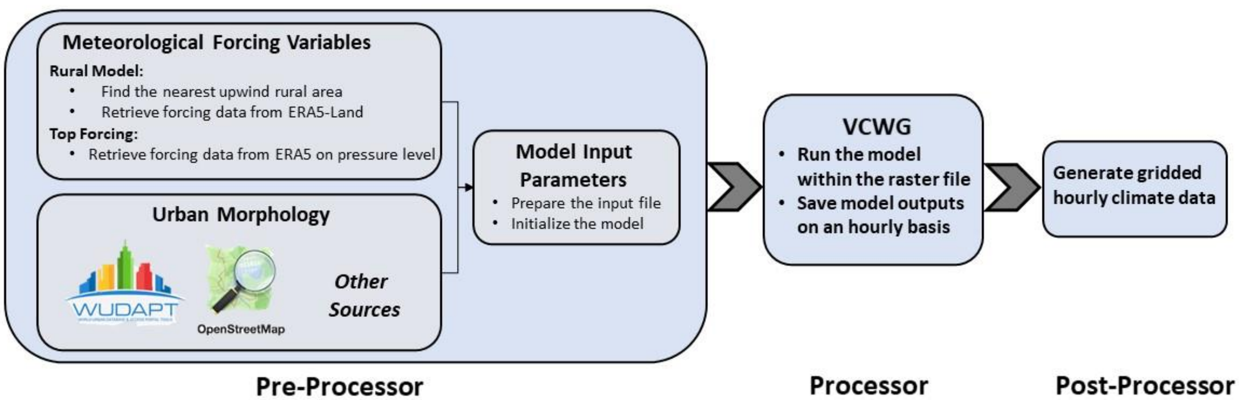

Figure 2. Illustration of the Vertical City Weather Generator (VCWG v2.1.0) model.

In the current analysis, the Vancouver morphometric parameters are obtained from the City of Vancouver open data portal [15], and OSMnx and WUDAPT datasets are used in a consistent way to modify the dataset. Every grid cell of the associated raster file contains building geometries, fraction of ground covered by vegetation, bare soil, impervious surface, land cover, and view factors. The view factors are calculated as a function of urban morphometric parameters using the ray tracing method in VCWG. Then VCWG simulations are conducted for each latitude and longitude of the raster file and calculate model output variables for each grid cell independently. Figure 3 shows the urban area in Vancouver considered for this simulation. VCWG is simulated for 7 days in 2007 starting from July 1st with a time step of 5 min and vertical resolution of 1 m. The horizontal spatial resolution of the domain is 100 m (see Figure 4), which is consistent with the WUDAPT dataset.

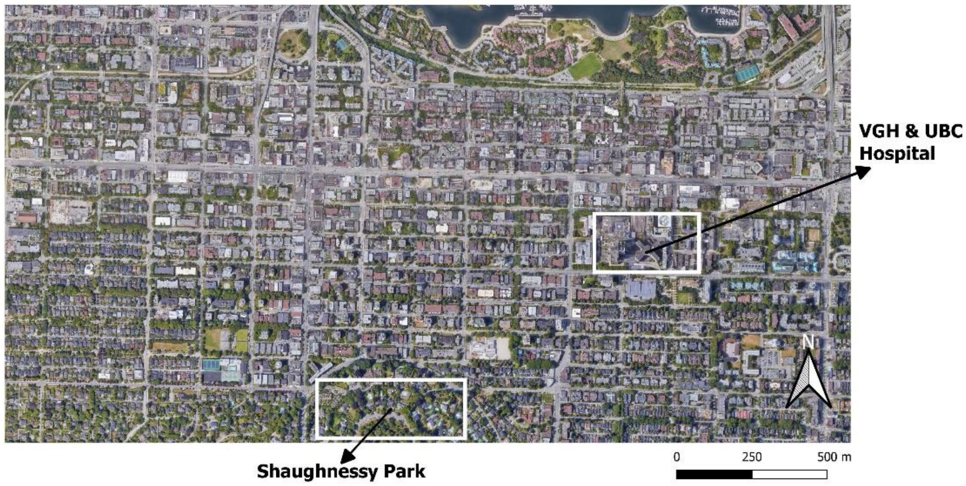

Figure 3. The VCWG domain for spatial analysis in Vancouver

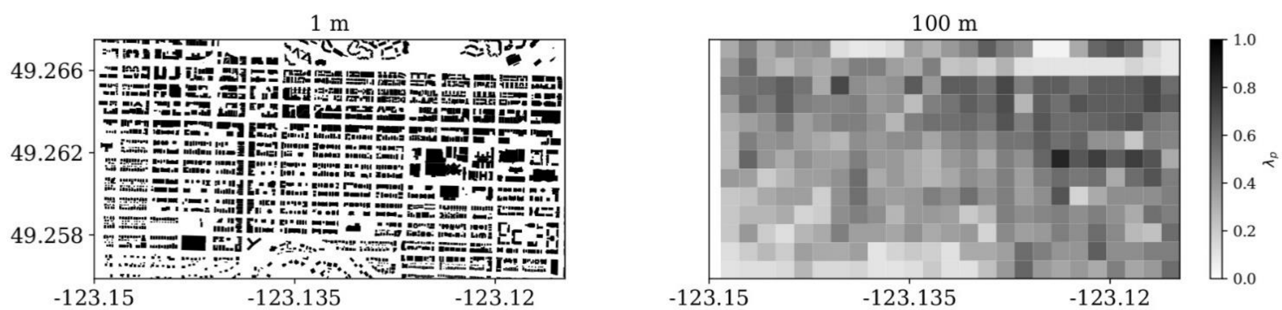

Figure 4. Plan area density calculated at 1 m resolution (left) and 100 m resolution (right) in Vancouver; the urban area is specified by latitudes and longitudes.

RESULTS AND DISCUSSION

Figures 5 to 7 depict the mean spatial distribution of canyon potential temperature, sensible heat flux, and latent heat flux during daytime (1100 to 1300 Local Standard Time (LST)) and nighttime (2200 to 0000 LST). It is evident that the residential neighbourhood close to Shaughnessy Park (latitude = 49.256°, longitude = -123.135°), where it is highly covered by low and high vegetation, has a lower magnitude of sensible heat flux and high magnitude of latent heat flux compared to other areas. Such a cooling effect provides lower temperatures in this neighborhood. The eastern part of the simulation domain (latitude = 49.265° to 49.270°, longitude = -123.128° to -123.120°) is mainly occupied with high-rise buildings (such as Vancouver General Hospital (VGH) & University of British Columbia (UBC) Hospital Foundation and BC Cancer Research Center) and less amount of vegetation, which leads to higher cooling demand and building waste heat (see Figure 8). So, the nighttime canyon air potential temperature is expected to be higher within this region, as well-captured by VCWG (see Figure 5).

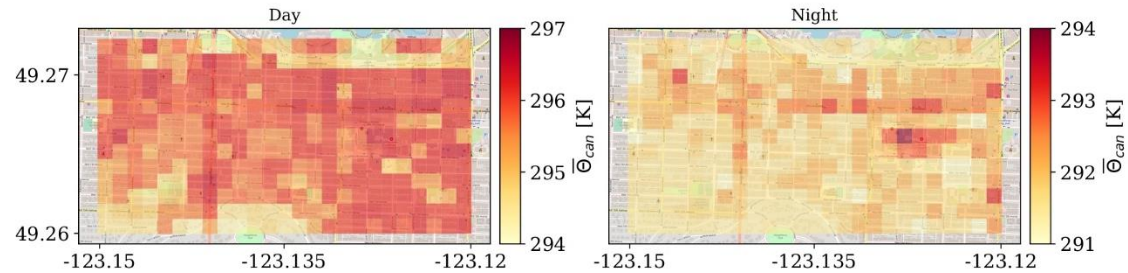

Figure 5. Spatial distribution of mean daytime (left) and nighttime (right) canyon air potential temperature from July 1st to July 7th in Vancouver in 2007.

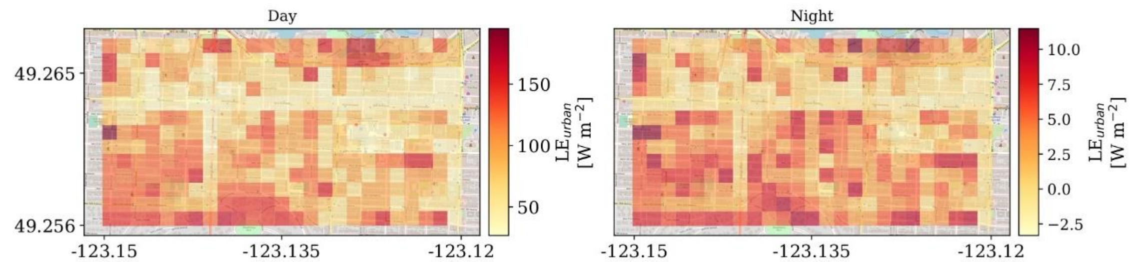

Figure 6. Spatial distribution of mean daytime (left) and nighttime (right) latent heat flux from July 1st to July 7th in Vancouver in 2007.

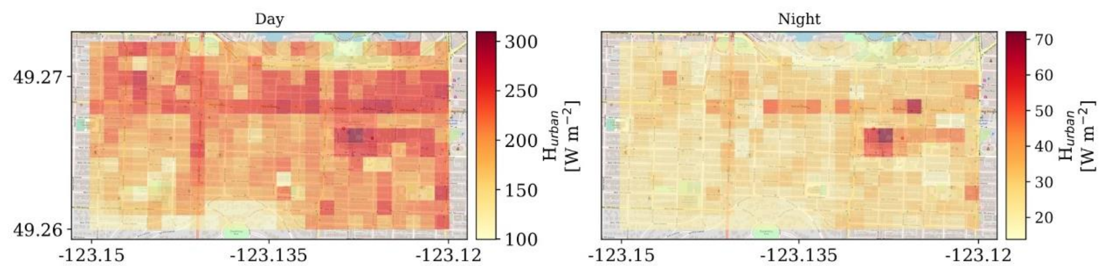

Figure 7. Spatial distribution of mean daytime (left) and nighttime (right) sensible heat flux from July 1st to July 7th in Vancouver in 2007.

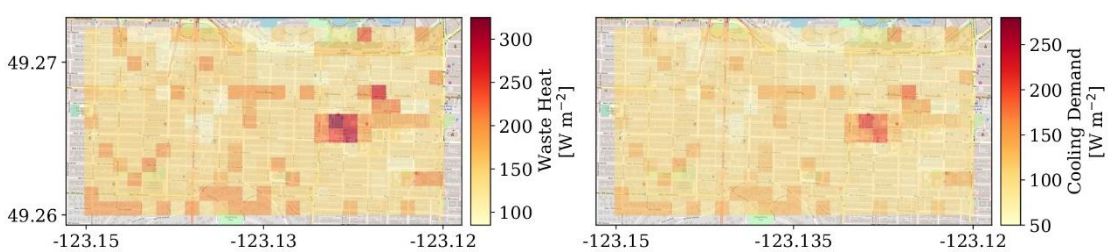

Figure 8. Spatial distribution of daily maximum building waste heat (left) and cooling demand (right) from July 1st to July 7th in Vancouver in 2007.

CONCLUSIONS

In this study, the Vertical City Weather Generator (VCWG v2.0.0) is further developed to generate a climate map at the scale of a city. The original VCWG v2.0.0 is composed of a rural model, urban vertical diffusion model, building energy model, radiation model, surface energy balance model, and an urban hydrology model. VCWG v2.0.0 is equipped with a pre-processor function to automate the Geographical Information System (GIS) processes, which results in VCWG v2.1.0. This tool can simulate the urban climate variables using a raster file, which describes the spatial distribution of urban morphometric, thermal, aerodynamic, and vegetative parameters. This analysis is successfully accomplished with a 100 [m] spatial resolution and 5 [min] temporal resolution for 7 days in July 2007 in Vancouver. The spatial distribution of canyon temperature, building energy fluxes, urban sensible and latent heat fluxes are well captured by VCWG v2.1.0. So, it signifies the capability of VCWG to account for the spatial variation of urban micro-climate variables in a computationally-efficient manner independent of an auxiliary meso-scale model.

ACKNOWLEDGEMENT

This work was supported by the University of Guelph through the International Graduate Tuition Scholarship (IGTS) for the lead author; the Accelerate program (460847) from Mathematics of Information Technology and Complex Systems (MITACS); the Discovery Grant program (401231) from the Natural Sciences and Engineering Research Council (NSERC) of Canada; the Government of Ontario through the Ontario Centres of Excellence (OCE) under the Alberta–Ontario Innovation Program (AOIP) (053450); and Emission Reduction Alberta (ERA) (053498). OCE is a member of the Ontario Network of Entrepreneurs (ONE).

REFERENCES

[1] R. E. Britter and S. R. Hanna, “Flow and dispersion in urban areas,” *Annu. Rev. Fluid Mech.*, 35, 1, 469-496, 2003.

[2] T. R. Oke, G. T. Johnson, D. G. Stetn, and I. D. Watson, “Simulation of surface urban heat island under ideal conditions at night part 2: Diagnosis of causation,” *Bound.-Lay. Meteorol.*, 56, 4, 339-358, (1991).

[3] S. G. Walesh, *Urban surface water management*. John Wiley & Sons, New York, 1991.

[4] H. Kusaka, H. Kondo, Y. Kikegawa, and F. Kimura, “A simple single-layer urban canopy model for atmospheric models: comparison with multi-layer and slab models,” *Bound.-Lay. Meteorol.*, 101, 3, 329-358, 2001.

[5] E. S. Krayenhoff, A. Christen, A. Martilli, and T. R. A. Oke, “A multi-layer radiation model for urban neighbourhoods with trees,” *Bound.-Lay. Meteorol.*, 151, 1, 139-178, 2014.

[6] E. S. Krayenhoff, J.-L. Santiago, A. Martilli, A. Christen, and T. R. Oke, “Parameterization of drag and turbulence for urban neighbourhoods with trees,” *Bound.-Lay. Meteorol.*, 156, 2, 157-189, 2015.

[7] M. Moradi, B. Dyer, A. Nazem, M. K. Nambiar, M. R. Nahian, B. Bueno, C. Mackey, S. Vasanthakumar, N. Nazarian, E. S. Krayenhoff, L. K. Norford, and A. A. Aliabadi, “The Vertical City Weather Generator (VCWG v1.3.2) ”, Geosci. Model Dev., 14, 961-984, 2021.

[8] A. A. Aliabadi, M. Moradi, R. M. McLeod, D. Calder, and R. Dernovsek, "How Much Building Energy Is Enough? The Vertical City Weather Generator (VCWG v1.4.4)," *Atmosphere,* 12, 882, 2021.
[9] M. Moradi, E. S. Krayenhoff, A. A. Aliabadi, "A comprehensive indoor-outdoor urban climate model with hydrology: The Vertical City Weather Generator (VCWG v2.0.0)," *Build. Environ.*, 207, 108406, 2022.
[10] H. Hersbach, B. Bell, P. Berrisford, G. Biavati, A. Horanyi, J. Munoz Sabater, J. Nicolas, C. Peubey, R. Radu, I. Rozum, D. Schepers, A. Simmons, D. Dee, and J-N Thepaut "ERA5 hourly data on pressure levels from 1979 to present," *Copernicus Climate Change Service (C3S) Climate Data Store (CDS),* (Accessed on 1 January 2021).
[11] OpenStreetMap contributors. Planet dump retrieved from https://planet.osm.org, 2017. Accessed 1 January 2021.
[12] G. Boeing, "OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks," *Comput. Environ. Urban*, 65, 126-139, 2017.
[13] O. Brousse, A. Martilli, M. Floey, G. Mills, and B. Bechtel, "WUDAPT, an efficient land use producing data tool for mesoscale models? integration of urban LCZ in WRF over Madrid," *Urban Climate,* 17, 116-134, 2016.
[14] I. D. Stewart and T. R. Oke, "Local climate zones for urban temperature studies," *B. Am. Meteorol. Soc.,* 93, 12 (1879-1900), 2012.
[15] City of Vancouver. Building footprints retrieved from https://opendata.vancouver.ca/pages/home, 2009. Accessed 1 January 2021.