Title

Regional Changes to Lake Effect Snow Levels in New York State Under Projected Future Climate Conditions

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REGIONAL CHANGES TO LAKE EFFECT SNOW LEVELS IN NEW YORK STATE UNDER PROJECTED FUTURE CLIMATE CONDITIONS

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Abstract

REGIONAL CHANGES TO LAKE EFFECT SNOW LEVELS IN NEW YORK STATE UNDER PROJECTED FUTURE CLIMATE CONDITIONS

By: Kathleen Uzilov

Lake-effect snowstorms are an important element of climate and weather in the Great Lakes region of North America. Here, I investigate how lake-effect snow levels could change in the future with anthropogenic climate change as predicted by a regional climate model (RegCM3) driven by two different sets of global climate model output (from GFDL CM2.1 and CGCM3, experiments run as part of the North American Regional Climate Change Assessment Program, Phase II). I analyze a subset of the domain focused on the Great Lakes area, paying particular attention to the southeastern Lake Ontario Snowbelt and the southeastern Lake Erie Snowbelt, both of which are mainly within New York State. My results show a decrease in lake-effect snow cover in the future (2040-2070) compared to the recent past (1970-2000) for this region. Total precipitation levels are shown to not change significantly, so it is likely that lake-effect snowstorms will be replaced largely by rain in the future. Both magnitudes of values as well as trends for snow levels in specific cities varied significantly depending on which global climate model output was used to drive RegCM3, pointing to a possibly serious source of uncertainty and error in regional climate modeling studies that do not utilize multiple global climate model output.

Acknowledgements

I am grateful to my thesis committee, Professors Lisa Sloan, Patrick Chuang, and Andy Moore, for their helpful feedback and suggestions that improved this work. Dr. Mark Snyder also provided guidance as well as assistance with difficulties I ran into during analysis. My husband, Dr. Andrew Uzilov, provided invaluable support. This research was supported in part by a grant from the National Science Foundation (NSF AGS 0533482).

1. Introduction

Lake-effect snowstorms are prominent meteorological phenomena in the Great Lakes region of North America, and are associated with significant amounts of snowfall each year. Occurring in late fall and winter (typically November through February), lake-effect snow is a consequence of cold Arctic air masses moving over the relatively warmer lakes. The air masses quickly absorb heat and moisture, become unstable, and convection occurs, resulting in precipitation. The increased precipitation usually takes place within 80 km of the lakeshore on the leeward side, forming distinct snowbelts. Lake-effect snow will cease if the lake freezes over, as frequently happens to Lake Erie in January or February. The other four Great Lakes retain significant ice-free portions during most winters (Kunkel et al., 2000).

Of the seven snowbelts associated with the Great Lakes, two are located in New York (NY) state: the southeastern Lake Ontario Snowbelt, and the southeastern Lake Erie Snowbelt, which also extends into Ohio and Pennsylvania. General trends in snowfall for all seven snowbelts will be addressed in this paper, but specific focus will be on the two snowbelts in NY. Potential effects of climate change on lake-effect snow near Lake Erie have previously been investigated in a study using Global Climate Models (GCMs) (Kunkel et al., 2002), but a study has not yet been done for this region using downscaled techniques appropriate to the size of the region. Lake-effect snow in the NY snowbelts can have important consequences for the local population: disruptions in transportation, property damage, injury and even deaths can occur. The region faces infrastructure issues due to snow as well, to deal with the physical burden it can create on buildings, for example (Kunkel et al., 2002; Schmidlin et al., 1992).

Unusually strong lake-effect snow events can cause even greater disruptions and costs; for instance, the lake-effect snow storm of October 12-13, 2006 near Lake Erie was a significant event not only for the amount of damage it caused – almost a million residents lost power, some for up to a week – but also for the early timing, with its 22.6 inches of snow recorded at the Buffalo airport greatly surpassing the previous October record of 6 inches (NOAA, 2006). Because the storm occurred so unusually early in the year, as much as 90% of Buffalo's trees were damaged, and clean-up for debris was estimated to cost at least $130 million (Beebe, 2006). It is critical to cities and towns near the Great Lakes to have access to scientific research results to investigate whether and how the severity and timing of lake-effect snowstorms may change in the future as a result of increasing atmospheric concentrations of greenhouse gases.

Lake-effect snowstorms may have already begun to be affected by anthropogenic climate change. An observational study that examined how lake-effect and non-lake-effect snowfall changed in the Great Lakes region throughout the 20th century found a statistically significant increase in snowfall for lake-effect sites only, thought to be a result of warmer lake surface waters and decreased ice cover associated with global warming (Burnett et al., 2003). Heavy rain events have been shown to be on the rise as well. Individual rainy days, short-duration (1-7 days) heavy rain events, and week-long heavy rain events all have been shown to have increased between 1931 – 1996, as well as the frequency of the heaviest rain events, which doubled in frequency (Kunkel et al., 1999; Angel and Huff, 1997).

Other studies have investigated effects of climate change on the Great Lakes, most often focusing on how net basin supply (NBS) and lake levels might be impacted (e.g. Chao, 1999; Logren et. al, 2002; Croley, 2003; Angel and Kunkel, 2010). Generally these studies first computed ratios or differences comparing observations with GCM output data and then used these to drive a river-routing/lake scheme. The results of these studies give a wide range of possible future lake levels, but most often predict a decline in mean annual levels. Because of how the river-routing/lake schemes are represented, temperature and precipitation are the main drivers of lake levels in this approach. Future temperature changes are generally predicted more consistently than precipitation, and are the major factor in projected Great Lakes level declines, as increased temperatures lead to increased evaporation over the lakes. Precipitation in the area was predicted to increase in a majority of 565 GCM simulations, which would somewhat balance the effects from the temperature increases; however, temperature predominates and decreases in lake levels are expected (Angel and Kunkel, 2010).

Recently this method has come into question and the use of a regional climate model (RCM) to dynamically downscale the GCM data first has been tested and deemed an improvement, as it corrects for two weaknesses previously encountered: it explicitly represents land surface-atmosphere feedbacks, and allows for changes in variability to be analyzed (MacKay and Seglenieks, 2012). By utilizing an RCM instead, MacKay and Seglenieks' results project a smaller decrease in lake levels for the Great Lakes than previous studies found, which they believe to be due to the inclusion of feedback processes. The median differences with this new method are only a few centimeters as compared to the most recent and extensive study using GCM data, that of Angel and Kunkel 2010. Another possible source of error in the general method has recently been identified as the process of using air temperature as a proxy for computing evapotranspiration (ET) over the lakes, which does not account for non-annual variability or secular changes in climate regime as it ties the ET too tightly to changes in sunlight amounts. When this is corrected for by using an energy-budget approach instead, the magnitude of change in ET with greenhouse gas concentrations decreased, resulting in smaller projected decreases in NBS and lake levels, which moderated or even reversed the reductions seen in earlier studies, including Angel and Kunkel 2010 (Lofgren et al., 2011).

There have also been studies that looked at other changes that could result from increased greenhouse gas concentrations, such as how precipitation and temperature might be different in the Great Lakes region. A recent study used statistical downscaling of atmosphere-ocean general circulation model (AOGCM) data to assess regional climate change for the US Great Lakes region, with the exception of NY state. The primary analysis used 3 AOGCMs, each forced by high (A1fi) and low (B1) emissions scenarios. The main findings included annual temperature increases of 3 +/- 1 °C under lower and 5.0 +/- 1.2 °C under higher emissions by the end of the century. Projected precipitation changes included increases in winter and spring of up to 20-30% by the end of the century. Especially relevant for our study are the findings of a small decrease in winter snow for the first half of this century, with 2-4 fewer snow days per year for more southern states. The number of snow days per year was projected to decrease much more by the end of the century: 30-45% for the lower emissions and 45-60% under the higher emissions scenario (Hayhoe et al., 2010).

Ice cover over the Great Lakes has also been studied, by constructing a record of the temporal and spatial variability of ice cover from 1973 – 2010. This study found that the standard deviations, or variability, of the seasonal cycle to be larger than the climatological means, which indicates that Great Lakes ice cover has poor predictability. The authors also did find a significant downward trend in ice cover over this time range for all of the lakes, with Lake Ontario experiencing the largest decrease (88%) and Lake Erie one of the smallest decreases (50%) (Wang et al., 2011).

For lake-effect snow over the Great Lakes, modeling and observational studies have demonstrated that several factors affect the likelihood of event formation, including: the temperature difference between the lake and adjacent land, wind speed and direction, lower tropospheric stability and surface air temperature over the lake (Hjelmfelt, 1990; Kunkel et al., 2002). Specific ranges of air temperature, wind speed and direction favorable for lake-effect snows are possible to determine when limiting the investigation to one specific lake, as Kunkel et al. (2002) performed for Lake Erie.

The Kunkel et al. (2002) study utilized two GCMs to predict how lake-effect snow levels could change by the late 21st century near Lake Erie. They found a decrease in conditions favorable for lake-effect snow by 50% or 90%, depending on the model used. The authors suggest lake-effect rain events may largely take the place of the less frequent lake-effect snow events, and they find this to be mainly the result of increased surface air temperatures. A statistically downscaled study has also been done investigating how lake-effect snow could change with future climate change for the Great Lakes region, as mentioned previously, but this study did not examine or report any changes over NY, confining their region of interest to the rest of the Great Lakes area instead (Hayhoe et al., 2010).

The present study aims to expand the current knowledge base of climate change impacts on the Great Lakes region by investigating the possible effects of future anthropogenic climate change on lake-effect snow near Lake Erie and Lake Ontario in NY using a dynamically downscaled regional climate model approach.

2. Material and Methods

The RCM used in this study is the International Center for Theoretical Physics (ICTP)'s RegCM version 3 (Pal et al., 2007). The dynamical core of RegCM3 is based on the hydrostatic version of the Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model version 5 (MM5), which is a primitive equation, compressible, sigma-vertical coordinate, hydrostatic model (Grell et al., 1994). The core is coupled to several other components, including: a radiative transfer scheme that is the same as that in NCAR's Community Climate Model version 3 (Kiehl et al., 1996); a nonlocal, counter gradient planetary boundary layer model (Holtslag et al., 1990); and the Biosphere Atmosphere Transfer Scheme (BATS) land surface scheme version 1e (Dickinson et al., 1993).

RegCM3 requires initial and boundary conditions for wind, temperature, surface pressure, and water vapor, along with prescribed sea surface temperatures (SSTs). For future studies, the values for these variables come from GCM output. Here, the future and historical RegCM3 boundary conditions come from Phase II of the North American Regional Climate Change Assessment Program (NARCCAP; Mearns, et al., 2009). As part of the NARCCAP project, RegCM3 was run for two time periods and driven by boundary conditions from two GCMs. The two GCMs used were the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 (GFDL, 2004) and the Canadian Climate Centre CGCM3 (Flato 2005), which both have climate sensitivities of 3.4 °C. The combinations were both run for a 30-year historical period from 1970 – 2000 and a 30-year future period from 2040 – 2070 using the relatively high greenhouse gas emissions A2 scenario from the Special Report on Emissions Scenarios of the Intergovernmental Panel on Climate Change (IPCC, 2007).

Though NARCCAP was run over a domain that included all of the coterminous United States and most of Canada, for the purposes of this study we have focused on a sub-region covering the Great Lakes and nearby land. We analyze the RegCM NARCCAP output over this region as a whole as well as focusing on eight cities in particular. Cities are analyzed by examining the grid cells within which a representative latitude and longitude from the city falls. Four of the sites are located within the lake-effect snow belts: Buffalo, Rochester, Oswego and Syracuse, NY. The other four are situated outside of the snow belts: Potsdam, Albany, Binghamton and Poughkeepsie, NY (Figure 1). Comparison between the sites experiencing lake-effect snow and those not will illuminate which trends from historical to future are unique to lake-effect snow in particular.

To validate the usage of RegCM in simulating snowfall over this region, snowfall values from four of the specified cities were calculated and compared to observational total monthly snowfall station data obtained from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) via the Climate Data Online tools. Of the cities chosen, two were lake effect (Buffalo and Syracuse) and two were non-lake effect (Binghamton and Poughkeepsie). In general, the CGCM and GFDL driven RegCM runs predicted snow depths that were slightly greater than the observations, but within a reasonably similar range as to justify the usage of this model (Figure 2). From additionally looking at snow depth, the overestimation bias tends to increase as snow depth increases, for both snowier locations and as the winter season goes on. This is likely a result of errors in the parameterization of snowmelt processes leading to underestimation of snowmelt rates, which is a known issue with GCMs including the GFDL and CGCM ones driving the regional model here (Roesch 2006). Though the model is over-predicting snow depths, snowfall is satisfactorily simulated, and the bias is likely systematic and will be present in the future experiments as well. Because this paper is focusing on trends between historical and future time periods, not absolute magnitudes of snowfall, this should not affect our conclusions.

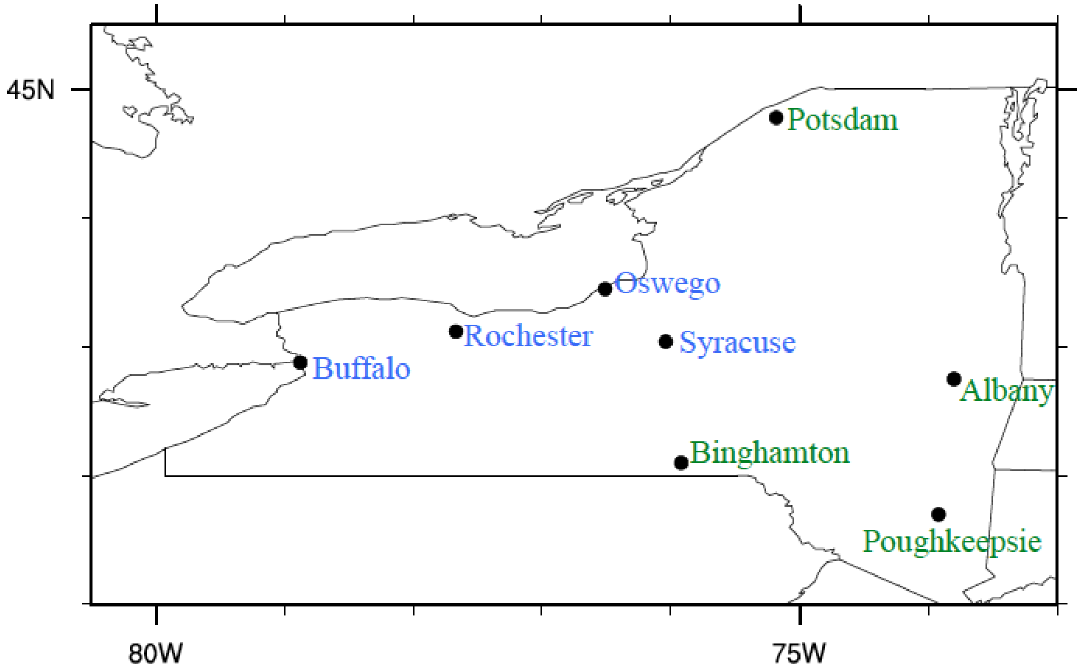

Figure 1. Locations of the sites focused on in this study. Lake effect sites are labeled in blue; non-lake effect sites in green.

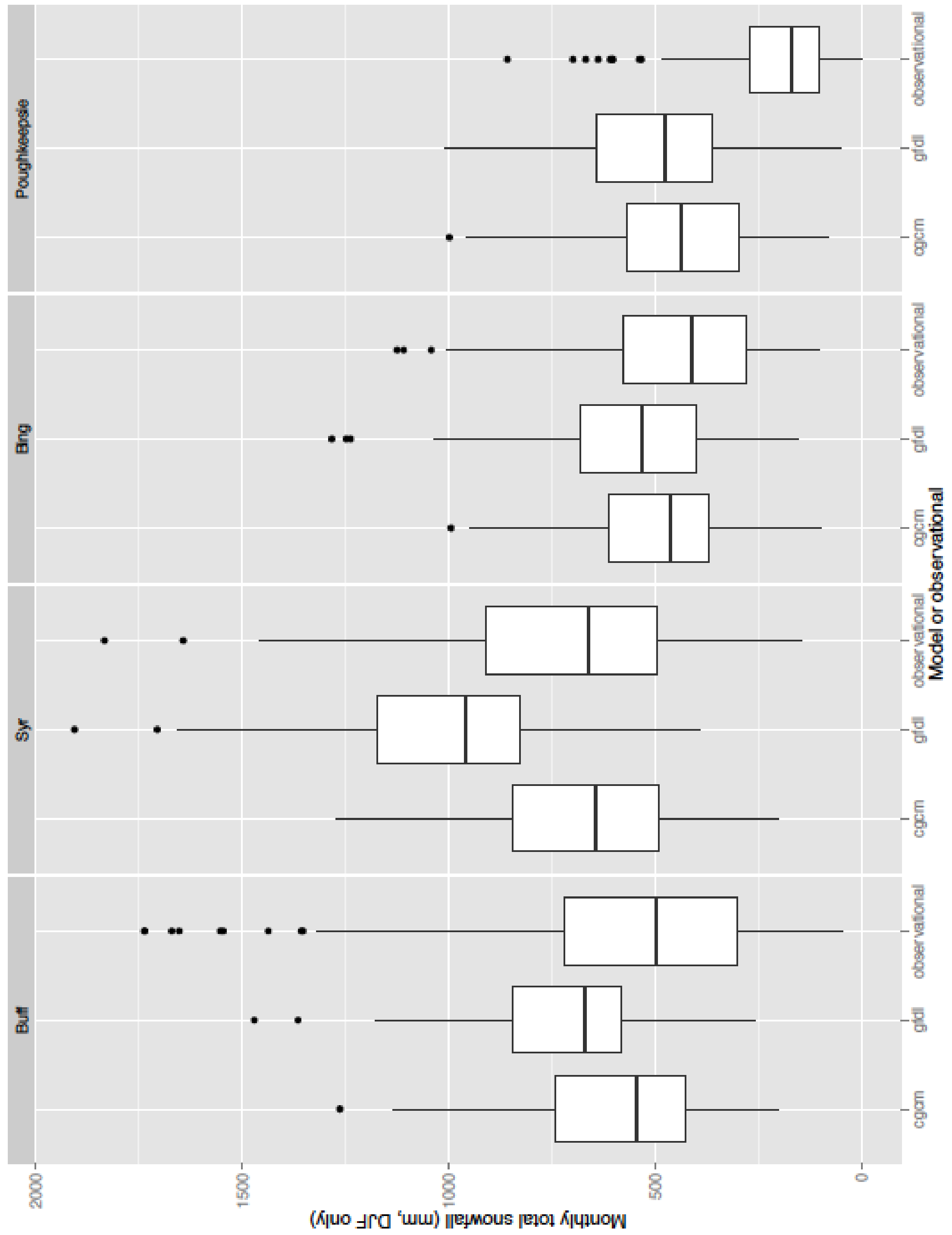

Figure 2. Maximum monthly snow depths (mm) from the period 1970 – 2000 as simulated by RegCM3 driven by CGCM and GFDL compared with station data from NOAA's NCDC. Whiskers are 1.5 times the interquartile range, and black dots are values that fall outside of this range.

RCMs in general have some advantages over GCMs specifically relevant for investigating Great Lakes phenomena such as lake-effect snow: for instance, snow-albedo feedbacks may be better resolved by an RCM than a GCM, and small scale processes like lake-effect snow are more likely to be captured well by an RCM than a GCM (Leung et al., 2004; MacKay and Seglenieks, 2012). RegCM in particular has been used to simulate precipitation over Lake Superior (the northern-most and largest Great Lake) previously and shown to give "robust and defensible" precipitation estimates that are even an improvement over gauge-based estimates, in that RegCM shows more realistic variations in over-lake atmospheric stability. This resulted in a lower over-lake to over-land precipitation ratio in warm months and a higher ratio in cold months (Holmon et al., 2012). RegCM was validated over the Great Lakes by comparing sea level pressure and surface temperature and found to fit well both annually and seasonally, though with a noticeable summertime warm bias (Holmon et al., 2012). Older studies have used earlier versions of RegCM over the Great Lakes basin as well and found it to reproduce temperature, precipitation and lake ice cover satisfactorily (Bates et al., 1993; Bates et al., 1995).

3. Results and Discussion

3.1. Snow Levels

Recent findings have shown that lake-effect snow in this area increased with increasing greenhouse gas concentrations and global temperature over the past half-century. Our results here show this trend reversing in the future and the opposite effect occurring instead: decreased lake-effect snow with increasing greenhouse gas concentrations. From the historical to the future period, the overall amount of snowfall in the Great Lakes region decreased for both GCM-driven regional runs (Figures 3 and 4). The decline in snow cover becomes larger for both runs as the season continues, becoming more drastic in each month from November to February and surpassing 50 mm H_2O difference in some areas in February for the GFDL-driven run, and 40 mm H_2O in February for the CGCM-driven run.

For the lake-effect snow cities, the results are noticeably model dependent in terms of the different driving GCMs used (Figures 4 and 5). Throughout the historical period, the snow amounts either increase slightly (for Buffalo and Rochester) or show little overall change (for Syracuse and Oswego) in the runs driven by CGCM. However, all four of these cities experience a decrease in snow amounts from the 1970's to 1990's when driven by GFDL, and this decrease is most significant for Syracuse and Oswego (Figure 5, model differences are discussed further below in III. Model Differences). For the future period, changes in snow levels are again model-dependent with the exception of Syracuse, which still shows consistent decrease in snow amounts over time.

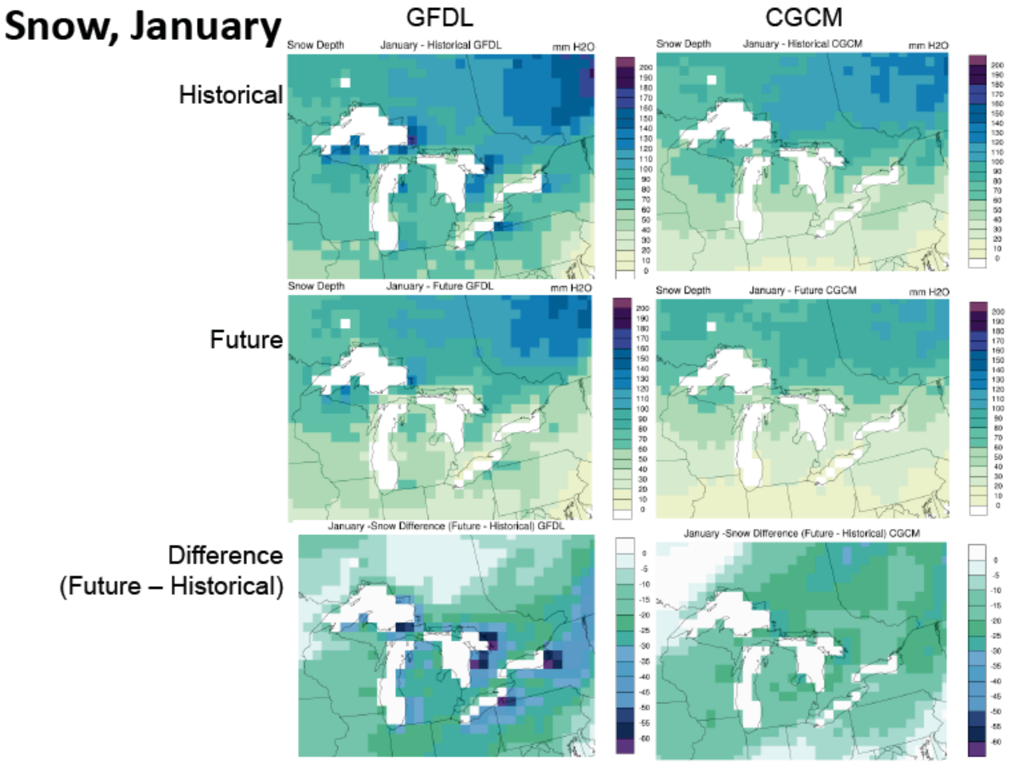

Figure 3. Snow depth in mm H_2O for historical period (1970 – 2000), top row; future period (2040 – 2070), middle row; and differences between future and historical, bottom row. Plots on the left are driven by GFDL; those on the left are driven by CGCM.

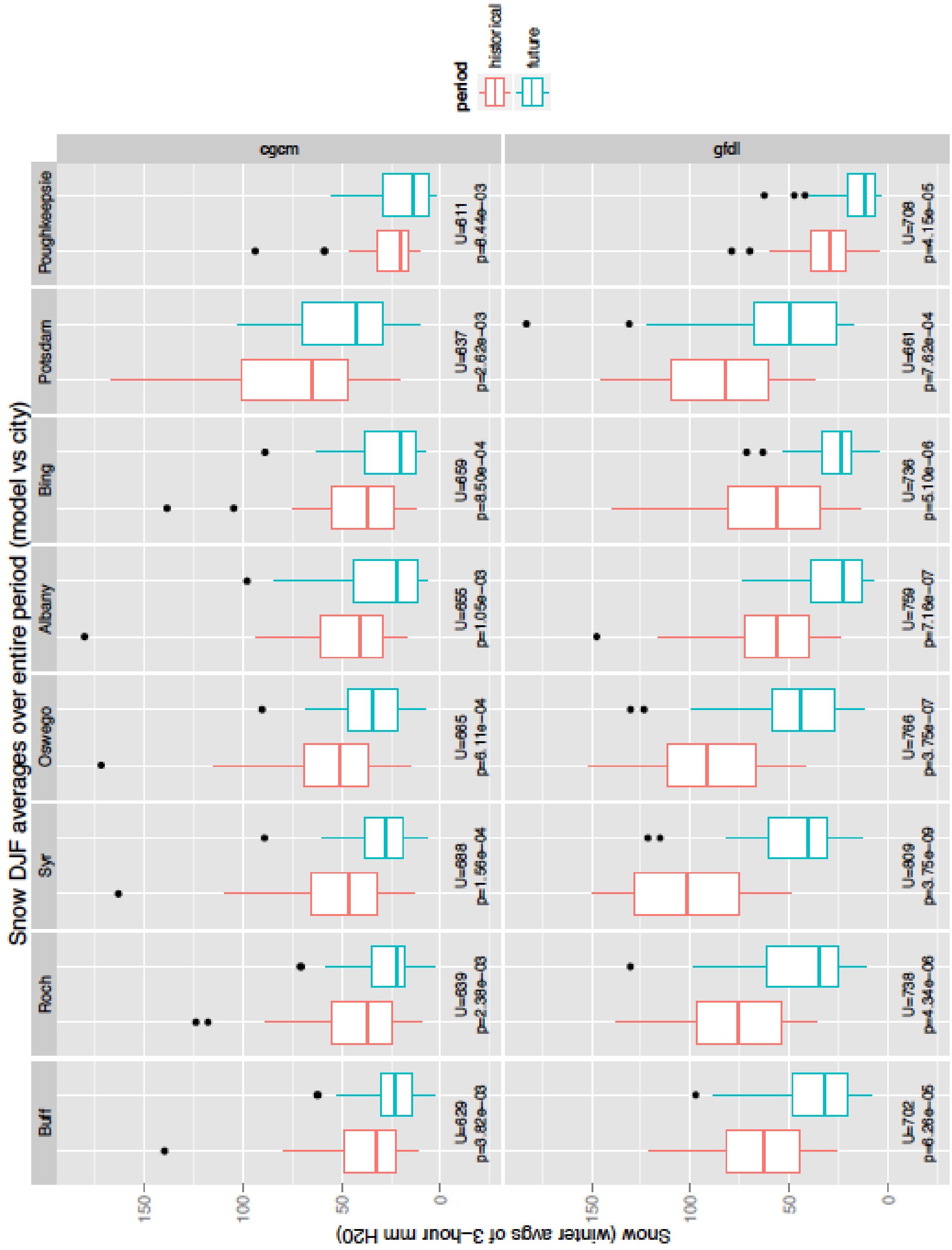

Figure 4. Box plots of snow depths (mm H_2O) for historical (1970-2000) and future (2040-2070) periods. Whiskers are 1.5 times the interquartile range, and black dots are values that fall outside of this range. Future and historical periods are shown to be statistically different by a one-sided, two sample Wilcoxon signed-rank test with U and p values displayed. The alternative hypothesis is that the historical snow depth values are greater than the future values.

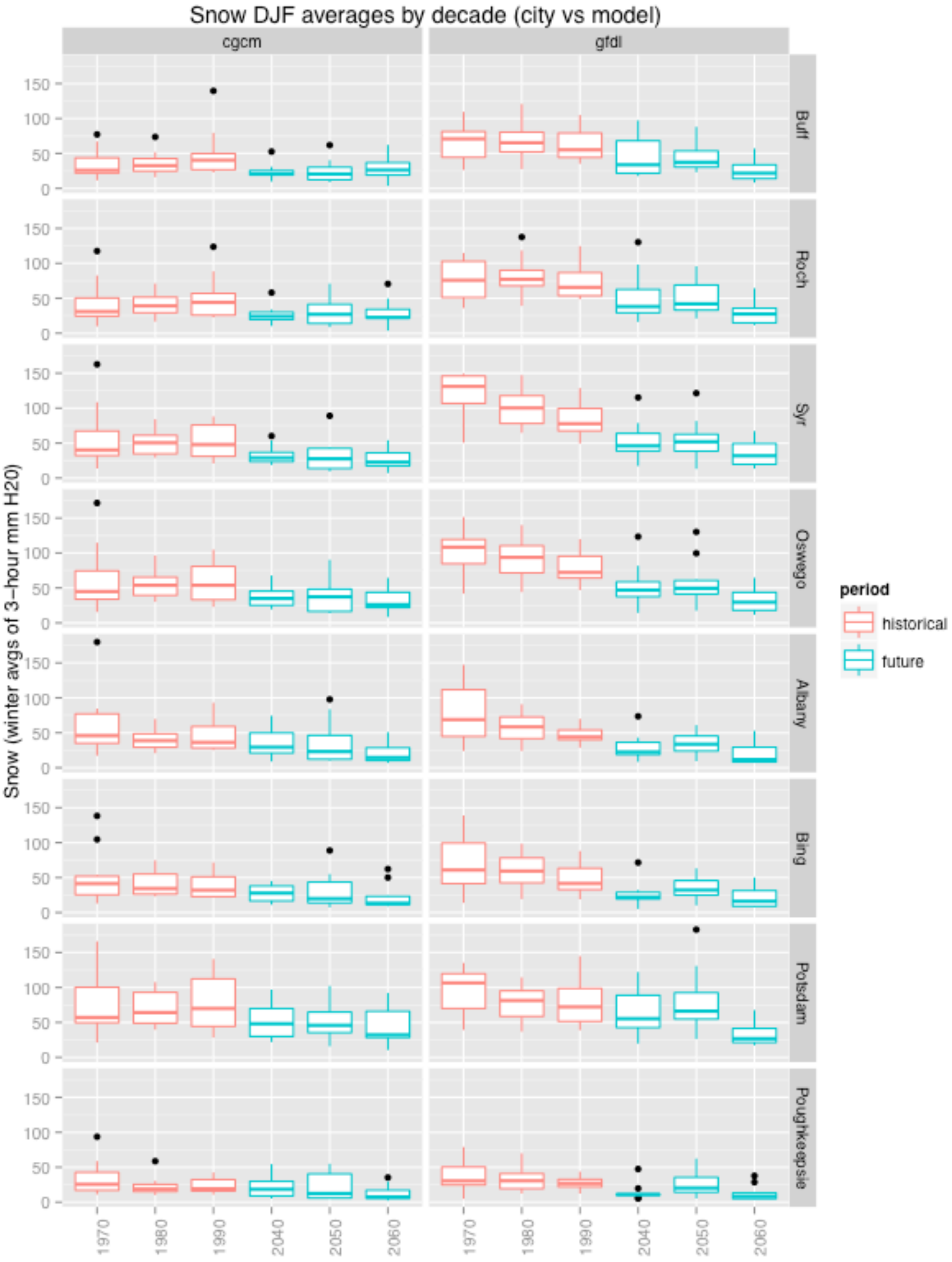

Figure 5. Box plots of snow depths (mm H_2O) broken down by decade; note jump between the historical period ending in 2000 and the future period beginning in 2040. Whiskers are 1.5 times the interquartile range, and black dots are values that fall outside of this range.

All cities, lake effect and non-lake effect, clearly project a decrease in snow amounts overall from the historical to the future periods (Figure 4). Within the historical period for the non-lake effect cities, snow levels decrease in all cases except for CGCM-driven Potsdam, which increases slightly. Historical decreases are more pronounced for GFDL-driven than CGCM-driven data. Future decades show a decrease in all four non-lake effect cities driven by CGCM. Although an overall decrease in snow depth is seen again within the future period driven by GFDL, there is first a jump up from the 2040's to the 2050's that is not seen in the CGCM experiments. This jump is also in the lake-effect cities, but less pronounced (Figure 5).

The lake-effect sites generally show higher snow levels overall than do the non-lake-effect sites (up to ~180 mm H_2O snow depth for lake-effect sites during February in the historical GFDL-driven run compared to values generally under 100 mm H_2O for non-lake-effect sites for the same time and experiment), but this difference is again model-dependent (lake-effect sites in the CGCM-driven historical run in February max out around 100 mm H_2O, with values around 70 mm H_2O for non-lake-effect sites). The difference in magnitude of monthly average snowfall between lake-effect and non-lake-effect sites is not as dramatic as might have been expected for the CGCM-driven run, especially from looking at the spatial distribution of snow levels from both experiments (Figure 3).

As mentioned in the introduction, certain factors are known to affect the likelihood of lake-effect snow events forming over the Great Lakes, and in particular

Lake Erie. These are the temperature difference between the lake surface and adjacent land, wind speed and direction, lower tropospheric stability, and surface air temperatures (Hjelmfelt, 1990; Kunkel et al., 2002). In Kunkel et al.'s (2002) GCM study investigating the change to lake-effect snow levels near Lake Erie by the late 21st century, the authors found the change in surface air temperatures to be predominantly responsible for the decrease in snow levels simulated. For this study, we have also investigated how these four factors changed from the historical to future time periods for both sets of simulations (results summarized in Table 1). There was no significant difference between historical and future ranges of values for the differences between lake surface temperatures and adjacent land temperatures. While there is a slight difference in the values (less than half a degree Celsius on average) between the CGCM and GFDL driven runs, the consistency between historical and future differences is seen in both sets of experiments.

Changes in wind speed and direction were mostly consistent between the CGCM and GFDL driven runs, with some variation from month to month. Differences between historical and future winds were most pronounced in December and March (less so during January and February), though all monthly average speed differences remained below 5 m/s. In general the direction remained largely the same, which was southwesterly to westerly, but became stronger in this direction, which could likely be more favorable for lake-effect snow over Lake Erie and Lake Ontario. Differences in tropospheric stability were largely dependent on the driving model used. The GFDL-driven runs had more negative values for the differences between tropospheric stability (future minus historical) than the CGCM-driven runs for every month, meaning the GFDL-driven run tended towards greater tropospheric stability for the historical period than the future period. From December to March, both models become increasingly positive in this difference, with the CGCM-driven run showing greater tropospheric stability for the future than the historical in January through March, and the GFDL-driven run showing this for March only.

Kunkel et al. (2002) also identified a surface air temperature range that they found to be most favorable for formation of lake-effect snow events: -10 °C to 0 °C. The area directly over Lake Erie and Lake Ontario had temperatures outside of this range for the GFDL-driven simulations in the future during December, February, and March, as well as in the historical time period during March. The CGCM-driven simulations' monthly average surface temperatures never exceeded the upper bound of this range for any month, whether in the historical or future case. This may partially explain why the changes in snow level are more drastic for the GFDL-driven run than the CGCM-driven run. Also, it should be noted that temperatures did increase from the historical to future case for the CGCM-driven run, just not sufficiently to exceed the limit found to be most favorable for lake-effect snow in this area.

Lake effect snow favorability factor	**Change from historical to future (GFDL-driven run)**	**Change from historical to future (CGCM-driven run)**
Temperature difference between lake surface and adjacent land	No significant change	No significant change
Wind speed and direction	More southwesterly in future; most pronounced in December and March	More southwesterly in future; most pronounced in December and March
Lower tropospheric stability	Greater in future than historical only during March	Greater in future than historical in January - March
Surface air temperatures in -10 to 0 degrees Celcius range	Values exceeded upper bound of this range over Lake Erie and Lake Ontario in December, February and March.	Values stayed within this range in the Lake Erie and Lake Ontario region throughout.

Table 1. Summary of changes to the four factors identified as favorable to lake-effect snow events in this region as simulated in the two RegCM experiments.

3.2. Total Precipitation

Since the model results indicate snow levels will decrease in this region in the future, a reasonable next question is whether this represents an overall reduction in precipitation for the area, or a shift in precipitation type from snow to rain. This is investigated by comparing total precipitation in the different model runs. For both models, the total precipitation levels do not change significantly from the historical to future time periods (Figure 6). There is a slight tendency towards increased precipitation over the larger domain in the future during December, January and February (DJF) for the GFDL-driven run, but the increase is small (less than 0.5 mm/day). Directly over the Great Lakes, slight drying is seen instead, although this decreases both in magnitude and spatial extent throughout as the winter continues, retreating to the northwest and only covering Lakes Erie and Ontario in December (the other three Great Lakes still show decreased precipitation of 0.1 – 0.3 mm/day during January and February). Again, these precipitation changes are only evident in the GFDL-driven run; the CGCM-driven run shows almost no difference between future and historical (less than +/- 0.1 mm/day) for most of the domain during DJF.

Overall, there is no general trend towards increasing or decreasing rainfall for either the lake-effect sites or non lake-effect sites investigated individually (Figure 7). There is slightly less of a spread in rainfall values for the non lake-effect sites compared to the lake-effect sites, and the range of values extends somewhat higher for the lake-effect sites for both historical and future times than for the non lake-effect sites. Because overall precipitation is not changing significantly, and snow events are predicted to decrease, it is likely that rain events will largely replace lake-effect snowstorms in the future.

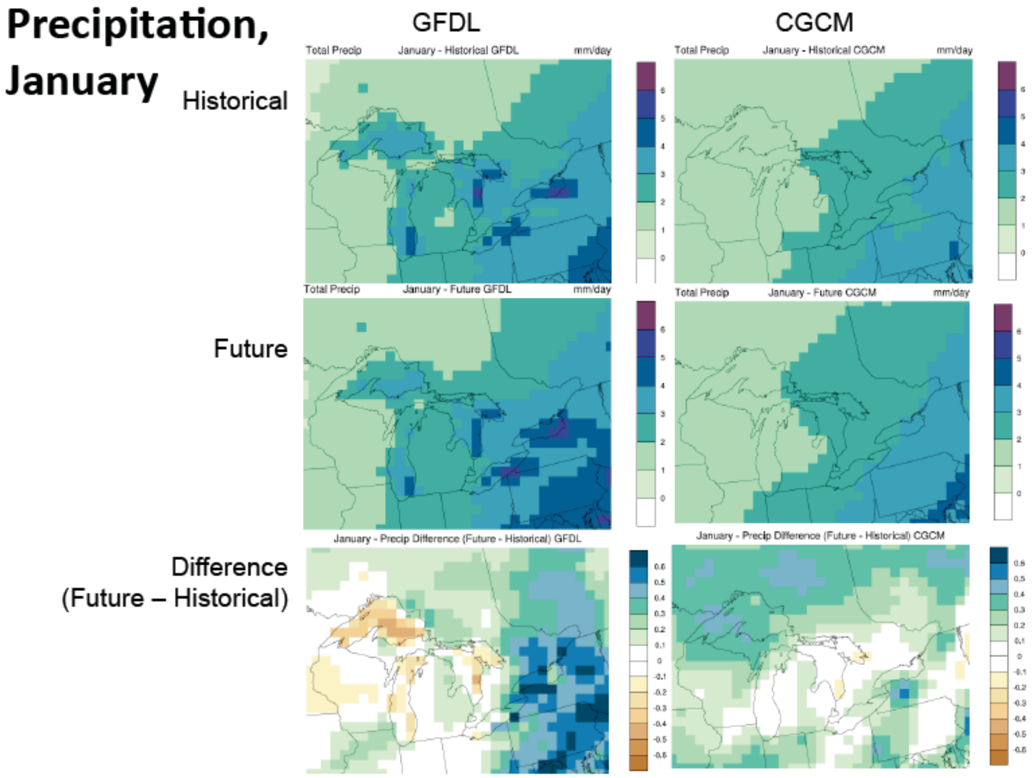

Figure 6. Total precipitation in mm/day for historical period (1970 – 2000), top row; future period (2040 – 2070), middle row; and differences between future and historical, bottom row. Plots on the left are driven by GFDL; those on the left are driven by CGCM.

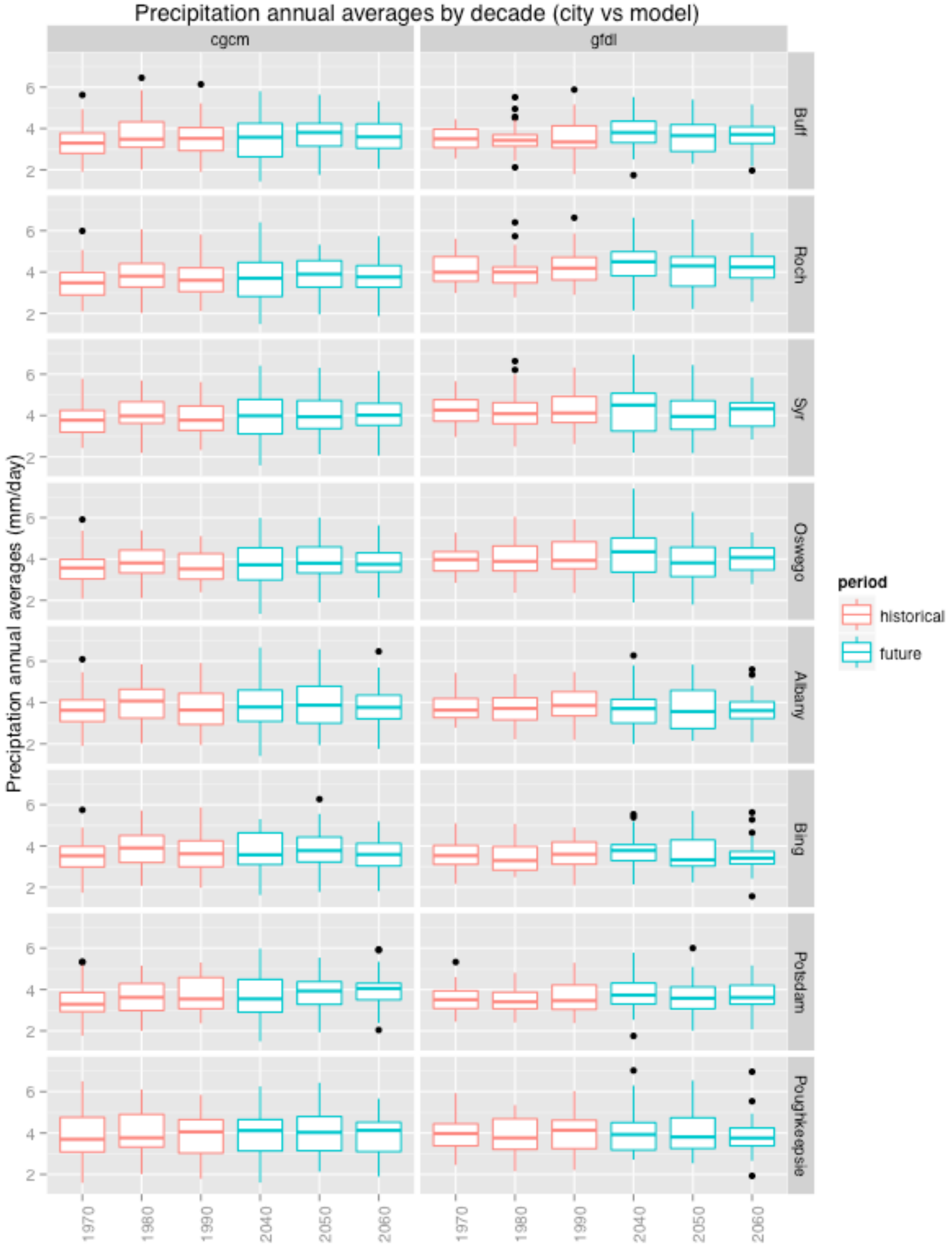

Figure 7. Box plots of total precipitation (mm/day) broken down by decade; note jump between the historical period ending in 2000 and the future period beginning in 2040. Whiskers are 1.5 times the interquartile range, and black dots are values that fall outside of this range.

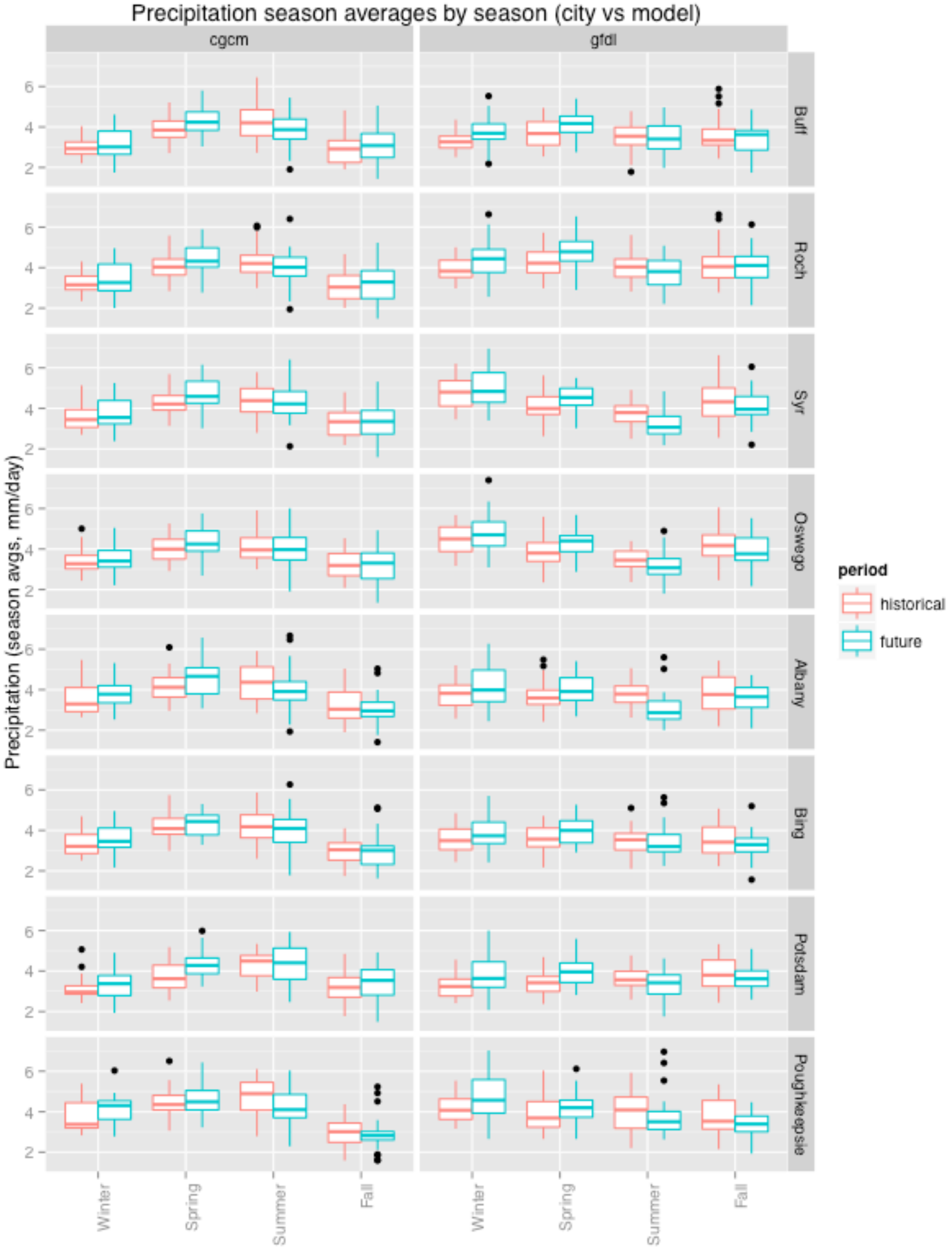

Figure 8. Box plots of total precipitation (mm/day) broken down by season; note jump between the historical period ending in 2000 and the future period beginning in 2040. Whiskers are 1.5 times the interquartile range, and black dots are values that fall outside of this range.

Changes in seasonal distribution of precipitation are seen in the future period compared to historical for both lake effect and non-lake effect sites. All cities generally show increased precipitation in winter and spring, though the winter increase in precipitation is minimal for lake effect cities and more pronounced for non-lake effect cities. Non-lake effect cities experience less summer precipitation in the future period, as do lake effect cities although the trend is less consistent between the cities and models there: Oswego and Syracuse show stronger decreases when forced by GFDL while Buffalo has a greater decrease when forced by CGCM. During the fall season, no consistent pattern is seen amongst the lake effect cities, and the non-lake effect cities display no real change (Figure 8).

3.3 Model Differences

An unexpected finding in our study was the marked differences in the results between the GFDL-driven and CGCM-driven regional model simulations. Though the overarching trends of snow and precipitation levels from the historical to the future periods were similar, the snow amounts themselves were consistently higher for the GFDL-driven runs, especially at the lake-effect snow sites. The trends within historical and future periods are also less consistent for the CGCM-driven runs at the lake-effect sites. In the historical period, two of the locations from the CGCM-driven experiment show an increase in snow levels over time (Buffalo and Rochester), while none of the historical GFDL-driven sites show this and in fact show the opposite, a decrease in snow amounts from the 1970's to 1990's, which is most significant for

Syracuse and Oswego. Similarly, in the future period, snow levels at Buffalo and Rochester are fairly steady and even increase slightly by the end of the time period (though all values are lower than in the historical period, so there has been a decrease) for the CGCM-driven run, while only decreases over time are seen for all four lake-effect sites in the GFDL-driven experiment (Figure 4).

Additionally, the GFDL-driven historical run (and to a lesser extent the future run as well) showed lake-effect snow ‘hot spots’ of intense snowfall downwind of the Great Lakes, whereas the CGCM-driven runs showed more monotonic levels of snowfall throughout the entire region (Figure 3). The severity of the difference between the amount of snow cover at the hot spots and the rest of the region increased throughout winter for the GFDL-driven run and the CGCM-driven run did start to show (much less pronounced) hot spots of increased snow cover in February only, for Lakes Huron and Ontario only, whereas the GFDL-driven run hot spots occurred leeward of all five Great Lakes, with the greatest effects seen at Lakes Huron, Ontario, and Erie. For the GFDL-driven run, the decrease in future snow cover at the hot spot locations exceeded 50 mm H_2O by February, as opposed to maximum decreases of around 30 mm H_2O in the rest of the area. In the CGCM-driven results, hot spots only showed a decrease of up to 30 mm H_2O, compared to maximum differences around 20 mm H_2O for the outlying region, less pronounced than for the GFDL-driven run.

Agreement between the CGCM and GFDL driven simulations is stronger for the non-lake effect sites in terms of both magnitudes and trends over time for snow levels. For total precipitation, the spread of values is much smaller for both experiments, but there are still differences to be seen. Whether precipitation increases or decreases (though slightly) for both the historical and future periods depends on which model driven experiment is looked at. Seasonal precipitation trends also vary depending on model for some of the cities, especially lake effect ones. In Buffalo, whether an increase or decrease in summer and fall precipitation is expected in the future compared with historical varies based on which model drove the run. Syracuse and Oswego both show almost no change in summer or fall precipitation in the future when forced by CGCM, but decreases in both of these seasons when forced by GFDL. Only one non-lake effect city seems to experience this seasonal dependency on driving model: Potsdam, for which the direction of fall precipitation change varies (Figure 8).

These differences are more dramatic than anticipated; the implication is that regional trends of increasing or decreasing precipitation or snow amounts, as well as the magnitude of snow levels themselves, as projected for the future are in this case entirely reliant on which GCM is chosen to drive the regional model. Researchers who utilize regional climate models commonly use only one set of driving conditions for their projections, but the findings of this study cast some doubt on the legitimacy of such an approach.

To investigate possible reasons for the discrepancies between the GFDL and CGCM driven experiments, biases in the GCMs themselves are considered. GFDL CM2.1 is known to have SST biases that are greatest at midlatitudes, which are thought to result from biases in the absorption of shortwave radiation in the model (Delworth et al., 2006). The biases in absorption of shortwave radiation result in initial biases in SSTs that then become amplified by positive feedbacks from sea ice albedo and low clouds. In the northern hemisphere, these biases are negative, leading to decreased SSTs, which increases cloudiness at low levels, which in turn further increases the negative bias in absorption of shortwave radiation. In the northeastern US, GFDL CM2.1 overpredicts annual mean precipitation by between 1-1.75 mm/day. Unfortunately no study can be found that describes the known biases of CGCM3 at this time.

Looking at circulation, there are not drastic differences between the GFDL CM2.1 and CGCM3 simulations over the Great Lakes region throughout the winter months. What small difference there is does increase from December through February, with the most noticeable difference in February (Figure 9). CGCM3 simulates winds that have a slightly greater northerly component over Lake Erie and Lake Ontario, resulting in northwesterly winds compared with the westerly winds simulated by GFDL. Because this is large scale circulation and not surface winds like we were looking at in the factors influencing lake effect snow event formation in Section I, more northerly winds here could be favorable for lake effect snow by bringing colder air to the area.

Most GCMs that were included in the IPCC AR4, including both GFDL CM2.0 (the preceding version to the GFDL model used here) and CGCM3, have known issues with simulating snowpack, as mentioned in the discussion of validating

RegCM3 driven by GFDL and CGCM. Generally, these models are known to overestimate snow levels in spring likely due to precipitation and temperature biases, and have errors in how they parameterize the process of snowmelt resulting in underestimation of melting rates (Roesch 2006).

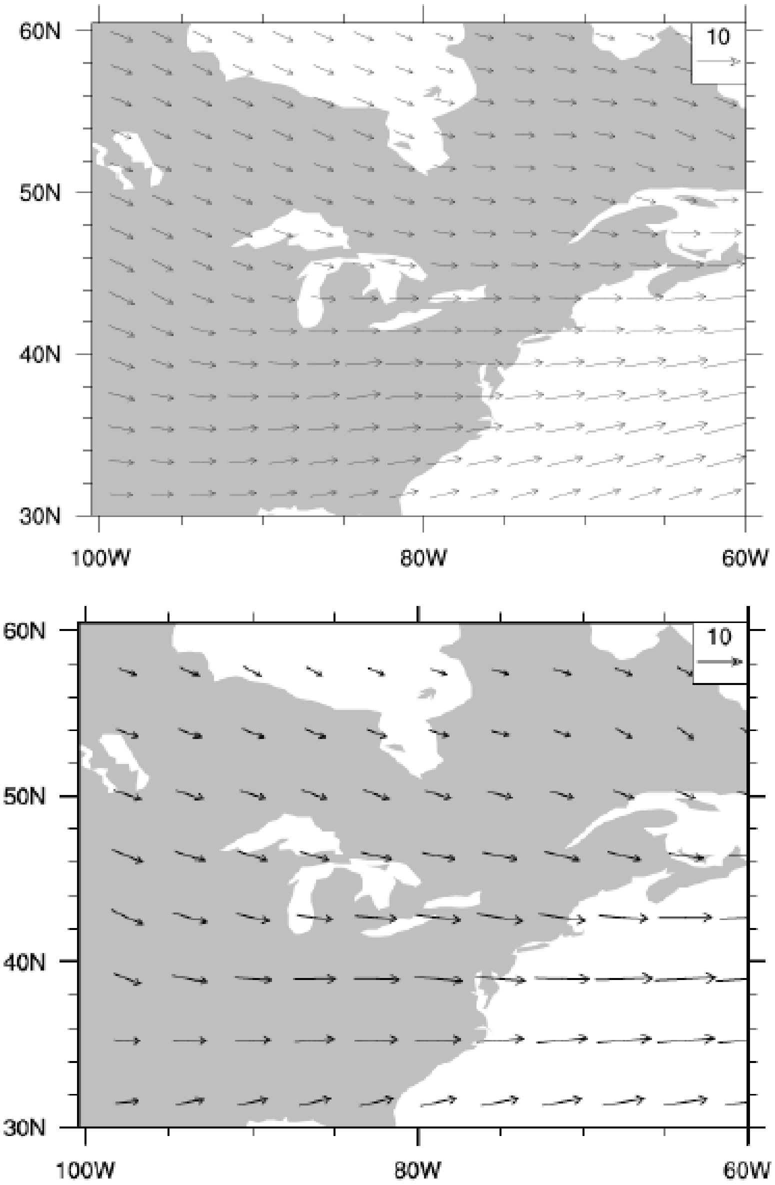

Figure 9. Winds (m/s) at 850 mb for GCM driving data: GFDL in upper plot, CGCM in lower plot

4. Conclusions

From analysis of the two sets of experiments using RegCM3 done as part of Phase II of the NARCCAP project, projections for future changes to lake-effect snow levels in New York State have been investigated. In contrast to what observations have shown for the 20th century, which was an increase in lake-effect snowstorms with increasing greenhouse gases and global temperatures, the results here suggest lake-effect snowstorms will decrease in the future (2040-2070) compared to the recent past (1970-2000). Four main factors influencing lake-effect snow were considered: temperature differences between the lake surface and adjacent land, wind speed and direction, lower tropospheric stability, and surface air temperatures. Of these four, the surface air temperatures were found to be most likely driving the decrease in future lake-effect snow events, as temperatures exceeding the upper bound of the range found to be most favorable to lake-effect snow formation are shown to be more common during winter months in the future experiments.

Total precipitation levels are not expected to change significantly, and so it is likely that lake-effect snowstorms will be replaced largely by rain in the future. Both magnitudes of values as well as trends for snow levels in specific cities varied significantly depending on which GCM output was used to drive RegCM3, pointing to a possibly serious source of uncertainty and error in regional climate modeling studies that do not utilize multiple GCM output.

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