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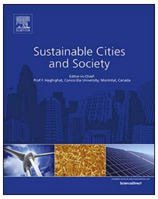

Assessing urban water security under changing climate: Challenges and ways forward

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ABSTRACT

Climate change has altered the elements of water availability, water demand and climate extremes in time and space. Such changes have various implications on water security, particularly in urban regions that are highly concentrated with human population and socio-economic activities. Assessing the climate change impacts on water security is often based on using the projections from an ensemble of climate models which are further downscaled into finer spatial resolutions. The availability of downscaled climate simulations has resulted in the optimism that future climate change threats to urban water security could now be quantified at the scale of individual cities; however, is this really the case? To showcase some of the challenges in the direct application of downscaled climate projections for impact assessment, here we explore the reliability of a state-of-the-art ensemble of downscaled climate simulations in the city of Montreal, Canada. We show that spatial variability in long-term climate over Montreal is misrepresented by downscaled climate projections. In addition, uncertainty in future projections as a result of climate models and/or concentration pathways can pose extra challenges in application of the downscaled projection in real-world design and operational contexts. Based on the currently available literature, we suggest few directions to handle current modeling uncertainties until improved climate modeling technology becomes available.

1. Introduction

Being home to more than 50% of the world's population, urban areas now represent the highest concentration of human population and socio-economic activities globally (Ibrahim, Sugar, Hoornweg, & Kennedy, 2012; Seto, Güneralp, & Hutyra, 2012; Seto, Sánchez-Rodríguez, & Fragkias, 2010). As water is prominent to human life and development, protecting human societies against adverse effects of water scarcity and surplus is central focus in water security (Wheater & Gober, 2013, 2015). Addressing water security in urban landscapes, however, is inherently complex. This is due to massively coupled relationships between water and human systems, which dynamically change across various temporal and spatial scales (see e.g. Chang, Praskievicz, & Parandvash, 2014; House-Peters & Chang, 2011; Parandvash & Chang, 2016). Most importantly, highly concentrated human activities initiate a large amount of water demand that requires a continuous supply, often with high management priority (Gleick, 2003; Nkomo & van der Zaag, 2004). Nonetheless, quantifying water demand in urban areas is not an easy task as it involves a highly varying interplay between climate, land and hydrological conditions in conjunction with details of socio-economy and technological developments (Breyer, Chang, & Parandvash, 2012; Franczyk & Chang, 2009; Ghiassi, Zimbra, & Saidane, 2008; Kenney, Goemans, Klein, Lowrey, & Reidy, 2008; Praskievicz & Chang, 2009). In addition, urban infrastructures are highly prone to extreme weather conditions, such as heavy precipitations, that can translate into severe floods (e.g., Barroca, Bernardara, Mouchel, & Hubert, 2006; Huong & Pathirana, 2013; Smith & Handmer, 1984) and result in large economic consequences (e.g., Pomeroy, Stewart, & Whitfield, 2016; Wake, 2013). Having said that, the resulting vulnerabilities are not only dependent on the climate but are also largely determined by the land management and socio-economic development within the urban areas (Chen, Zhou, Zhang, Du, & Zhou, 2015; Hollis, 1975).

During the current *Anthropocene* (see Crutzen, 2006; Steffen, Grinevald, Crutzen, & McNeill, 2011), coupled natural-human systems are highly threatened due to ever-increasing changes in both human and natural systems (Steffen, Crutzen, & McNeill, 2007; Steffen, Persson, et al., 2011). In the context of urban water security, growing population and socio-economic activities has continuously increased both water demands and vulnerability to droughts and floods in urban areas (e.g. Cutter, 1996; Hallegatte, Green, Nicholls, & Corfee-Morlot, 2013; Hanasaki et al., 2013; Hejazi et al., 2014; Mokrech et al., 2015). In addition, climate change has perturbed the elements of water cycle and affected both water availability (McDonald et al., 2011;

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Vörösmarty, Green, Salisbury, & Lammers, 2000) and water demand (Hanasaki et al., 2013; Hejazi et al., 2014). On one hand, changes in form and magnitude of precipitation affected local water availability, which can be an important source of supply, particularly for a number of urban water demands such as watering green areas (e.g., Daniel, Lemonsu, & Viguié, 2016). On the other hand, it is known that warmer climate can increase municipal water use, particularly consumptive uses, due to the direct effect on the evapotranspiration (e.g., Parkinson et al., 2016). In addition, climate change-induced alterations in extreme precipitation pose extra vulnerability to urban water security, as the magnitude, duration and frequency of extreme rainfall events are directly linked to the design of urban infrastructures, such as storm water management systems (e.g., Mirhosseini, Srivastava, & Stefanova, 2013; Rodríguez et al., 2014; Schreider, Smith, & Jakeman, 2000; Simonovic, Schardong, & Sandink, 2016).

Addressing water security in the era of climate change, therefore, requires a careful attention to the alterations of relevant hydroclimate variables and how they can affect urban water security by changing the interactions within the coupled human–water systems. According to the general “top-down” climate change impact assessment framework, this essentially requires a predictive capability to identify the implications of climate change on the urban water resource management, with a greater goal of highlighting operational thresholds for accommodating future water demands and/or staying resilient against climate-induced hazards. Various models have been already proposed to quantify the impact of climate along with other influencing variables on urban water demand and/or water-related natural hazards. These models are either in the sense of standalone assessment tools (see Chang et al., 2014 for a number of examples) or as part of larger socio-economic (Hejazi, Edmonds, Chaturvedi, Davies, & Eom, 2013; Hejazi et al., 2014) and/or Earth System models (Nazemi & Wheater, 2015a, 2015b). Regardless of the context and/or predicting capability, the application of impact models for understanding future water security threats requires the availability of high-quality climate projections that can portray likely climate futures at the appropriate scale, relevant to forcing impact models. These projections should not only represent the temporal changes in climate variables, but should be also able to adequately represent the spatial variability in climate over urban areas.

The advent of publically available climate projections produced by the Intergovernmental Panel on Climate Change's 5th Coupled Model Intercomparison Project (IPCC-CMIP5; see IPCC, 2014; Taylor, Stouffer, & Meehl, 2012) provides the scientific basis to account for the effects of climate change globally. These projections have been recently coupled with various downscaling schemes (e.g., Harding, Snyder, & Liess, 2013; Timm, Giambelluca, & Diaz, 2015) to provide the data support required for quantifying climate change impacts at local to regional scales (e.g., Mearns et al., 2013; Thrasher et al., 2013). However, there is still no formal evaluation on whether the available downscaled climate projections can be readily used for addressing the impact of climate change in urban areas, for which capturing both spatial and temporal variability in climate variables has a prime importance. This obviously requires a body of benchmarking studies to inspect the reliability of available downscaled products across various urban regions throughout the globe. This is yet to appear; however, to demonstrate potential complications in direct applications of downscaled simulations in the context of urban design and management, we provide a general notion of reliability for a state-of-the-art ensemble of downscaled climate simulations at the Greater Montreal area and the neighboring region in Quebec, Canada. We look at how downscaled climate simulations can reproduce the observed long-term evolutions in a suite of annual climate variables that have relevance to urban water security in Montreal. It should be noted that we performed the same study at finer seasonal and monthly scales; however, we only report our results in the annual time scale for the sake of brevity and the fact that similar issues have been identified at finer time scales. As a result, the analysis of annual data can lead us to the identification of key sources of uncertainty in existing downscaled climate simulations in our case study. By looking at the prospective climate model simulations, we also provide a comprehensive view on wide ranges of projected changes in future hydroclimate variables as a result of different climate models and/or concentration pathways. By focusing on a real-world engineering design example, we then discuss how spatial variability and local uncertainty can lead into complexities for decision making. Accordingly, we suggest few directions to handle these obstacles until improved predictive climate modeling capability becomes available.

2. Case study

City of Montreal, referred to as “Canada's Cultural Capital”, is a major urban center in southern Quebec. Being home to around 4 million people, the 4259 km^2 Greater Montreal is the second most populous region in the country (Statistic Canada, 2012) and the second-largest economy of Canadian cities based on GDP (Brown & Rispoli, 2014). Montreal has a humid continental climate. Annual total precipitation is around 1000 mm per unit of area, for which about one fourth is in the form of winter snowfall. Summers are warm and humid and maximum daily temperature can exceed 30 °C. Conversely, winter brings cold weather with minimum daily temperature falling below −20 °C for several days during the season. Spring and fall are mild but prone to drastic temperature swings and extreme precipitation events, with thunderstorms being common in late spring to early fall (see Environment Canada, 1987).

Key socio-economic sectors in the city includes high-tech and service industries, higher education, as well as business and finance (see Ville de Montreal, 2002), all requiring secure water and electrical energy supply for day-to-day operations. There is a strong nexus between water and energy in the city as the hydroelectric power supply is the main energy source in the province (CBC, 30 March 2011). Municipal water supply is provided by the water stored at lac Saint-Louis, lac des Deux-Montagnes, Rivière des Prairies as well as the St. Lawrence River. This water is then treated in seven plants with the total capacity of around 3 million cubic meters per day (see http://ville.montreal.qc.ca/portal/page?_pageid=6497,54201575&_dad=portal&_schema=PORTAL). The treated water is then distributed through water mains to the end users. The water distribution network is old, ranging between 83 to 123 years of age in some areas of the city, and several bursting incidents have taken place in recent years due to various reasons, including extreme temperature swings (Riga, 12 January 2016). The city has been also prone to flooding, most notably during the deadly flood of July 14, 1987 that caused by overwhelmed sewer systems, unable to carry the extreme rainfall in parts of the city.

3. Available data

We considered the Greater Montreal and its surrounding 25 km neighboring regions that strongly links to the city in terms of water and energy security. This forms a grid box with the total area of 12,500 km^2, which still stays in the sub-grid resolution of majority of IPCC-CMIP5 models (see https://verc.enes.org/data/enes-model-data/cmip5/resolution). Within this region, there are eight climate stations with complete historical record at the daily scale going back to 1950 – see Table 1 for a brief description of the climate stations. Daily climate data in these stations are available through Environment and Climate Change Canada (ECCC)’s National Climate Archive. The considered stations are homogeneous in terms of the elevation, with an exception of St. Jerome being the only station with the elevation more than 100 m above the sea level. Having said that, no significant orographic effect was noted as St. Jerome shows strong correlation and insignificant deviation from the three nearby gauges located in lower altitudes. Here we used the climate information at these stations as the ground truth for inspecting the reliability of the available downscaled climate simulations.