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Projected monthly temperature changes of the Great Lakes Basin

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ABSTRACT

The Great Lakes Basin is an important agricultural region for both the United States and Canada. The regional crop growths are affected by inter-annual climatic conditions and intra-seasonal variability. Consequently, monthly climate change projection data can provide more useful information for crop management than seasonal climate projections. However, very few studies undertaken for the Great Lakes Basin have focused on monthly timescales. In this study, we investigate the projected mid-century (2030–2059) monthly mean maximum temperature (Tmax) and minimum temperature changes of this region, relative to the baseline period (1980–2009). Future Tmax increases in this region are likely to be greater during the May to October period (coinciding with the region's growing season) than in other months. The order of magnitude of future Tmax and Tmin changes of the five Great Lakes sub-basins are Superior > Huron > Michigan > Erie and Ontario. Most future Tmax changes over land areas are higher than those over the lakes, whereas Tmin changes are likely to be higher over lakes than over the adjacent land areas in this region. The future number of extreme warm days (Tmax ≥ 29–32 °C) in this region will increase by between about 5 days (in the north) to 40 days (in southern parts of the basin), while the number of winter cold days (Tmax ≤ −5 °C ~ 0 °C) may decrease by between 3 days (south) and 35 days (north). This study furthermore identifies some fluctuations of latitudinal temperature gradients in the Great Lakes Basin, these areas covering the north latitude 40.5–41.5°, 43.5–44.0°, 45.5–46.5°, and 47.5–49.5°.

1. Introduction

The Laurentian Great Lakes Basin is important to the economies and societies of both the United States and Canada. This region comprises over 20% of the world's surface freshwater (80% of North America's freshwater resources), not only providing drinking water to over 33 million people (10% of the US and 30% of the Canadian population), but also supporting the huge industrial and agricultural sectors of the two countries (Kling et al., 2003; Wuebbles et al., 2010). Agriculture in the Great Lakes Basin is important for both the US and Canada, accounting for approximately 7% and 25% of the total US production and Canadian production, respectively (USEPA, 2008). In Canada, Ontario farms provide jobs for 1.4 million people and account for $9.1 billion in annual revenues. Food processing companies in Ontario also generate 120,000 jobs and $32.5 billion in annual revenues (OMAFRA, 2016). Corn and soybeans are the two largest planted crops in this region.

Temperature is a very important factor affecting plant growth. In a recent corn growth experiment in Iowa US, the corn yield of the chamber under normal temperature was 471.2 g/m^2, but the corn yield of the controlled chamber (mean temperature increased 4 °C) declined sharply to 59.9 g/m^2 (Hatfield and Prueger, 2015). Prior to that, based on the historical (1976–2006) crop production for the US state of Wisconsin, Kucharik and Serbin (2008) found that both corn and soybean yield trends were enhanced in counties that experienced a trend towards cooler and wetter conditions during the summer. They also suggested that for each additional degree (1 °C) of future warming during summer months, corn and soybean yields could potentially decrease by 13% and 16%, respectively. Based upon the national climate and crop data, Schlenker and Roberts (2009) reported increases in crop yields (1950–2005) in the United States as a function of temperature increases up to 29 °C for corn, 30 °C for soybeans, and 32 °C for cotton. However, those crops yields sharply decreased when temperature increased beyond these thresholds. A study of historical (1965–2008) corn production in Northeast China (latitudes similar to those in the Great Lakes basin) showed that the corn yield was significantly correlated with the daily minimum temperature in May and September (Chen et al., 2011).

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The temperature optimum of different crops (including corn and soybean) varies among different growing stages during the between April and November in North America (Neild and Newman, 1987; Hatfield and Prueger, 2015; Andresen, 2017). For example, the two, four and six corn leaf fully emerged stages need an accumulated 200, 345 and 475 growing degree days (GDDs), respectively. Attainment of the corn kernels dented and physiological maturity stages require a total of 2450 and 2700 GDDs, respectively (Neild and Newman, 1987). These studies indicated that crop growth estimates rely on knowledge of monthly temperature variation rather than estimates of seasonal temperature variation. Similarly, a recent study on six Wisconsin (US) lakes (Winslow et al., 2017) also revealed that seasonal temperature changes could not fully represent the effects of climate change on lake temperatures change, and suggested that monthly temperature changes should be a proxy for seasonal patterns. Clearly, projected monthly temperatures data could provide more detailed and reliable information than the seasonal temperature patterns (e.g. Gula and Peltier, 2012; Wang et al., 2016) for agricultural management in practice.

The HadCM3Q Perturbed Physics Ensemble (PPE) of GCMs is a version of the United Kingdom Met Office Hadley Centre's third generation coupled ocean-atmosphere general circulation model HadCM3, in which the Great Lakes are explicitly represented by the model (Wilson et al., 2010). This allows the HadCM3Q GCMs to simulate interactions between the atmosphere and surface of the Great Lakes more realistically than using a non-flux corrected GCM alone. The PRECIS (Providing REgional Climates for Impacts Studies) regional climate modeling (RCM) system was developed by the Hadley Centre (Jones et al., 2004). It can generate high-resolution climate change information for any region of the world, thus providing detailed projections of climate (Jones et al., 2004; Massey et al., 2015). PRECIS has been applied to regions throughout the world, many of which encompass large expanses of both land and water (e.g. the Caribbean (Campbell et al., 2011), Southeast Asia (McSweeney et al., 2012), the Mediterranean and Middle East (Constantinidou et al., 2016)). Other studies have investigated regions adjacent to large water bodies (e.g. the Pacific Northwestern United States, Zhang et al., 2009).

In this study, we use PRECIS to downscale selected HadCM3Q GCMs. The objective is to project and compare mid-century (2030–2059) monthly temperature (Tmax and Tmin) with a baseline period (1980–2009), with an additional focus on understanding how Tmax and Tmin will change over land areas and the lake surfaces.

2. Methods

The HadCM3Q perturbed physics ensemble contains 17 GCMs. Individual GCMs are named HadCM3Q0, HadCM3Q1, HadCM3Q2, HadCM3Q3 and so on up to HadCM3Q16 (Wilson et al., 2010; McSweeney et al., 2012). The external forcing in the HadCM3Q PPE are according to the Special Report on Emissions Scenarios (SRES) A1B emissions scenario (Wilson et al., 2010), and the water-surface boundary conditions are taken directly from the water component of the HadCM3Q0 GCM model (Wilson et al., 2010).

PRECIS is a comprehensive model that considers both the water and land surface components of the climate system. It can represent important physical processes within the climate system, such as dynamic flow, the atmospheric sulfur cycle, clouds and precipitation, radiative processes, and the interactions between land surface and deep soil (Jones et al., 2004; Massey et al., 2015). PRECIS can downscale at two resolutions: $0.44 \times 0.44^{\circ}$ (about $50\,km \times 50\,km$) and $0.22 \times 0.22^{\circ}$ (about $25\,km \times 25\,km$) (Wilson et al., 2010). A previous study had revealed that five HadCM3Q GCMs (HadCM3Q0, Q3, Q10, Q13, and Q15) span most of above mentioned 17 GCMs parameters (McSweeney et al., 2012). In this study, we downscale five GCMs (HadCM3Q0, Q3, Q10, Q13, and Q15) with PRECIS at $25\,km \times 25\,km$ resolution to project future Great Lakes Basin climate changes for the mid-century (2030–2059). The various physical configurations of the five GCMs (Table 1) enable us to estimate uncertainties in the climate change projections that arise from GCMs parametrization. We chose a baseline period of 1980–2009 for this study. All the projections of future climate differences are expressed as the future period (2030–2059) estimates minus the baseline period (1980–2009).

The Mann-Kendall trend test (Mann, 1945; Kendall, 1975) and Sen's slope (Sen, 1968) have been widely used to quantify the significance of trends and changing rates in hydro-meteorological time series, respectively (Gocic and Trajkovic, 2013). To assess the historical temperatures changing trends of the 16 sites, we calculated the Mann-Kendall Z values and Sen's slopes of the temperature series (Tmean, Tmax, and Tmin) of the 16 weather stations (upon the observation data between 1980 and 2009).

3. Results and discussions

3.1. Data validation

To validate the performance of PRECIS simulation, we chose eight Canadian weather stations and eight US weather stations (Fig. 1) from the two countries' long-term weather observation networks. We obtained daily climate data from the 16 stations for comparison with the PRECIS results generated over the same baseline period (1980–2009). The locations of the 16 stations encompassed the whole basin and were situated on land areas adjacent to lakes (Duluth MN, Flint ON, Chicago IL, Toronto ON, Cleveland OH, etc.) and the bordering landmass of the lakes (Lansing MI, Sudbury ON, Ottawa ON, etc.), allowing us to assess the models' performance (five GCMs and PRECIS) in capturing the land and water variations across this region.

Comparisons for monthly mean Tmax, Tmean, and Tmin of observed versus output data from five simulations are shown in Fig. 2. Most (46 in 48) observations fell within the range of simulated results, except for Tmin at Flint and Wawa stations. Point to point data validations may yield gaps at some sites, but the overall performance of the simulation should be considered on a large scale as in previous studies (Vavrus and Van Dorn, 2010; Wang et al., 2016), because no climate simulations could accurately (100%) project all single sites (grids) climate in practice.

In Table 2, we compared our simulation performance with other recently published climate simulation data validations that focused on (or involved) this region. The data validation biases (-0.9 °C to +0.7 °C) in this study are comparable to (or smaller than) the biases (-2 °C to +1.93 °C) in recent studies despite different downscaling methods (statistical and dynamical) (Vavrus and Van Dorn, 2010; Gao et al., 2012; Gula and Peltier, 2012; d'Orgeville et al., 2014; Notaro et al., 2015). The data validations indicate the models we selected could do well in simulating the temperature variations of the Great Lakes Basin. Because the historical data observed from 16 stations represent the climate results reflecting the complex land-lake interactions and closely match the data simulations for the validation portion of this study, we