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Projected precipitation changes within the Great Lakes and Western Lake Erie Basin: A multi-model analysis of intensity and seasonality

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Abstract

The Great Lakes region encompasses the largest freshwater lake network in the world and supports a diverse network of agriculture, transportation and tourism. Recently, Lake Erie has experienced increased hypoxia events, which have been attributed to agricultural practices and changes in runoff. Here we examine the projected changes in extreme precipitation events to address concerns regarding regional agriculture, surface runoff, and subsequent water quality. Precipitation projections within the overall Great Lakes basin (GLB) and the Western Lake Erie basin (WLEB) sub-region are examined using climate model simulations of varying spatial resolutions to understand historical precipitation and projected future precipitation. We develop three model ensembles for the historical period (1980-1999) and the mid-century (2041-2060) that cover a range of spatial resolutions and future emissions scenarios, including: (1) 12 global model members from the fifth Climate Model Intercomparison Project (CMIP5) using Representative Concentration Pathway (RCP) 8.5, (2) 10 regional climate model (RCM) members from the North American Regional Climate Change Assessment Program (NARCCAP) driven by CMIP3 global models using the A2 emissions scenario, and (3) 2 high resolution regional climate model simulations (RCM4) driven by CMIP5 global models using the RCP8.5 scenario. For the historical period, all model ensembles overestimate winter and spring precipitation, and many of the models simulate a summer drying that is not observed. At mid-century, most of the models predict a 10-20% increase in precipitation depending on the time of year. Daily probability distribution functions from three model ensembles reveal spring seasonal

increases in high precipitation event probabilities when compared to the historical period, suggesting an increase in the frequency of high intensity precipitation at mid-century. Overall, the presence of lakes or higher spatial resolution does not ensure improved representation of historical processes, and more complex interactions between large-scale dynamics, local feedbacks, and physical parameterizations drive the model spread.

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1.0 Introduction

The Laurentian Great Lakes have the largest freshwater lake surface area in the world and support a diverse network of agriculture, transportation and tourism. Precipitation is a key element of the water cycle in the Great Lakes Basin [Gronewold *et al.*, 2013; Gronewold and Stow, 2014], and the impacts of shifts in seasonal and daily precipitation have been documented across the region [Cherkauer and Sinha, 2010; Mishra and Cherkauer, 2011; Michalak *et al.*, 2013]. The release of greenhouse gases which feedback to a rise in global temperatures are associated with changes in precipitation, and are likely to induce more frequent heavy rain and flooding events [Karl *et al.*, 2009; Melillo *et al.*, 2014]. The most recent National Climate Assessment identifies an increasing regional trend in total precipitation over the Midwestern United States since 1991 [Melillo *et al.*, 2014]. Further, for the Midwest and Northeast regions that encompass the Great Lakes, the amount of precipitation falling in very heavy events (the heaviest 1% of all daily events) has increased by 37% and 71% respectively over the same period [Melillo *et al.*, 2014]. Here, we investigate climate model simulations of precipitation seasonality and intensity in the Great Lakes Basin and how they are projected to change with future climate.

Climate model simulation of precipitation depends on a suite of atmospheric and terrain-induced physical processes. Both the models' spatial resolution and the inclusion of complex terrain and coastlines such as the Great Lakes have a large impact on simulated precipitation. Many of the global climate models in the third Climate Model Intercomparison Project (CMIP3;

[Meehl *et al.*, 2007]) and the fifth iteration (CMIP5; [Taylor *et al.*, 2012]) have coarse spatial resolution such that they do not explicitly represent the Great Lakes. To increase the resolution in complex topographic regions such as the Great Lakes, two common downscaling techniques are employed: dynamical downscaling and statistical downscaling [Wilby *et al.*, 1998]. Dynamical downscaling is a technique that uses high-resolution regional models driven by global climate model boundary conditions. For example, the North American Regional Climate Change Assessment Program (NARCCAP) ensemble of regional climate model simulations was driven with initial and lateral boundary conditions obtained from global climate model output from the CMIP3 archive [Mearns *et al.*, 2013]. In contrast, statistical downscaling relies on observed relationships between large-scale variables and local variables over a historical period, and applies these relationships to increase the spatial resolution of existing global climate model output. While less computationally intensive than dynamical downscaling, a major drawback of statistical downscaling is the stationarity assumption, which requires that the statistical relationships remain the same in the observed period and in the future.

Previous climate and climate impact studies centered around or in the Great Lakes region have used either ensembles of global climate model data or downscaled data to understand how future precipitation may change in the Great Lakes region. Using a suite of global models from CMIP3, a statistical downscaling study suggests that winter and spring precipitation may increase between 20-30% by the end of century (2070-2099) [Hayhoe *et al.*, 2010]. [Patz *et al.*, 2008] calculated a 10-40% increase in the magnitude of extreme precipitation events in southern

Wisconsin also based on CMIP3 model projections. A study using the NARCCAP ensemble to investigate changes across the agriculturally dominated Canadian prairie regions found up to a 15% increase in spring and summer precipitation as well as change in return periods for rain-dominated precipitation extremes [Khaliq *et al.*, 2015]. [Vavrus and Behnke, 2014] compared precipitation from global models with statistical and dynamically downscaled model output, and found a projected increase of annual precipitation < 10% with more seasonal precipitation in all seasons except summer, increases in the intensity of daily extreme precipitation events (< 30% increase in accumulation), and an even larger change in the return periods of extreme events (up to -50%).

Dynamically downscaled experiments have improved our understanding of the role of lake-atmosphere interactions in the present and under future climate conditions. [Bryan *et al.*, 2015] used dynamical downscaling with RegCM4 for the Great Lakes region to examine land-lake-atmosphere feedbacks in a high-resolution ensemble under present day conditions, and found that the simulation of lake temperature can introduce biases in simulated precipitation. Similar results were found when dynamically downscaling with the Weather Research and Forecast model (WRF) [Mallard *et al.*, 2014]. For future climate, [Notaro *et al.*, 2015] used dynamically downscaled simulations to show that cold-season precipitation is projected to increase due to reductions in lake ice cover, yet the frequency of the lake effect snowstorms is expected to decrease. [Gula and Peltier, 2012] found that a regional model (WRF) and its global driving model (the Community Climate System Model (CCSM)) produced different spatial

patterns of projected precipitation over the Great Lakes region. The global model (CCSM) projected an increase 15-25% in annual precipitation by midcentury (2050-2060), whereas the dynamically downscaled WRF simulations showed a precipitation reduction in the southern Great Lakes region and an increase in the northern Great Lakes. This difference was attributed to atmosphere-lake feedbacks. [d'Orgeville *et al.*, 2014] also used WRF with different physics parameterizations, and found that precipitation extremes are expected to increase in the Great Lakes region. Together, these studies highlight that there may be added value in using high-resolution simulations that accurately resolve the lake and its physical properties, and that global models are not likely to capture these regional nuances.

In this study, we conduct a multi-scale regional analysis of Great Lakes precipitation to identify the role of climate model method and grid resolution on precipitation projections. We examine the Great Lakes Basin (GLB) as a whole, which is noted to be difficult to simulate due to the treatment of the lakes [Mearns *et al.*, 2013]. We also evaluate the specific subregion of the Western Lake Erie Basin (WLEB). The WLEB is the subject of ongoing agricultural management studies connected to recurring harmful algal blooms in western Lake Erie, and these events are influenced by regional precipitation intensity [Michalak *et al.*, 2013]. Our analysis utilizes modeled output from one global model ensemble and two dynamically downscaled regional model ensembles. We compare output between a historical period (1980-1999) and high emissions scenario experiments for a mid-century period (2041- 2060). We quantify changes in precipitation intensity and seasonality in the defined regions using daily and monthly rates to

inform future climate change adaptation planning. Moreover, we highlight areas of confidence and uncertainty for the different ensembles to summarize the value of the multi-scale analysis.

2.0 Methods

The seasonal timing and daily magnitude of precipitation events are two metrics that can be used to quantify precipitation impacts. We use a suite of gridded observation products, regional climate model output and global climate model output to assess present-day and future projections of precipitation in the Great Lakes region. We evaluate models during a historical time period, defined in this study as 1980-1999 based on overlapping data availability of observations and NARCCAP regional climate simulations [Mearns *et al.*, 2013]. For the future time period, we evaluate 2041-2060 based on NARCCAP timeslice experiment. We evaluate the seasonal cycle of precipitation (e.g., DJF, MAM, JJA, and SON) for the historical period to understand model biases and also for the mid-century period to understand future changes in seasonality. To assess extreme precipitation, we use the maximum 1-day precipitation which is a common metric used to understand changes in intensity between the two time periods and model ensembles.

2.1 Precipitation observations

Modeled historical climate data is evaluated with the Climate Prediction Center's (CPC) Daily US Unified Precipitation dataset between 1980 and 1999. The CPC Unified Precipitation

dataset uses distance weighting and optimal interpolation methods to resolve observations from over 30,000 global observation stations to a $0.25^{\circ} \times 0.25^{\circ}$ gridded product [Chen *et al.*, 2008]. The 20-year historical time period was selected based on the revised definition of climatological time period by the World Meteorological Organization from a 30-year average to a 20-year average [Arguez and Vose, 2011] and the intersection with regional climate model simulations.

2.2 Global climate model data

Twelve atmosphere-ocean (AO) models of the Climate Model Intercomparison Project 5 (CMIP5; [Taylor *et al.*, 2012]) comprise the global climate model ensemble (Table 1), with model data accessed through the Earth System Grid Federation's PCMDI, DKRZ, and NCAR nodes. For the future, we selected the Representative Concentration Pathway 8.5 (RCP 8.5) experiment, as present-day emissions are currently following this emissions projection [Peters *et al.*, 2013]. Only CMIP5 AO models with daily temporal output for the present-day and RCP8.5 experiments were selected. The AO configuration is defined to include interactive atmosphere, land surface, ocean and sea ice models as well as aerosol components, and captures water cycle feedbacks with the atmosphere [Flato *et al.*, 2013].

2.3 Regional climate model data

Regional climate models, i.e. dynamical downscaling, have the potential advantage of preserving physical and dynamical relationships between variables, thus reducing the issue of stationarity associated with statistical downscaling [Gutierrez *et al.*, 2013]. These regional,

higher resolution simulations require global climate model data or reanalysis data for lateral boundary conditions. For our analysis, we use ten regional NARCCAP simulations that provided daily precipitation for the present-day and future time periods at 50 km resolution for the A2 emissions scenario (Table 1). NARCCAP output was accessed through the Earth System Grid Federation PCMDI and NCAR nodes as 3-hourly precipitation fluxes, which were converted to daily precipitation rates (mm day^{-1}). The full NARCCAP ensemble includes twelve simulations, but two of the simulations (WRFG-CCSM and HRM3-GFDL) use different treatment of the lakes in present day and future conditions, making the comparison of present day and future precipitation not possible given our focus region. In addition to the NARCCAP RCM ensemble, we also evaluate two RCM simulations at 25 km resolution (RCM-HiRes) with the RegCM4 [Giorgi *et al.*, 2012], which uses two different CMIP5 GCM RCP8.5 simulations as boundary conditions [Bryan *et al.*, 2015] (Table 1).

2.4 Spatial and temporal averaging

The gridded observations, global ensembles and regional ensembles were analyzed for the Great Lakes basin (GLB; 40°N to 50°N, 75°W to 95°W), and the Western Lake Erie basin (WLEB; 40°N to 43°N, 82°W to 85.5°W) (Figure 1). Each simulation was spatially averaged over the GLB and WLEB regions, with the number of grid cells within each region for each simulation detailed in Table 1 to highlight the range of resolution within the global and regional models.

Daily precipitation data were downloaded for the global model simulations, and 3-hourly precipitation data from the NARCCAP and RCM-HiRes were downloaded and aggregated to a daily basis for present-day (1980-1999) and future (2041-2060) precipitation intensity. We note that two NARCCAP ensemble members (CRCM-CCSM and MM5I-CCSM) did not simulate the complete year for 1999 and for these two members we use the present-day period of 1980-1998. For seasonal climatology, daily data were averaged to monthly for both the historical and future periods. Differences in precipitation rates between the present-day and future time periods were calculated from the monthly climatologies. For intensity, daily precipitation rate probabilities were sorted into 15 bins ranging from 0 to 90 mm day⁻¹. To account for the spatial variability within the GLB and WLEB averaging regions, maximum precipitation rates within each region were also evaluated using 20 bins ranging from 0 to 500 mm day⁻¹. For the WLEB, seasonal and daily spring biases were calculated for the historical period to inform runoff sensitivity modeling for the Maumee watershed located in northwestern Ohio. Over the historical period, precipitation events greater than 24 mm day⁻¹ (99th percentile) were considered “extreme” for the Maumee watershed based on comparisons with daily gauge precipitation data between 1981 and 1999.

3.0 Evaluation of Precipitation Seasonality and Intensity

3.1 Precipitation Seasonality

3.1.1. Observed Historical Precipitation (1980 – 1999)

Observed seasonal precipitation for the GLB and the WLEB sub-regions show a clear unimodal pattern with a summer maximum (Figures 2a and 3a, respectively). For the period 1980-1999, observed annual precipitation over the GLB is 832.6 mm with an annual minimum during late winter (30.6 mm month⁻¹ in February) and maximum during summer (99.0 mm month⁻¹ in June and 99.4 mm month⁻¹ in July) (Figure 2a). The seasonal cycle is similar in the WLEB region, with a similar peak precipitation (97.1 and 97.8 mm month⁻¹, in June and July respectively) and the mean minimum precipitation is higher (46.7 mm month⁻¹ in February; Figure 3a). Over the WLEB, total annual precipitation of 908.2 mm is slightly higher than the GLB region average. For the GLB, the summer season (June-July-August; JJA) includes the largest fraction (over one-third) of the averaged annual precipitation (294.6 mm), with just less than one-fourth annual precipitation occurring in spring (198.7 mm; March-April-May; MAM). Summer also contains the highest fraction of WLEB precipitation (284.8 mm), however spring contains over one-fourth of its total precipitation (236.9 mm) (Table 2).

3.1.2 Modeled Historical Precipitation (1980 – 1999)

We compare simulated annual and seasonal precipitation from the global and regional ensembles with CPC observations averaged over 1980-1999 (Figures 2-3 and Table 2). For the GLB basin over the historical period, 11 of the 12 CMIP5 members and 8 of the 10 NARCCAP members simulate more annual precipitation than the observed historical value, while both RCM-HiRes members have a negative or dry bias. The GLB averaging region has wet biases in both spring and winter in all 12 CMIP5 models and all 10 NARCCAP models (Figure 2a and

2b). In both RCM-HiRes members, the seasonality of the modeled precipitation is relatively flat as noted by Bryan et al. (2015), with a positive winter bias and a negative summer bias. All of the models in the region exhibit a positive winter bias, while the summer bias in these simulations may be due to a weak parameterization of convective precipitation. All ensemble members show a wet bias in DJF precipitation ranging from 19.7 mm (17.3%) to 108.3 mm (95.2%) (Figure 2a-c), although this may be in part attributed to the low observed values in the region influenced by gauge error for solid phase precipitation [Legates and Willmott, 1990]. For example, gauge corrections based on the Legates and Willmott data can increase winter precipitation in the Great Lakes region by up to 0.5 mm d⁻¹. The CMIP5 ensemble mean overestimates MAM precipitation by 61.0 mm (30.7%), with individual wet model biases ranging between 2.3 mm (1.2%) and 112.2 mm (56.5%). Similar to the global models, the NARCCAP ensemble mean shows a positive bias in MAM of 50.4 mm (25.4%) but with a narrower range in the model bias (18.3- 96.0 mm). All NARCCAP models show a late spring/early summer (MJJ) peak that is stronger than observed (Figure 2b), and indicates that this ensemble shifts precipitation earlier in the season than observed and produces too much precipitation. In JJA, the inter-ensemble model spread grows, with 14 of the 24 total models exhibiting a summer dry bias and the rest exhibiting a wet bias (Figure 2a-c). As the summer progresses into fall, the intermodel CMIP5 spread narrows and individual model biases are reduced. In late summer/early fall (ASO), the NARCCAP ensemble reduces precipitation closer to observed, but then precipitation increases again in the winter, a feature not evident in the

observations (Figure 2b). For the RCM-HiRes simulations, there is very little amplitude in the seasonal cycle, as discussed in Bryan et al. (2015). This leads to a comparatively small spring dry (negative) bias of 5.8 mm (-2.9%) in the ensemble mean, although this is largely due to the flat seasonal cycle relative to the increase in winter to spring precipitation (Figure 2c).

For the WLEB region, most models also have a wet annual bias with the exception of one CMIP5 model (CSIRO), one NARCCAP model (CRCM-CCSM) and the RCM-HiRes simulations (Table 2; Figure 3a-c). The seasonal bias is strongest in MAM for all model ensemble means, with a positive bias of 69.9 mm (29.5%) for CMIP5, a positive 60.1 mm (25.4%) bias for NARCCAP, and dry bias of 27.8 mm (-11.7%) for RCM-HiRes. The bias of individual CMIP5 members is similar to the larger region, falling between 4.7 mm (2.0%) and 122.9 mm (51.9%), likely due to the differing model processes and wide range of spatial resolution in this ensemble. Similar to the GLB, the NARCCAP ensemble produces MAM precipitation that ranges close to the CMIP5 models, from 12.1 mm (5.1%) and 112.4 mm (47.4%) for individual model members (Figure 3c). Unlike the other ensembles, the RCM-HiRes shows a dry bias over land in the region [Bryan *et al.*, 2015] with individual members showing a dry bias of 18.3 mm (-7.7%) and 37.2 mm (-15.7%; Figure 3e).

3.1.2 Modeled Future Precipitation (2041 – 2060)

With knowledge of the biases in the historical simulations, we examine the relative percent change in seasonal precipitation for midcentury (2041-2060) for the GLB and the WLEB respectively (Figures 2d-f and 3d-f, respectively). For the GLB, the annual relative change in

precipitation is typically positive and does not differ much between ensembles (CMIP5: -0.7 to 16.1%, NARCCAP: 4.7 to 10.6%, RCM-HiRes: 6.7 to 14.3%; Figure 2d-f). The projected increase in annual precipitation is similar for the WLEB region, however the increase is slightly higher in the global and regional ensembles (CMIP5: -5.4 to 17.8%, NARCCAP: 0.0 to 13.9%, RCM-HiRes: 0.8 to 12.9%; Figure 3d-f).

During spring and winter, precipitation is generally projected to increase across all ensemble members within both regions (Figures 2 and 3). Ensemble mean changes in MAM precipitation are small (7.0-14.7%) for the GLB, with individual models ranging between 1.4-30.0% for the CMIP5 ensemble, -1.6-12.7% for the NARCCAP ensemble, and 12.5-17.0% for the Hi-Res ensemble. For the WLEB, the spring ensemble mean changes have a smaller range (8.4-12.8%) with more member variability (CMIP5: -3.6 to 33.6%, NARCCAP: 1.5% to 19.2%, Hi-Res: 9.8 to 15.8%). The magnitude of winter precipitation change for the CMIP5 ensemble mean is similar for both regions (GLB: 17.4%; WLEB: 17.9%). The NARCCAP and RCM-HiRes ensemble means, present a lower increase than CMIP5 for the GLB (11.1%, 13.6%, respectively). The regional models' magnitude of increase is slightly higher for the WLEB (11.5%, 14.0%; Figure 3d,f).

The greatest spread in the simulated future precipitation occurs in JJA, with some models showing decreases in future summer precipitation and some showing relative increases compared to the historical period (Figures 2 and 3). Although the ensemble mean changes show increases ranging from 0.9-8.8% in the GLB, in the WLEB, this range is -1.4 to +1.6%. For both the GLB

and WLEB, 8 out of the 12 CMIP5 models show an increase in JJA precipitation (GLB: 0.2-9.3%, WLEB: 1.3-14.1%), while 4 show relative decreases (GLB: 0.2-19.0% decrease, WLEB: 1.0-20% decrease) (Figures 2d and 3d). For the regional NARCCAP ensemble, there is more variability between members although there is a similar spread in JJA between regions, with 7 models predicting an increase in GLB precipitation and 4 models predicting an increase for the WLEB (GLB: 0.5-13.4%, WLEB: 2.5-16.4%, Figures 2-3d). The range of predicted decrease is also similar from 3 models in the GLB and 6 models for the WLEB (GLB: 0.3-7.6 decrease, WLEB: 3.5-12.7% decrease, Figures 2-3d). The RCM-HiRes simulations are also split on the change in JJA precipitation for the WLEB (-8.4 decrease and 9.7% increase), leading to a near zero change in precipitation in the ensemble mean whereas they both indicate an increase for the GLB (4.9% and 12.8%; Figures 2-3f).

Overall, the response of seasonal precipitation at the midcentury time period is similar across both regions with most ensemble members, with ensemble means indicating an increase between 8.5-12.6% in the spring and 11.5-18% in the winter for the WLEB (Figures 2 and 3). The overall response of precipitation to the future climate scenarios is more variable during the summer and early fall, depending on the ensemble and member. However, we note that this increase is slightly smaller than the model bias in these seasons. This result is consistent with [Hayhoe *et al.*, 2010], who used two statistical downscaling techniques for precipitation in the Chicago and Great Lakes area and found that that winter and spring precipitation may increase

up to 20% before end of century (2070-2099) under the similar A2 (or moderate) emissions scenario. Possible explanations for these changes are explored in Section 4.

3.2 Precipitation Intensity

3.2.1 Observed Historical Period Precipitation Intensity (1980-1999)

We examine daily precipitation rates (or precipitation intensity) over the historical period with probability density functions, dividing daily precipitation into 15 equally spaced bins spanning 0-90 mm day⁻¹. We define three categories of events: small (0-5 mm day⁻¹), moderate (6-23 mm day⁻¹), and extreme events (≥ 24 mm day⁻¹). Simulated precipitation intensity is compared with daily CPC gridded observations, although we note that using a gridded product for intensity may smooth out individual stations that may experience higher, localized rainfall. However, this product provides continuous coverage of historical data for evaluation and a daily precipitation value that is spatially consistent with a model grid cell.

In the GLB region (Figure 4a-d), all ensemble members generally capture the observed intensities in all seasons except for DJF, where the models overestimate daily precipitation. For DJF, this suggests that the seasonal wet bias (Section 3.1.2) is due to both more precipitation during the moderate events in most of the models (e.g., 6-23 mm day⁻¹) as well as the simulation of higher intensity events by some model members (≥ 24 mm day⁻¹) (Figure 4d). Other seasons, such as MAM, show that the models capture the frequency of moderate events (6-23 mm day⁻¹) but some model members simulate additional high intensity events (≥ 24 mm day⁻¹) (Figure 4a).

The same pattern is evident in JJA (Figure 4b) and SON (Figure 4c). When comparing the model type in both MAM and DJF, the global models produce more intense events than the regional models (Figure 4a-d). For the RCM_HiRes ensemble, the spatially averaged precipitation shows lower mean probability values, consistent with the previously described summer season dry bias (Figure 4b).

For the WLEB subregion, simulated intensities are higher (up to 90 mm day⁻¹) than the GLB because of spatial averaging techniques (e.g., the WLEB subregion is 3°×3.5° and the GLB is 10°×20°). With fewer grid cells, more of the individual grid intensities are captured with a smaller averaging region, increasing the regionally-averaged intensity (Figure 5a-d). All model ensembles generally capture the JJA and SON moderate range intensities (e.g., 6-23 mm day⁻¹) but again have individual members that simulate higher intensity events that reach up to 83 mm day⁻¹ (Figure 5b-c). For MAM and DJF, the models overestimate the observed precipitation in the 18-41 mm day⁻¹ range as well as simulating additional, high intensity events (Figure 5a,d). For extreme intensity values in the WLEB (defined here as ≥ 24 mm day⁻¹, informed by historically modeled streamflow data for the Maumee basin), the relative error in historical spring (MAM) probabilities ranged from 75-1175% for CMIP5, 50-667% for NARCCAP, and 125-181% for RCM-HiRes (Table 2). As in the GLB region, there are several CMIP5 model members that show more intense events than the regional models in MAM and JJA (Figure 5a-b). Summer in the WLEB shows good agreement with historically observed probabilities for small to moderate events (≤ 24 mm day⁻¹), however the simulations include higher events that

are not present in the observations (Figure 5b). The CMIP5 mean exceeds the historical range by 8 bins, equating to almost 48 mm (6 mm per bin) or 1.9 inches (Figure 5b). However, the associated probabilities indicate a low frequency of these events with values close to 0.1%, or 1.8 events per 20 years (Figure 5b).

3.2.2 Future Precipitation Intensity (2041-2060)

We examine the change in daily precipitation rate probabilities between the historical (1980-1999) and future (2041-2060) periods for the three ensembles (Figures 4e-h and 5e-h). We calculate the change in probability as the difference of the future probability with that of the historical probability. For example, from the ~1800 days included in MAM over 20 years, a typical extreme event may have a 1% probability. This is equivalent to about 18 events over the 20-year period for that season. If the probability of such an extreme event increased relatively by 0.1%, that would increase total MAM extreme events by 1.8 events between the 20 year periods. For small precipitation events, the GLB ensemble means show negative changes across all seasons (1.0-3.4% decrease in probability; Figure 4e-h). The WLEB ensemble means for small events show a similar result for the spring and winter seasons, however with a slightly smaller range (0.9-1.9% decrease), while summer and fall have a mixed sign of change (Figure 5e-h). For each of the GLB ensemble means, moderate daily precipitation events across all seasons show the largest positive change (1.0-3.4%), with extreme events showing no change (Figure 4e-h). This is in part due to the spatial averaging used in this study, where averaging over a large region causes a relatively sharp drop off in the tail end of the probability distribution function

(24-90 mm day⁻¹) for each ensemble. As compared to the GLB, the WLEB ensemble means also show less consensus for the sign of moderate events, and with about half of the models showing overall positive changes (0.1-0.7%) for spring and winter extreme events which translate to a projected increase of about 1-12 more events over the 20-year midcentury period (Figure 5e-h).

4.0 Discussion

To place these results in context, we discuss several factors related to the spatial averaging employed in this study, the climate model resolution and the model representation of physical processes such as lakes to understand model biases and projections of future precipitation in the GLB and WLEB regions.

4.1 Spatial Averaging Effects

Spatial averaging across regions effectively smooths the extreme daily events, especially for the GLB region. For example, GLB intensity values (Figure 4a-d) are lower than the WLEB basin (Figure 5a-d) and may underrepresent the intense events in the overall GLB region, suggesting that the larger spatial extent of the GLB may reduce the calculated precipitation intensity. To understand how the spatial averaging affects the calculation of the extremes, we evaluate the maximum daily precipitation rates across each region. The maximum daily precipitation intensity is defined as the greatest intensity that occurs within any individual grid cell in the region during the selected season over all years. The probability distribution of these

maxima shows the likelihood of the maximum possible precipitation that can occur within each averaging region (Figure 6 for the GLB and Figure 7 for the WLEB). For example, in the GLB in MAM, observations show a 0.05% probability in the 150-174 mm d⁻¹ bin, which indicates that at least one grid cell in the GLB reached a daily precipitation value in this range. This probability is equivalent to about one spring event of this intensity over the 20-year averaging period (1980-1999). This provides a metric for the spatial distribution of precipitation intensity at any point within the region and can be useful to compare with the regional averages (Figures 4 and 5).

Over the GLB region, CMIP5 models tend to underestimate the maximum probability values (Figure 6a-d). Generally, the regional model ensembles (NARCCAP and RCM_HiRes) simulate a larger number of extreme events that more accurately captures the maximum daily precipitation distribution (Figure 6e-l). The dynamically downscaled models do tend to have some models that overestimate the maximum intensity, most notably in the spring (Figure 6e and 6i) and summer (Figure 6f and 6j). In the fall, not all NARCCAP ensemble members capture the event range and only one model (HRM3-HadCM3) extends beyond the historical CPC range (Figure 6g) while the HiRes members are split for larger event sizes (above 50 mm d⁻¹) (Figure 6k). In the winter, the NARCCAP ensemble shows a spread around historical probabilities (Figure 6h) while the HiRes members have more occurrences of extreme events above 50 mm d⁻¹ (Figure 6l). In the WLEB region (Figure 7), the dynamically downscaled models also show an improvement over the global models in the simulation of intense precipitation. NARCCAP extends the range beyond CPC probabilities for all WLEB seasons (Figure 7e-f), while the HiRes

shows a higher intensities for WLEB summer and winter (Figure 7j and 7l). The tendency for the NARCCAP models to produce large extremes in excess of observed values has been noted in other studies that evaluated the model performance over the entire United States [Caldwell, 2010; Kawazoe and Gutowski, 2013b; Wehner, 2013]. Here, these results show that the regional models produce some grid cells with very high intensity events (e.g. $> 250 \text{ mm d}^{-1}$ in JJA), but overall, the finer resolution models better capture the high intensity events across the two regions.

To further evaluate the effects of area averaging, we also examined the spatial distribution of the 99th percentile precipitation (considering rain days on which the precipitation was over 1 mm day^{-1}) in the WLEB region to determine if certain grid points have substantially higher precipitation extremes. Evaluation of seasonal averages shows no appreciable spatial pattern in seasons outside of DJF. Figure 8 shows the 99th percentile for the ten NARCCAP models and the CPC observations. In several of the NARCCAP members, and to some extent in the observations, the 99th percentile precipitation is largest near the lakes, suggesting these larger extremes are related to the production of lake effect snow in winter. For some models, the lake temperatures are interpolated from the nearest sea surface temperatures. [Bryan *et al.*, 2015] showed that southern Great Lakes SSTs lake temperatures were biased warm compared to observations when using this method, enhancing precipitation near the lake in this model. Examination of the patterns of the GCMs did not reveal similar lake effects (not shown), likely

because the grid spacing is too large to simulate lake-precipitation feedbacks or the lakes are absent, as discussed below.

4.2 Resolution Effects

Another potential factor in the differences in precipitation intensity is the climate model resolution. In the GLB region, the CMIP5 ensemble mean has higher intensities than the dynamically downscaled models (Figure 4a-d) and this effect is magnified for the WLEB (Figures 5a-d). Within the CMIP5 ensemble, the CMCC-CMS model consistently places non-zero probabilities in higher intensity bins beyond those of the historical record for both regions (individual model members not shown in Figures 4 and 5).

For the WLEB we evaluated two simulations with the CMCC model, the CMS version (1.875° resolution, which resolves the stratosphere) and the finer CMCC-CM (0.75° resolution, the highest resolution CMIP5 model in our ensemble). While these model versions have several parameterization differences, the increase in horizontal spatial resolution does not explain the historical bias for intense daily events. The two resolution versions show similar bias in the spring extreme event probability (1075%, 1175% respectively; Table 2). However, CCSM4 and CESM1-CAM5 (0.9 x 1.25° each) are also relatively high resolution in our CMIP5 ensemble (187 grid cells for the WLEB), but show a larger difference in extreme event probability bias (75% and 300% respectively; Table 2). Interestingly, the CSIRO model, which has a coarser resolution equal to the CMCC-CMS model (1.875°), has less bias for extreme daily events (125% and 1075%, respectively; Table 2) and also exhibits a lower bias for MAM seasonal

precipitation than CMCC-CMS (22.0% and 41.4%, respectively; Table 2). While it is not surprising that the models produce very different precipitation distributions due to large number of variable parameterizations in the model (e.g., convective precipitation, microphysics and land surface), the comparison here shows that higher resolution alone within the CMIP5 ensemble does not improve the precipitation intensity bias simulated in the region. This is consistent with other studies, e.g., [Kawazoe and Gutowski, 2013a] found that CMIP5 model resolution could not explain biases in precipitation intensity over the upper Mississippi region in the winter. Additionally, six global models show relatively low bias for spring precipitation (CCSM4 at 16.6%, CESM1 at 7.2%, CSIRO at 22.0%, FGOALS at 18.2%, HadGEM2 at 24.7%, and MIROC at 2.0% respectively; Table 2), which is similar to several of the regional models for this metric (about 7-25%; Table 2).

For the WLEB spring and summer seasons (Figure 5a-b), observed intensities reach up to 30-35 mm day⁻¹. However, 10 of the CMIP5 models place probabilities in the next available bin (36-41 mm day⁻¹) for spring, summer and fall (9 models for winter), showing that most of the CMIP5 ensemble overemphasizes the magnitude of intense events by at least 6 mm day⁻¹ (0.2 inch day⁻¹) for these seasons. Multiple models go beyond this lower end bias and have nonzero probabilities in even higher bin ranges, with half of the CMIP5 ensemble represented in the 42-47 mm day⁻¹ range for spring and fall, 8 models for summer and 3 models for winter producing a bias of at least 12 mm day⁻¹ (0.5 inch day⁻¹). Further, 7 models in the CMIP5 ensemble place nonzero probabilities in the 48-53 mm day⁻¹ range giving a bias of at least 18 mm day⁻¹ for the

summer period. In contrast, the regionally averaged RCM simulations overall do not exhibit such a high intensity, with lower average probabilities across all seasons in both regions. This suggests that the maximum probabilities with very high intensities (Figures 6 and 7) are likely occurring over a very small number of grid cells at different times and locations, and these grid cells do not affect the overall regional average (Figures 4 and 5). For example, HRM-HadCM (Figure 8k) shows that a grid cell north of Lake Erie (1 of 56 grid cells in the WLEB region in this model, or 1.78% of the model grid cells) has the highest precipitation over the WLEB 12% of the time.

4.3 Lake Representation

Even if topographic features such as the lakes are better resolved at higher resolution, physical parameterizations may not result in better evaluation with observations [Caldwell, 2010; Rauscher *et al.*, 2010]. The representation of lakes in the region is known to play an important role in regional precipitation [Notaro *et al.*, 2013a; Suriano and Leathers, 2016]. One advantage of higher resolution models would be to include these important features at the lower model boundary condition, but resolution alone does not determine whether or not the surface is represented as bodies of water. In most of the global model members of the CMIP5 ensemble (9 of the 12 models), the Great Lakes are not differentiated from land (Table 1). In the NARCCAP ensemble, the lakes are represented in terms of land cover but have different treatment of lake processes that drive lake temperatures and the presence of ice. For example, most of the NARCCAP models do not use a lake model and interpolate lake surface temperatures from

nearby sea surface temperatures (Table 1). As a result, there is no prognostic calculation of lake ice coverage. Three members of the NARCCAP ensemble (CRCM-CGCM3, CRCM-CCSM and WRFG-CGCM3) simulate dynamic lake ice across the Great Lakes.

We group model members across the multiple ensembles used in this study to understand the role of lake representation in the simulation of regional precipitation. The 15 models that represent lakes include 3 CMIP5 models (Table 1), and all 12 regional scale models (10 NARCCAP and 2 RCM HiRes). The ensemble without lakes includes the remaining 9 CMIP5 models (Table 1). For the historical period, the multi-model average seasonal cycle between the models that include lakes versus those that do not is similar over the GLB (Figure 9a,c), yet there is much more variability among the members of seasonal precipitation in the lake ensemble. Both sets of models show wet biases in the winter and spring for the GLB, as well as slight dry bias in the late summer and early fall. The model bias improvement due to the lakes is inconsistent across seasons, with the spring bias slightly reduced by the models that include lakes (from a bias of 53.9 to 49.3 mm, for models without lakes and with lakes, respectively) and the winter bias slightly increased (from 52.4 to 64.0 mm).

For the WLEB, there are greater differences in the monthly precipitation between the simulations with lakes (Figure 9b) and without lakes (Figure 9d). The summer-fall transition period shows a different response, with a small dry ASO bias for the models with lakes (0.4 mm below the historical mean) while the models without lakes have a wet bias of 20.9 mm (Figure 9b,d), suggesting that the lake feedback during this transition period is weak. Both sets of models

still overestimate winter precipitation across both regions by 54.4 mm for models with lakes and 51.0 mm for models without lakes (Figure 9c and d). This wet bias could be attributed to the lack of dynamic lake ice in many simulations, which would suppress winter precipitation [Wright *et al.*, 2013]. In addition, the lack of dynamic lake ice could also affect the projected change in precipitation, where less ice in the future may lead to greater winter precipitation.

The NARCCAP ensemble also explores the differences between local parameterizations and driving large-scale global conditions. For example, the difference in precipitation between the two similar RCM3 simulations from the NARCCAP ensemble (RCM3-CGCM3 and RCM3-GFDL, Figure 9b) is larger than between GCM models with lakes, with the RCM3-CGCM3 showing a large springtime precipitation bias of over 60 mm (Figure 9b). Other model pairs with different boundary conditions (e.g., ECP2-GFDL and ECP2-HadCM3; CRCM-CCSM and CRCM-CGCM3; MM5I-CCSM and MM5I-HadCM3) also show that the driving boundary conditions play an important role. In the CRCM simulations that have the most complex lake treatment, the summer drying in the WLEB is more pronounced in the CRCM-CCSM simulation (47 mm in August as compared to the observed value of 90 mm) than in the CRCM-CGCM3 simulation (74 mm) (Figure 9b). Interestingly, the other regional model driven by the CCSM (MM5I-CCSM) does not have such a strong summer dry bias and is similar to the other CRCM member. This suggests that while the driving global boundary conditions are important, the interactions between the regional and local processes may be the dominant driver in determining precipitation rates. Overall, this suggests that the inclusion of lakes alone does not necessarily

improve model simulations of precipitation, and that the accurate representation of lake processes (e.g., [Notaro *et al.*, 2013a; Mallard *et al.*, 2015]) and their interactions with large-scale dynamics are as important as including the lakes themselves.

5.0 Conclusions

We evaluate the simulation of seasonal and daily precipitation for a suite of climate models at varying resolutions for present-day and future conditions, and use resolution and configuration options to understand model biases and the range in simulated future changes in precipitation. Using seasonality as a metric, each ensemble shows positive (wet) winter and spring biases for the historical period, with greater intermodel variability in the summer and fall. At mid-century, most models show an increase in spring season precipitation of 7-18%, in agreement with prior studies in the Midwest using the CMIP3 ensemble and other regional climate models (e.g., Hayhoe *et al.*, 2010; Vavrus and Behnke, 2014). All model ensembles including both the global CMIP5 simulations and regional simulations show a mixed signal for future summer drying. Compared to historical daily precipitation intensity, all models overestimate the observed intense precipitation events in winter and spring. Mid-century projection consensus for each region shows small increases in moderate and intense daily spring events.

This analysis highlights model biases in the region and informs the application of future climate data to specific problems. Potentially, these results highlight the need to understand the springtime bias evident in almost all of the global models and can contribute to improved representations of regional processes feedbacks and physical features. The advantage of increased resolution between the global and regional ensembles depends largely on location, boundary conditions and physical parameterizations. For the Great Lakes region, increased resolution shows benefits in resolving daily precipitation events for the spring period as well as for the spring and summer periods in the WLEB. However for other seasons and at longer temporal averaging, boundary conditions and physical parameterizations may still play an important role in understanding and reducing the regional bias in simulated precipitation. Further analysis is needed to determine the dynamical drivers of the spring wet biases that is consistent in the global and regional models, understand how these biases affect future projections of precipitation in the region, and relay these insights to aid adaptation planning around the Great Lakes Basin.

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Figure Captions

Figure 1. Boundaries representing the Great Lakes Basin (GLB) and Western Lake Erie Basin (WLEB). The GLB includes the U.S. Great Lakes states (U.S) and Canada, and the WLEB includes the geographic extent of the watersheds that drain into the western basin of Lake Erie, including southeastern Michigan, northwestern Ohio, and northeastern Indiana.

Figure 2. Monthly averages for the historical period (1980-1999) spatially averaged over the Great Lakes Basin (GLB) for (a) the CMIP5 ensemble, (b) the NARCCAP ensemble, and (c) the RCM-HiRes ensemble. Individual model members in colored lines, the multi-model average in solid black lines, and the Climate Prediction Center observed precipitation in black dotted lines. Monthly average changes projected for mid-century (2041-2060) normalized to a percent change from the historical period for (d) the CMIP5 ensemble, (e), the NARCCAP ensemble, and (c) the RCM-HiRes ensemble.

Figure 3. As for Figure 2, but for the Western Lake Erie Basin (WLEB)

Figure 4. Historical (1980-1999) probabilities of precipitation events (binned every 6 mm day⁻¹) spatially averaged over the GLB for (a) MAM, (b) JJA, (c) SON and (d) DJF. Mid-century (2041-2060) projections of probability change for each bin, calculated as the difference from historical values for the GLB for (d) MAM, (e) JJA, (f) SON and (g) DJF. Precipitation bins are

averaged for each ensemble, including the CMIP5 ensemble (red), the NARCCAP ensemble (green) and the RCM-HiRes ensemble (blue). Numbers above each bin denote the total number of model members that simulated precipitation in that bin. CPC observations are denoted with a black X.

Figure 5. As for Figure 4, but for the WLEB region.

Figure 6. Maximum probabilities for each precipitation size (bins spaced every 6 mm day⁻¹) extracted from the GLB region before averaging. Ensemble probability distribution functions are shown for each season; **(a-d)** CMIP5, **(e-h)** NARCCAP, **(i-l)** RCM-HiRes. CPC observations are denoted with a black X.

Figure 7. Maximum probabilities for each precipitation size (bins spaced every 6 mm day⁻¹) extracted from the WLEB region before averaging. Ensemble probability distribution functions are shown for each season; **(a-d)** CMIP5, **(e-h)** NARCCAP, **(i-l)** RCM-HiRes. CPC observations are denoted with a black X.

Figure 8. 99th percentile DJF precipitation (mm d⁻¹) (for days with greater than 1 mm d⁻¹ of precipitation) over the WLEB grid cells for (a) observations and (b-e) the NARCCAP ensemble members (Table 1), including (b) CRCM-CGCM3, (c) CRCM-CCSM, (d) RCM3-CGCM3, (d)

RCM3-CGCM3, (e) RCM3-GFDL, (f). EPC2-GFDL, (g) EPC2-HadCM3, (h) MM5I-HadCM3, (i) MM5I-CCSM, (j) WRFG-CGCM3, (k) HRM3-HadCM3. Darker blue colors indicate higher values of extreme precipitation within that grid cell.

Figure 9. Monthly averages for the historical period (1980-1999) spatially averaged over the GLB and WLEB. Climate Prediction Center values displayed in dashed lines. **(a,b)** Models with lakes; including 3 of the CMIP5 Atmosphere-Ocean models, as well as the complete NARCCAP and Hi-Res ensembles (Table 1). **(c,d)** Models without lakes; including 8 of the CMIP5 Atmosphere-Ocean models (Table 1).

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Table 1. Global and regional model ensemble details.

Model Emission Scenario	Type and Scenario	Atmospheric Horizontal Resolution	Gridpoints (lat × lon=total)	Lake Mask	Lake Temp	Lake Ice^a
GLOBAL, RCP 8.5		<i>(lat x lon, °)</i>	WLEB	GLB		
ACCESS1.0		1.25 x 1.875°	3x2=6	9x11=99	NO	
ACCESS1.3		1.25 x 1.875°	3x2=6	9x11=99	NO	
CCSM4		0.9 x 1.25°	4x3=12	11x17=187	NO	
CESM1-CAM5		0.9 x 1.25°	4x3=12	11x17=187	NO	
CMCC-CM		0.75 x 0.75°	4x5=20	14x27=378	YES	1D ^b Yes
CMCC-CMS		1.875 x 1.875°	2x2=4	6x11=66	YES	1D Yes
CSIRO-Mk3.6.0		1.875 x 1.875°	2x2=4	6x11=66	NO	
EC-EARTH		1.125 x 1.125°	2x4=8	9x18=162	YES	Interp ^c No
FGOALS-g2		1.8125 x 2.8125°	1x1=1	4x7=28	NO	
HadGEM2-AO		1.25 x 1.875°	3x2=6	9x11=99	NO	
MIROC5		1.4 x 1.4°	2x2=4	7x14=98	NO	
MRI-CGCM3		1.125 x 1.125°	2x4=8	9x18=162	NO	
REGIONAL, SRES A2		<i>(lat x lon, km)</i>				
(RCM-Driving GCM)						
CRCM-CGCM3		50 x 50	9x8=72	30x38=1140	YES	1D Yes
CRCM-CCSM		50 x 50	9x8=72	30x38=1140	YES	1D Yes
ECP2-GFDL		50 x 50	9x8=72	31x39=1209	YES	Interp No
EPC2-HadCM3		50 x 50	9x8=72	31x39=1209	YES	Interp No
HRM3-HadCM3		50 x 50	8x7=56	28x35=980	YES	Interp No
MM5I-CCSM		50 x 50	8x6=48	26x33=858	YES	Interp No
MM5I-HadCM3		50 x 50	8x6=48	26x33=858	YES	Interp No
RCM3-CGCM3		50 x 50	7x7=49	27x34=918	YES	Interp No
RCM3-GFDL		50 x 50	7x7=49	27x34=918	YES	Interp No
WRF3-CGCM3		50 x 50	8x6=48	26x33=858	YES	Interp Yes
REGIONAL, RCP 8.5		<i>(lat x lon, km)</i>				
RCM4-HadGEM		25 x 25	15x14=210	53x68=3604	YES	Interp No
RCM4-GFDL		25 x 25	15x14=210	53x68=3604	YES	Interp No

^a Lake ice present in Great Lakes region

^b 1D Lake Model for inland water points [Goyette *et al.*, 2000]

^c Lake surface temperature interpolated from nearest lake point (if in parent GCM) or from the nearest sea surface temperature (e.g., from coastal regions)

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