Journal of Environmental Management 206 (2018) 145–157

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Analysis and modelling of surface Urban Heat Island in 20 Canadian cities under climate and land-cover change

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ARTICLE INFO

Article history:
Received 7 June 2017
Received in revised form
29 September 2017
Accepted 5 October 2017

Keywords:
Urban Heat Island
Canada
Elevation
City-size
SP model

ABSTRACT

Surface Urban Heat Island (SUHI) is an urban climate phenomenon that is expected to respond to future climate and land-use land-cover change. It is important to further our understanding of physical mechanisms that govern SUHI phenomenon to enhance our ability to model future SUHI characteristics under changing geophysical conditions. In this study, SUHI phenomenon is quantified and modelled at 20 cities distributed across Canada. By analyzing MODerate Resolution Imaging Spectroradiometer (MODIS) sensed surface temperature at the cities over 2002–2012, it is found that 16 out of 20 selected cities have experienced a positive SUHI phenomenon while 4 cities located in the prairies region and high elevation locations have experienced a negative SUHI phenomenon in the past. A statistically significant relationship between observed SUHI magnitude and city elevation is also recorded over the observational period. A Physical Scaling downscaling model is then validated and used to downscale future surface temperature projections from 3 GCMs and 2 extreme Representative Concentration Pathways in the urban and rural areas of the cities. Future changes in SUHI magnitudes between historical (2006–2015) and future timelines: 2030s (2026–2035), 2050s (2046–2055), and 2090s (2091–2100) are estimated. Analysis of future projected changes indicate that 15 (13) out of 20 cities can be expected to experience increases in SUHI magnitudes in future under RCP 2.6 (RCP 8.5). A statistically significant relationship between projected future SUHI change and current size of the cities is also obtained. The study highlights the role of city properties (i.e. its size, elevation, and surrounding land-cover) towards shaping their current and future SUHI characteristics. The results from this analysis will help decision-makers to manage Canadian cities more efficiently under rapidly changing geophysical and demographical conditions.

1. Introduction

More than half of the world's current population lives in cities and this fraction is expected to increase to 66% by 2050 (United Nations, 2014). To cater to the safety and comfort of rapidly growing urban population, it is necessary to enhance our current understanding of urban climate and processes affecting it. The difference between urban and rural temperatures, commonly referred to as the Urban Heat Island (UHI), is one such important climate phenomenon that has been investigated in the past (Oke, 1982; Rizwan et al., 2008). Surface Urban Heat Island (SUHI) is a type of UHI phenomenon where urban-rural differences in climate are measured in terms of surface temperatures (Voogt and Oke, 2003).

SUHI phenomenon has been detected in many cities across the globe (Peng et al., 2012; Imhoff et al., 2010; Wang et al., 2007; Clinton and Gong, 2013; Keramitsogloua et al., 2011; Zhao et al., 2016; Qiao et al., 2014). Peng et al. (2012) for instance calculated SUHI magnitudes over the period 2003–2008 for 419 global big cities using day and night-time MODerate-resolution Imaging Spectrometer (MODIS) surface temperature. They found significant variation in SUHI magnitudes across the cities. Averaged across all cities, the magnitude of SUHI was found higher in the daytime than in the nighttime. Imhoff et al. (2010) used MODIS land-surface temperature and impervious surface area from Landsat Thematic Mapper to analyze SUHI magnitudes in 38 most populous cities in USA located in different biomes. They found SUHI to be significantly affected by the ecological context in which the cities were located.

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https://doi.org/10.1016/j.jenvman.2017.10.002

They obtained considerably higher SUHI magnitudes for cities located in biomes dominated by temperate broadleaf and mixed forests than those located in arid regions. Zhao et al. (2014) investigated the association between background climate and SUHI magnitudes recorded at 65 selected cities across North America. They found daytime SUHI magnitudes to be considerably higher in cities with higher precipitation than cities located in drier environments. They contributed this observation to (higher) lower aerodynamic resistance in the cities as compared to densely vegetated rural areas in (drier) humid regions. Evidence of increase in SUHI magnitudes with city sizes has also been noted. Zhao et al. (2016) detected increase in SUHI magnitude with the expansion of metropolitan areas of Shanghai, China between 1984 and 2014. Hove et al. (2015) found SUHI magnitudes in Rotterdam, Netherlands to be significantly influenced by wind-speed and seasonal cycles. These and other studies (reviewed in Arnfield, 2003; Rizwan et al., 2008) provide observational evidence of existence of SUHI in cities across the globe and its variation with time of the day, ecological settings, large scale climate, city size, and seasonal cycles.

Reliable predictions of future urban-rural differences are necessary for long-term planning of cities. Prediction of urban climate is complicated by the presence of sources of non-stationarity such as climate and land-use land-cover change, which are expected to bring drastic changes in climatic regimes across the globe (Stocker et al., 2013; Pielke et al., 2011). Global Climate Models (GCMs) have been used to simulate the response of climate system to future greenhouse gas emissions. GCM simulations are downscaled before they can be used to estimate future urban climate. Statistical and dynamical methods have been used in the past to downscale GCM projections. Statistical downscaling methods derive a statistical relationship between coarse resolution atmospheric variables and local climate over the observational period, and use these relationships to downscale GCM projections in both historical and future timelines. On the other hand, dynamic downscaling methods typically use Regional Climate Model (RCM) to simulate higher resolution climatic projections using boundary conditions simulated by the GCMs.

Future urban-rural differences have been investigated in the past using dynamic downscaling methods (Kusaka et al., 2012; Argueso et al. 2014; Georgescu et al., 2013; Hamdi et al., 2014; McCarthy et al., 2012; Adachi et al., 2012). One of the limitations of dynamic downscaling methods is that they require significant computational resources and hence previous UHI projection studies have considered representative GCM projections and cities for analysis. For instance, Argueso et al. (2014) used Weather Research and Forecasting (WRF) modelling system to downscale future temperature projections made by GCM: CSIRO-MK3.5 and estimate future UHI projections for Sydney (Australia). Kusaka et al. (2012) and Adachi et al. (2012) estimated summertime UHI magnitudes for three largest urban centers in Japan: Tokyo, Osaka and Nagoya under SRES A1B future scenario. Recently, Physical Scaling (SP) downscaling model has been developed and used to downscale future GCM projections (Gaur and Simonovic, 2016a; 2016b, 2017a). In SP model, large scale climate, and local elevation, land-cover characteristics are used to define local climate within a Generalized Additive Modelling (GAM) framework. The benefit of SP model over other statistical downscaling models is that it can be used to model the effects of changes in large scale climatic as well as ecology on local climate. The objectives of this study are:

- to calculate observed SUHI magnitude at 20 Canadian cities;
- to estimate future changes in SUHI magnitudes for these cities using SP downscaling model;
- to investigate factors effecting current and future SUHI phenomenon at these cities.

The rest of the paper is organized as follows. Sections 2 and 3 describe the study area, and models and data used respectively. Analysis and results are described in section 4, followed by section 5 where most important findings of the study are discussed. Finally, conclusions are summarized in section 6.

2. Study area

Twenty cities distributed across Canada are selected for analysis in this study. The selection of the cities is made with the intention of choosing cities that are characterized with varying geophysical characteristics and city sizes.

The list of selected cities is provided in Table 1 and their distribution across Canada is presented in Fig. 1. It can be noted that the selected cities (hereafter referred by their short names as provided in Table 1) are evenly distributed across the Canadian landscape, have considerably varying sizes, climate types, and elevations. Among the selected cities, five cities: TOR, MNT, OTT, LON, COL are located in the Great lakes and St. Lawrence climatic region (Statistics Canada, 2009) that is characterized by moderate winters and summers, uniform precipitation across the year, and a mix of both continental and maritime climatic conditions due to the presence of great lakes and St. Lawrence river. Three cities: VAN, VIC, COU are located in Pacific Coast climatic region characterized by mild winter and summer seasons due to the presence of Pacific Ocean which moderates climate in the region. This climatic region is also characterized by high wintertime relief precipitation. Three cities: MOJ, REG, WIN are located in Prairies climatic region that is characterized by flat lands, long sunshine hours, hot summers and cold winters, convection driven precipitation primarily concentrated in spring and summer seasons. Two cities: CAL and EDM are located at the edge of Canadian prairies region and are also affected by the presence of mountains in their neighborhood. Two cities: KEL, VER are located in the Southern BC mountains climatic region that is characterized by highly uneven climates due to the presence of mountains and valleys. The climate type is also characterized by long winters, and coastal influences in the offshore regions. Three cities: THB, DRY (Northeastern forests) and FMM (Northwestern forests) are located in the two climatic regions with largely forested

Table 1
List of cities considered for analysis in this study.

S.No	Name	Short-name	Province	Area (km^2)	Elevation (masl)
1	Toronto	TOR	ON	7124	85
2	Montreal	MNT	QC	4258	40
3	Vancouver	VAN	BC	2700	31
4	Ottawa	OTT	ON	2778	77
5	Calgary	CAL	AB	825	1050
6	Edmonton	EDM	AB	684	661
7	London	LON	ON	1572	12
8	Victoria	VIC	BC	696	343
9	Kelowna	KEL	BC	211	245
10	Moncton	MON	NB	141	15
11	Thunder Bay	THB	ON	448	21
12	Fort McMurray	FMM	AB	60	395
13	Vernon	VER	BC	96	250
14	Moose Jaw	MOJ	SK	47	540
15	Courtenay	COU	BC	27	180
16	Collingwood	COL	ON	33	371
17	Dryden	DRY	ON	65	4
18	Kentville	KEN	NS	18	85
19	Regina	REG	SK	180	577
20	Winnipeg	WIN	MB	464	239