THESIS

CHANGES IN WINTER STORM CHARACTERISTICS AND LAKE-EFFECT SNOW IN CONVECTION-PERMITTING REGIONAL CLIMATE SIMULATIONS IN THE U.S.

Submitted by

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In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2019

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ABSTRACT

CHANGES IN WINTER STORM CHARACTERISTICS AND LAKE-EFFECT SNOW IN CONVECTION-PERMITTING REGIONAL CLIMATE SIMULATION IN THE U.S.

Lake-effect snowfall events have extreme regional impacts with some of the largest snowfall totals on record. Previous studies hypothesize that in a future climate, less ice coverage will be present over the Great Lakes in winter, allowing for more latent and sensible heat fluxes released into the atmosphere. An investigation of the changes in winter season precipitation systems, including lake-effect snowstorms, uses two convection-permitting regional climate continuous 13-year simulations driven by: (1) ERA-Interim reanalysis and (2) ERA-Interim reanalysis plus a climate perturbation for the RCP8.5 scenario. These simulations are used to investigate meteorological and land surface changes in a future climate during the winter months across the U.S. Results from this study show that weak precipitation decreases, while moderate to stronger precipitation is enhanced in a future climate with strong signals over the Great Lakes. Therefore, a lake-effect snowstorm event in the Great Lakes region is used to examine the effects of a warming climate on mesoscale lake-effect snowstorm dynamics and their regional impacts. Analysis of these simulations shows that lake-effect snowstorms in a future climate may have enhanced snow accumulations downwind of the lakes due to more frequent ice-free conditions of the Great Lakes. Enhanced latent and sensible heat fluxes, as a result of less ice-coverage, add moisture and energy to the atmosphere to enhance storm development. The increase in surface fluxes are important for meteorological processes within the planetary boundary layer, which interact with the overlaying atmosphere. These interactions may change the mechanisms that are important for lake-effect snowfall events, such as the 850 mb to surface temperature differences,

relative humidity, layer instability, and surface pressure. In addition, less ice coverage may enhance mesoscale circulations due to the thermal contrast (i.e., land-lake breeze) and differential surface roughness. This research will improve our understanding of the question, "What will today's weather look like in a future, warmer climate?" to examine possible socioeconomic and public safety implications of changing precipitation patterns in the winter season.

ACKNOWLEDGEMENTS

I would like to thank my advisor Kristen Rasmussen for giving me such a unique opportunity to work on research under her supervision and to be a part of such a great research group. Her mentorship, motivation, and guidance has been an integral part of my success during my studies at CSU. I would also like to thank my committee members, Russ and Steven, for their time and support throughout my thesis writing. A very special thank you to Dave and Gail Liniger for their support to student combat veterans at CSU through the Liniger Honor, Service and Commitment Scholarship of which I was a recipient, and to the U.S. Department of Veterans Affairs for supporting me with the use of the G.I. Bill. It is critical to our nation's success and security to continue to provide educational benefits to veterans to help keep America great. Finally, I would like to thank all of my colleagues who helped me throughout my entirety of this degree especially those who helped me get through programming issues including but not limited to Zach Bruick, Erin Dougherty, Jack Kodros, and Ben Trabing.

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Chapter 1 - Introduction

Clouds and precipitation are generally poorly represented in global climate models (GCMs) primarily due to their coarse resolution with horizontal grid spacing of between 60 – 300 km (Kendon et al. 2017) and the traditional use of a convective parameterization, yet they are extremely important in determining Earth's energy and water balance in a current and future climate (Allen and Ingram 2002). For example, snowfall and snowpack typically are underestimated and are coarsely resolved due to the poor representation of topography due to grid spacing (Rasmussen et al. 2011, 2014). Hydrometeorological characteristics of a changing climate, including how the water cycle may change, is a critical issue for water managers. In response to these challenges, new efforts to use high-resolution convection-permitting regional climate models have been conducted in many regions around the world (Hohenegger et al. 2008, Rasmussen et al. 2011, Liu et al. 2016, Ban et al. 2015, and many others). High-resolution simulations over the Colorado Headwaters region demonstrated that such simulations of seasonal snowfall showed very good agreement with observations if a grid spacing of <6 km is used (Ikeda et al. 2010, Rasmussen et al. 2011, 2014, Liu et al. 2011).

Based on the previous Colorado Headwaters simulations, new simulations were conducted that expanded to the entire contiguous U.S. (CONUS) and surrounding areas (Liu et al. 2016). Liu et al. (2016) explains how these new simulations can address changes in extreme precipitation events such as severe convective weather in response to greenhouse gas induced global warming by the end of the century. Extreme weather events are typically very localized and require high-resolution data to investigate. For example, high-resolution convection-permitting simulations accurately represent the diurnal cycle of precipitation (Rasmussen et al. 2017) and organized and propagating convective systems (Prein et al. 2017), primarily due to the absence of a convective parameterization in these simulations that allows for cloud and mesoscale processes to occur naturally, as is not possible in GCMs that use convective parameterizations. Furthermore, extremes are typically associated with mesoscale processes, such as mesoscale terrain forcing, gust fronts, dry lines, land-sea contrasts, and mesoscale snow bands, which are not resolved in GCMs. The use of a convection-permitting grid spacing over a large domain available in these new simulations overcomes the limitations of coarse resolution models, which allows improvements in reproducing extreme precipitation, particularly on a short time scale (Knote et al. 2010, Kendon et al. 2012, 2014, Prein et al. 2013a, b, 2015, Chan et al. 2014).

A motivating previous study (Rasmussen et al. 2017) examined changes in the convective population and thermodynamic environments in a future climate during the warm season using high-resolution convection-permitting regional climate models. This study concluded that the frequency of extreme values of precipitable water (50 mm and greater) increases at least two-fold in many regions of the U.S. in a future climate. They also found that a widespread decrease in weak to moderate convection and an increase in strong convection over the CONUS region is seen in a future warmer climate. Furthermore, from investigating the thermodynamic environments associated with the spectrum of convective systems, this study found that both mixed-layer convective available potential energy (MLCAPE) and convective inhibition (CIN) increase in magnitude in a future climate, which explains the increase in extreme storms and decreases in moderate to weaker storms. Building on the results from this study, the motivating question for the current study is how do winter storms, specifically lake-effect snow events in the Great Lakes region, change in a future warmer climate? This study uses high-resolution convection-permitting climate simulations to examine this question. More specifically, this study will examine the dynamical and thermodynamical changes that may be the primary forcing in changes of the lake-effect snow events.

Lake effect snow develops during the cool season when a cold airmass crosses relatively warmer lakes. The relatively warm waters of the Great Lakes can create convective instability over the region even in a stable environment after a cold air mass passes across the region. Lake effect snow events are mesoscale precipitation events which usually develop downwind of the Great Lakes during the late fall through the winter months leading to extreme amounts of snowfall. The lakes act as a source of heat and moisture to the overriding atmosphere. Latent and sensible heat fluxes off of the lake aid to destabilize and energize the overriding atmosphere increasing cloudiness and precipitation (Kristovich and Laird 1998, Markowski and Richardson 2010). At some point during the winter, parts of the Great Lakes usually freeze over. The presence of the ice decreases the amount of snow activity by significantly reducing the heat and moisture supply (Vavrus et al. 2012).

To understand the future of lake effect snow events requires an understanding of the forecasting tools used to predict them in the current climate. Niziol et al. (1995) lays out these forecasting metrics. The greatest amount of snowfall is seen when the prevailing winds blow across the longest fetch of a lake, particularly where orographic features subsequently enhance the precipitation processes. Due to limitations of modeling in the Great Lakes region, including unresolved lake-effect snowfall and improper parameterization of the lakes as separate entities from the surrounding landmasses (Niziol et al. 1995), forecasters have developed many of their own forecasting techniques and local guidance. To examine the thermodynamic potential for snow band development, both the temperature difference between the lake and the 850 and 700 mb levels are used as well as the height/strength of a subsidence inversion, to predict the snow band location, type, and evolution with locally derived forecast rules. The direction and speed of the steering wind (surface to 700 mb), in addition to the low-level surface wind field and divergence, are used to examine the snow band initiation, persistence and evolution, and the amount of directional wind shear (with height). To examine the synoptic-scale enhancement or retardation of the snow band, synoptic-scale vertical motion forcing metrics are used. Another example of a locally derived forecast technique is the Lake Effect Snow Guidance (LSG) product developed at the Weather Service Forecast Office in Buffalo, NY. Wind direction guidance from the boundary layer through 700 mb provides the forecaster with information to evaluate the location and orientation of the snow band. Directional shear and fetch are also calculated to determine the organization and strength of the band (Niziol et al. 1995).

Through mesoscale modeling, Lavoie (1972) found the air-lake temperature difference to be the most important forecast parameter for lake effect snow. Operationally, Rothrock (1960) and Holroyd (1971) noted that a 13°C temperature difference between the lake and 850 mb was the necessary lapse rate to produce pure lake effect snow. Wilson (1977) showed that when this temperature difference was greater than or equal to 7°C, a modest increase in precipitation occurs downwind of Lake Ontario. Forecasters at WSFO Buffalo generally consider that significant lake snows are possible when the lake-850-mb temperature difference is greater than 10°C when accompanied with synoptic-scale forcing. Lavoie (1972) noted that the local flux of heat and moisture from the lake could act to lift and erode an inversion layer from mixing. The degree of low-level instability, described by the air-lake temperature difference and the depth of the unstable layer, defined by the inversion height and its strength, together play vital roles in the evolution of lake effect snow. Vertical motions produced in convergence zones over the lake can sometimes be intense which in turn plays a role in raising the inversion layer that can enhance convective cloud growth. Additional vertical enhancement due to orographic lifting further raises the height of the capping inversion (Niziol et al. 1995).

Lake-effect snow events often produce significant and localized extreme amounts of snowfall around the Great Lakes, making them hard to forecast (Niziol 1987, Campbell and Steenburgh 2017a) and are known to disrupt transportation, education, utilities, and commerce. One particular area that experiences significant lake-effect snow is on the east side of Lake Ontario on the Tug Hill Plateau, which rises more than 500 m above the eastern shore of Lake Ontario. A climatological precipitation maximum is observed over the Tug Hill Plateau region and was the primary region for an observational field campaign studying lake-effect snowstorms (Ontario Winter Lake-effect Systems (OWLeS) field program, Campbell and Steenburgh 2017a). During the OWLeS field program, WRF simulations demonstrated that a lake-breeze front that formed along Lake Ontario's southeastern shoreline was a key contributor to the area of precipitation maximum over the Tug Hill (Campbell and Steenburgh 2017a). Even when the Tug Hill Plateau was removed from the simulation, the region saw localized ascent along this boundary contributing to an inland precipitation maximum associated with the lake-land breeze circulation. The presence of the Tug Hill Plateau intensified and broadened the region of ascent. In addition, previous studies highlighted the role of land-breeze convergence in the initiation and organization of lake-effect convection (Campbell and Steenburgh 2017a, 2017b).

This study uses two WRF simulations, one being a control (CTRL) simulation which simulates the current climate, and the other being a pseudo-global warming (PGW) simulation which adds future climate changes into the forcing data and allows us to ask the question "what will today's weather look like in a future warmer climate?" A specific focus on lake-effect snowstorms in the Lake Ontario region along with a case study of a specific record-breaking event in this region will be analyzed. Lake Ontario is a fairly deep lake with a mean depth of 283 feet (Encyclopedia Britannica 2019a) and stays mostly ice-free throughout the winter depending on the severity of the winter season, unlike the shallower Lake Erie that freezes more often

(Niziol et al. 1995) with a mean depth of 62 feet (Encyclopedia Britannica 2019b). The question investigated in this thesis is, how will ice coverage change in a warmer, future climate and how will this impact the amount of lake-effect snowfall? The hypotheses examined in this study include the following: (1) With warmer temperatures in a future climate, ice coverage could be substantially less throughout the winter months resulting in more snowfall over the Great Lakes region; (2) Reductions in ice coverage in a future climate will lead to enhanced sensible and latent heat fluxes that will provide additional energy into the atmosphere to enhance lake-effect snow production; and (3) Land-lake breezes and other mechanisms producing mesoscale lake-effect snow bands will be enhanced in a future climate due to the enhanced energy and deeper vertical circulations associated with mesoscale snow bands. These hypotheses are tested with a combined approach looking at 13-year averages and a lake-effect snow case study. Given the importance of lake-effect snowstorms in the Great Lakes region, a goal of this study is to enhance the knowledge provided to climate forecasters for the use of hydrometeorological forecasts, public safety and emergency management associated with such high-impact events in a current and future climate.

Chapter 2 - Methodology

The National Center for Atmospheric Research (NCAR) Research Applications Lab (RAL) conducted high-resolution convection-permitting regional climate simulations over the contiguous United States (CONUS) using the Weather Research and Forecasting (WRF) model V3.4.1 (Liu et al. 2016). The WRF model was configured to have 4-km horizontal grid spacing with 1360 by 1016 grid points in a single domain with 51 stretched vertical levels to 50 km with the highest vertical resolution in the boundary layer. The physical parameterization schemes used in the simulations include the Thompson aerosol-aware microphysics (Thompson and Eidhammer 2014), the Noah-MP land-surface model (Niu et al. 2011) that was improved for the quality of these simulations (see Liu et al. 2016 for specific modifications to the Noah-MP scheme), the Yonsei University (YSU) planetary boundary layer (PBL) (Hong et al. 2006), and the Rapid Radiative Transfer Model (RRTMG) (Iacono et al. 2008).

Several significant upgrades to the Noah-MP LSM physics package were made by the NCAR team to sustain long-term climate simulations (Liu et al. 2016). These upgrades corrected many performance challenges, specifically, reducing the winter-time cold bias (of more than -6°C) which stemmed from too much assumed snow coverage near the Great Lakes. The cold bias was reduced by modifying the vegetation-dependent snow fraction/melt curves in order to represent surface snow coverage more realistically. These upgrades were incorporated into recent WRF model releases (since Version 3.7) and are incorporated in this study (Liu et al. 2016). The cold bias is important to mention specifically because this experiment deals with the winter months and in more detail around the Great Lakes. Another advantage built into the WRF model includes an upgraded lake water temperature algorithm. By default, WRF uses the nearest sea surface temperature to interpolate in-land water temperature resulting in temperatures too warm in the cold seasons. This upgrade uses an algorithm that calculates time-varying lake temperatures from the diurnal average of surface skin-temperatures, therefore, mitigating excessive lake-effect snow over some of the lakes due to high SSTs when the default approach is used. This model also incorporates large-scale spectral nudging of temperature, geopotential height and wind was applied to the simulations above the planetary boundary layer and with scales above 2000 km. It was also performed along the domain edges, allowing smaller scale and mesoscale features to evolve freely through time, and to prevent climate drift within the model from the synoptic pattern (Liu et al. 2016).

Two simulations were conducted and are used in this research (Liu et al. 2016): (1) The retrospective or control simulation (CTRL) is forced with 6-hour ERA-interim reanalysis data to create a 13-year continuous integration during the period of 1 October 2000 - 30 September 2013 over the US CONUS domain; (2) Pseudo-global warming (PGW) simulation is forced with the 6-hour ERA-interim reanalysis data plus a climate perturbation for the same 13-year time period as the CTRL simulation. These perturbations were derived from a 19-model CMIP5 ensemble monthly mean climate change signal for the RCP8.5 scenario, which is the worst-case scenario where emissions continue to increase rapidly through the early to mid-century along with high population growth to 12 billion people by the end of the century (Furphy 2013). The variables used to create the PGW simulation climate delta forcing data are temperature, horizontal wind, geopotential, specific humidity, sea surface temperature, soil temperature, sea level pressure and sea ice (Liu et al. 2016). As described in Liu et al. (2016), the WRF input for the PGW simulation is as follows:

$$WRF_{input} = \text{ERA-Interim} + \Delta CMIP5_{RCP8.5}$$

where $\Delta CMIP5_{RCP8.5}$ is the 95-year CMIP5 multi-model ensemble-mean change signal under the RCP8.5 emission scenario:

$$\Delta CMIP5_{RCP8.5} = CMIP5_{2071\text{-}2100} - CMIP5_{1976\text{-}2005}$$

For both the CTRL and PGW simulations described above, the winter months of December, January and February (DJF) are used to compare and contrast the differences in precipitation and snowfall throughout the CONUS domain, and what mechanisms may be contributing to their changes. Liu et al. (2016) noted that in DJF, as much as 40% more precipitation is shown in the PGW simulations in the western U.S. and Canada, with up to 70% increases at elevated mountain peaks (Liu et al. 2016).

In order to examine changes between the PGW and CTRL simulations, 13-year averages were performed on many different variables provided by WRF 2-dimensional hourly output data including accumulated precipitation and snow water equivalent (SWE), column-integrated cloud liquid water, ice and snow, and water vapor content, and the fraction of frozen precipitation at the surface. Output data for the DJF season from December 2000 to February 2013 for these variables was added up and averaged monthly. Just as in Rasmussen et al. (2017), one of the primary goals of this study is to assess changes in the storm population in a future climate. This requires analysis of the full spectrum of wintertime reflectivity values, from weak to strong reflectivity for DJF. The methodology used in this study employs composite reflectivity (dBZ), defined as the maximum reflectivity from any level at each grid point, from the CTRL and PGW WRF simulations. Hourly composite reflectivity data from each simulation is used to calculate the frequency of occurrence in six reflectivity ranges defined as weak precipitation (-20 to 10 dBZ), moderate precipitation (10 to 30 dBZ), and strong precipitation (30 to 50 dBZ). The difference (PGW-CTRL) of the frequency of occurrence for each range represents potential future changes in the storm population in the weak to strong precipitation categories (Rasmussen et al. 2017). In order to begin to understand changes in the snowfall in and around the Great Lakes region in a future climate, SWE and albedo are averaged for this 13-year period and broken up into three months (Dec, Jan, Feb separately). The latent heat flux averaged over the 13-year period in the Great Lakes region was also calculated. The following months were not included in the analysis due to unavailable data: February 2005, January 2004 and December 2010.

After reviewing results of the 13-year DJF averages, a specific record-breaking case-study was examined from 1-14 February 2007. For the case study, both the 2-dimensional and the 3-dimensional data, which are available every 1 hour and 3 hours, respectively, were used to examine the dynamical, thermodynamical and hydrometeor changes. Accumulated SWE is calculated from the beginning of the case study and starts with 0 mm and accumulates every hour; it does not account for melting or sublimation.

Chapter 3 - Results

Accurately representing synoptic to mesoscale precipitating systems in a future climate requires high-resolution simulations at convection and terrain-resolving scales. Using a high-resolution convection-permitting grid spacing, such as 4 km, is critical to gain understanding of the detailed processes and mechanisms that contribute to highly localized and small scale events. In addition, high-resolution simulations alleviate the need to use a convective parameterization, allow for a more realistic representation of the physical processes, represent orographic precipitation and snow mass balance, and much more. These simulations therefore allow us to ask scientific questions about the mechanisms involved to better understand how and why the weather will change in a future climate. The following results are designed to try and answer the specific hypotheses outlined in Chapter 1.

Figure 1 shows averaged monthly differences of several different WRF 2-dimensional variables for the 13-year averages in the boreal winter (DJF) as described in the methodology section. Figure 1a shows increases in accumulated precipitation across the CONUS region, particularly in the California Sierra Nevada and coastal ranges, the northwestern U.S. peaks, and in areas around the U.S. Great Lakes. Figure 1b shows increases in column-integrated cloud liquid water content in the whole domain besides the southeastern U.S., into Mexico and over the Gulf of Mexico with the most noticeable increase around the western U.S. mountains, the Great Lakes and the Appalachian Mountains. Increases in the column-integrated ice and snow content are shown in figure 1c over most of the CONUS region, especially over the Great Lakes region, while decreases are seen along the western U.S. mountains and southeastern U.S. Although an

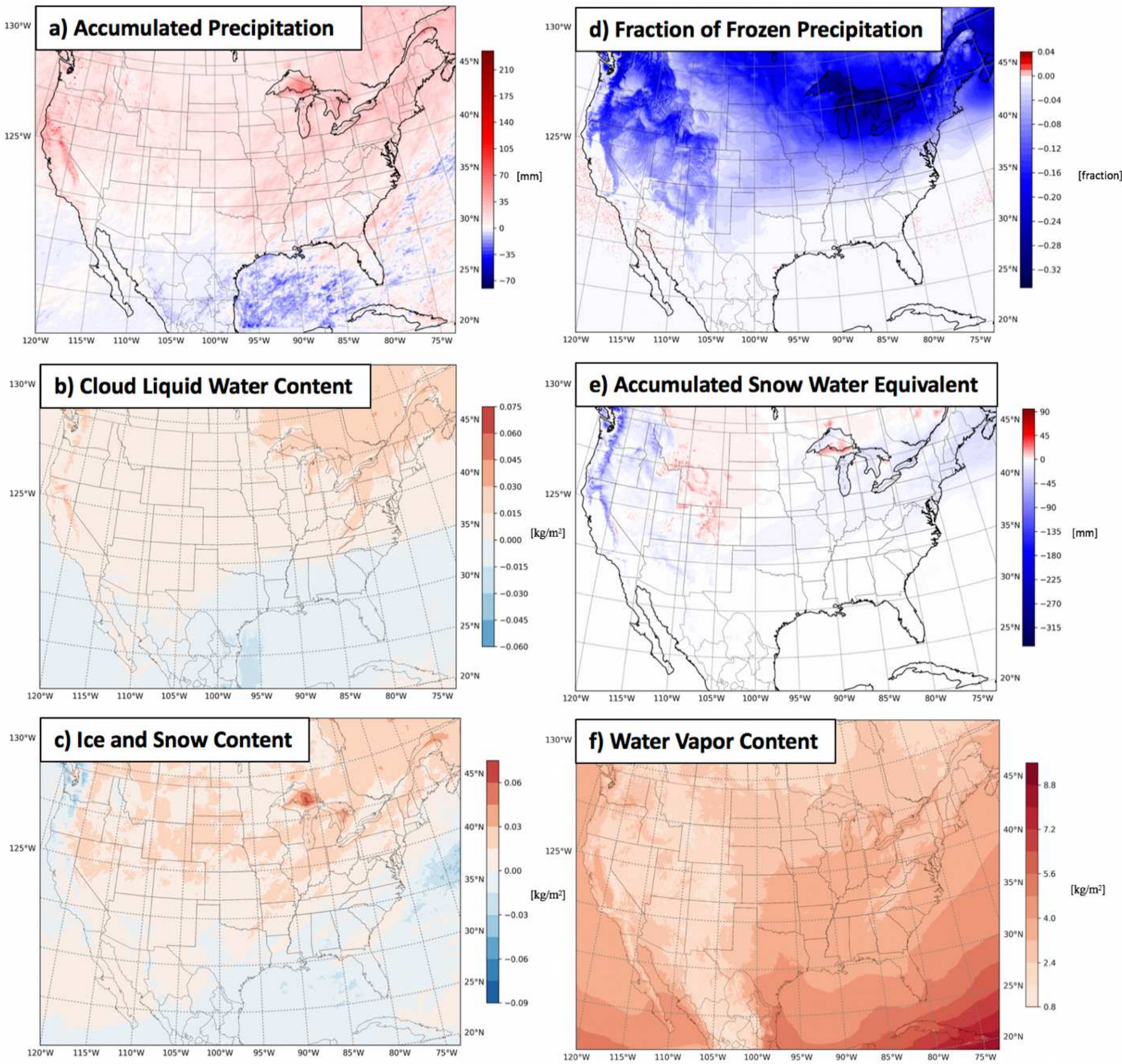

Figure 1: Averaged monthly difference over the CONUS domain in all 13-years of the simulation between the PGW and CTRL simulations (PGW-CTRL) for DJF in (a) accumulated precipitation [mm], (b) column-integrated cloud liquid water content [kg/m^2], (c) column-integrated ice and snow content [kg/m^2], (d) fraction of frozen precipitation reaching the ground [fraction], (e) accumulated snow water equivalent [mm], and (f) column-integrated water vapor content [kg/m^2].

increase in ice and snow hydrometeors is apparent (Fig. 1c), Figure 1d suggests that the particle phases (i.e., liquid vs. solid hydrometeors) reaching the surface are shifting relative to the current climate. The fraction of frozen precipitation decreases almost everywhere in the CONUS region with the largest decreases over the Great Lakes and western U.S. (Fig. 1d), suggesting that more rain and less snow is expected in a future climate at the surface. Finally, the highest decreases in snow water equivalent (SWE) are located along the western U.S. mountain ranges and the northeastern U.S. with the highest increase in SWE being in the Rockies and some areas downwind of the Great Lakes (Fig. 1e). This decrease in SWE shows that more of the hydrometeors are falling as rain in the future in those particular regions, in agreement with Fig. 1c.

The results from Figure 1 are all consistent with warmer temperatures in a future climate across the entire CONUS domain (Liu et al. 2016). The increases in column-integrated cloud liquid water content and the column-integrated ice and snow content along with the decreases in frozen precipitation reaching the ground and SWE over much of the eastern U.S., seem to be the reasons for the increases in accumulated precipitation. Figure 1f shows increases in column-integrated water vapor content throughout the entire domain with the values increasing towards the southwest portion of the domain closer to the water source (i.e. Gulf of Mexico and the Atlantic Ocean). It is important to note that there are localized increases of water vapor over the Great Lakes region as well.

Similar to the analysis presented in Rasmussen et al. (2017), who looked at the characteristics of convection in the warm season, a complementary analysis was conducted for the cool season. Figure 2 shows the differences in occurrences per month in composite radar reflectivity separated into ranges (a) -20 to 0 dBZ, (b) 0 to 10 dBZ, (c) 10 to 20 dBZ, (d) 20 to 30 dBZ, (e) 30 to 40 dBZ, and (f) 40 to 50 dBZ. It is important to note that snow hydrometeors typically have reflectivity values between -20 and 30 dBZ and can be higher if the particles are melting due to the brightband effects (Wolfe and Snider 2012). At low reflectivity ranges from – 20 to 10 dBZ, which represent weak to moderate snowfall and very weak rainfall, moderate

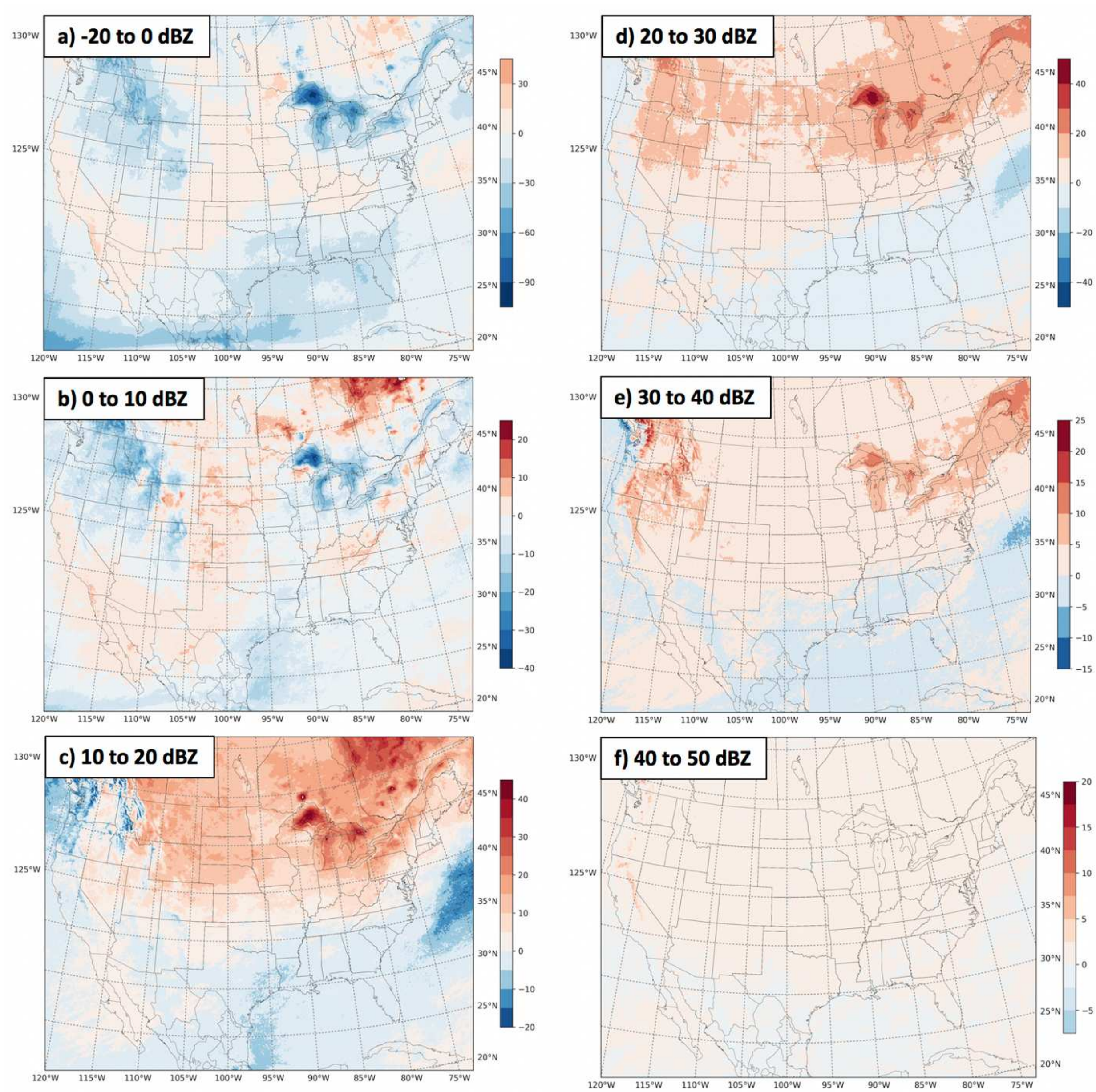

Figure 2: Differences occurances per month over the CONUS domain in all 13-years of the simulations between the PGW and CTRL simulations (PGW-CTRL) for DJF in composite radar reflectivity separated as (a) -20 to 0 dBZ, (b) 0 to 10 dBZ, (c) 10 to 20 dBZ, (d) 20 to 30 dBZ, (e) 30 to 40 dBZ, and (f) 40 to 50 dBZ.

decreases are seen in the northwestern U.S. and stronger decreases are visible over and around the Great Lakes region. In the reflectivity ranges from 10 dBZ to 40 dBZ, which represent moderate to heavy snowfall and weak to moderate rainfall, significant increases are present over the Great Lakes region. The differences in the 40 to 50 dBZ range, which represent heavy rainfall, are fairly negligible which would be expected during the winter months when there is less convective activity. In summarizing Figs. 1 and 2, the Great Lakes region in particular sees the most significant changes between the CTRL and PGW simulations. The amount of precipitation, available moisture and hydrometeor content all have sharp contrasts of increases in the Great Lakes region. The decreases in the fraction of frozen precipitation reaching the ground and the localized increases in SWE downwind of the Great Lakes warrant a further look at this particular region and will therefore be the focus for the remainder of this study.

Given the focus on the Great Lakes region, a more specific analysis of the conditions present over this region is presented by month in this section. Figure 3 shows the SWE and albedo differences by month over the Great Lakes domain. SWE decreases almost everywhere in December around the Great Lakes region and then increases downwind of the Great Lakes throughout the remainder of the winter months. Very little changes in albedo are shown for December but begin to decrease throughout the rest of the winter, suggesting that the lakes have less ice in a future climate moving through the winter months. The reason for the decreases in SWE during December likely relates to the fact that the Great Lakes are generally not frozen over this early in the winter[1] and with warmer temperatures, more rain than snow may be expected in a future climate. The results from comparing the differences in SWE and albedo suggest that there is a relationship between to the amount of SWE in the region and the change in albedo over the Great Lakes. This suggests one possible reason: in a future warmer climate, the Great Lakes do not completely freeze over throughout the winter months, resulting in more lake effect snow events especially in the later part of the season. For the 13-year DJF period, latent heat fluxes increase over the Great Lakes in a future climate (Fig. 4). This further suggests that less ice coverage provides more instability and moisture to the environment, further supporting

[1] https://www.weather.gov/cle/GreatLakesIceclimo

the increases in SWE and is consistent with less ice coverage as previously seen (Fig. 3). This hypothesis will be tested by examining a record-breaking lake-effect snow case study detailed in the following section.

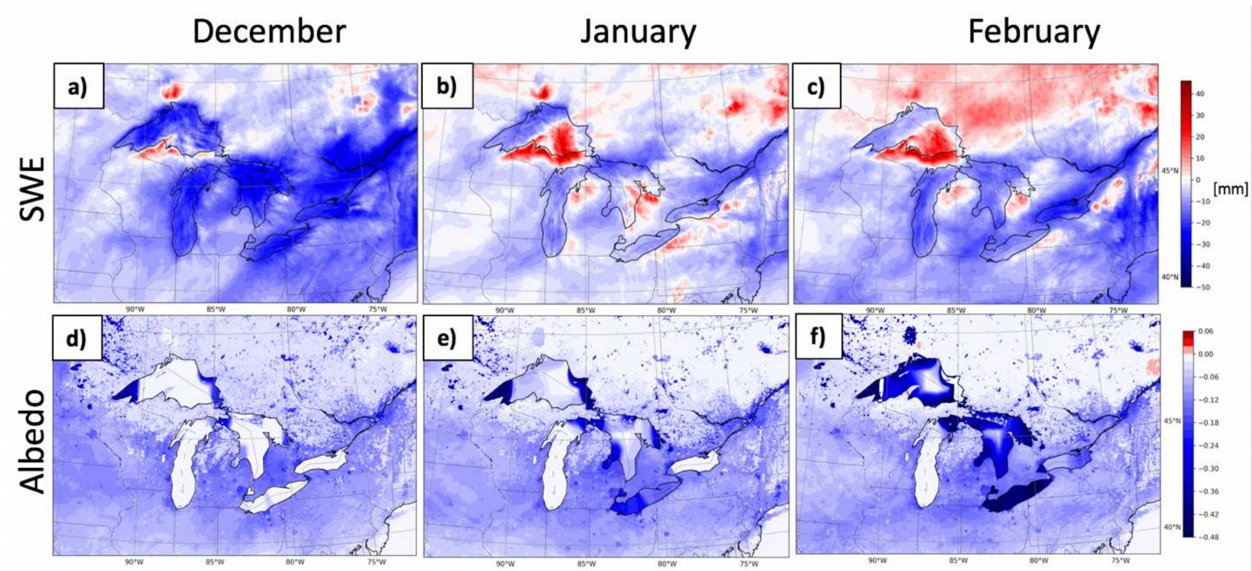

Figure 3: Averaged difference by month of snow water equivalent (SWE) in mm for (a) December, (b) January, and (c) February and albedo for (d) December, (e) January, and (f) February over the Great Lakes domain in all 13-years of simulations between the PGW and CTRL simulations (PGW-CTRL).

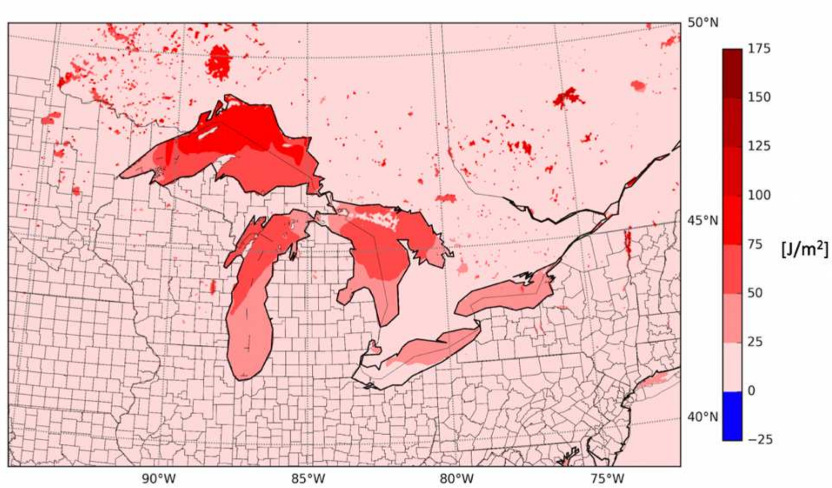

Figure 4: Averaged difference in the latent heat flux [J/m^2] over the Great Lakes domain in all 13-years of simulations between the PGW and CTRL simulations (PGW-CTRL) for DJF.

Subsection: Case Study

Precipitating systems in the cool season exhibit distinct characteristics in a future climate. Significant differences are found over the Great Lakes region, primarily due to the changing state of the lake from primarily frozen in the CTRL simulation to partially or mostly unfrozen in the PGW simulation (Fig. 3). Cold air flowing over open water is well known to produce significant latent and sensible heat fluxes in winter and is a major factor in the occurrence and intensity of lake-effect snow downstream of the Great Lakes (Kristovich and Laird 1998, Markowski and Richardson 2010). Thus, given the importance in understanding the detailed processes related to the production of lake-effect snow in the CTRL and PGW simulations, a record-breaking lake-effect snow event will be examined in this section.

This event occurred from 3-12 February 2007 and broke several records for duration and amount of snowfall and has been the focus of other studies such as Veals and Steenburgh (2015). The maximum snowfall was found in Redfield, New York just east of Lake Ontario which is in proximity to the Tug Hill plateau, suggesting that topography played a large role in this event as is typical in lake-effect events in this region (Campbell and Steenburgh 2017a, 2017b). Figure 5 shows the synoptic conditions at 0 UTC on 5 February 2007 from the NAM model[2]. Figures 5a and b show a classic lake-effect snow setup represented by a very cold wintertime baroclinic trough with winds parallel to the fetch of Lake Ontario at both levels, secondary troughs embedded in the large-scale flow, cyclonic vorticity advection and minimum directional shear as described by Niziol (1987). More specific information related to this event can be found from the National Weather Service in Buffalo, NY lake-effect snow event archive[3].

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[2] http://weather.unisys.com/archive/eta_init/0702/07020500.gif
[3] https://www.weather.gov/buf/lesEventArchive?season=2006-2007&event=L

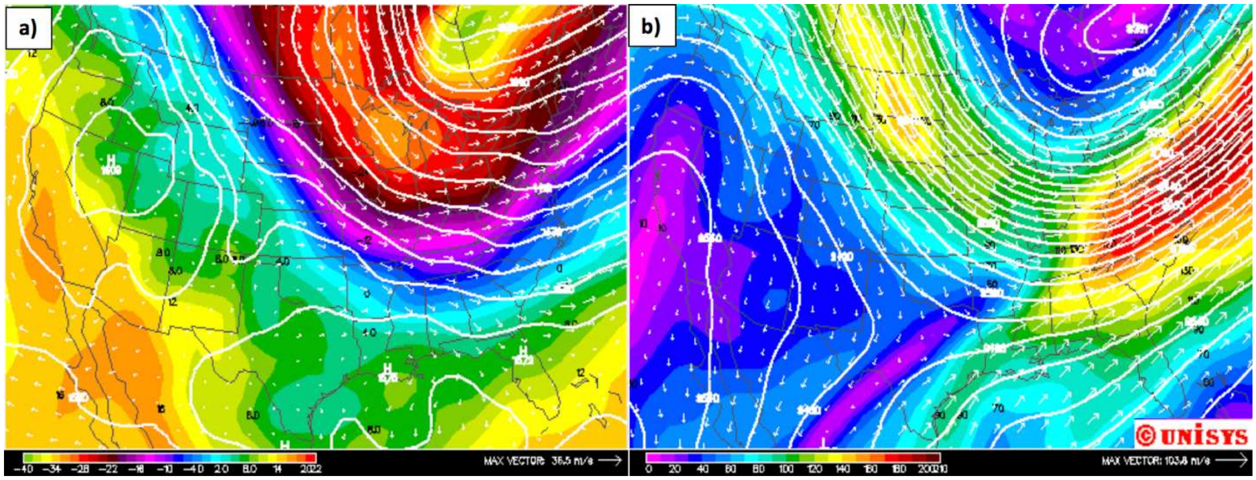

Figure 5: NAM model analysis from Unisys corp. for 0 UTC on 5 February 2007 of (a) temperature [°C], geopotential height [m], and winds [m/s] at 850 mb, and (b) geopotential height [m] and winds [kts] at 300 mb.

Moving to the mesoscale, Figure 6 provides an overview of the mesoscale features associated with this event. Fig. 6a clearly shows that this event, especially at 0 UTC on 5 February 2007, exemplifies a classic lake-effect storm event with banded precipitation on the eastern end and inland regions of Lake Ontario and Lake Erie. The mesoscale banded precipitation visible in the radar mosaic also matches with the location of the maximum total snowfall (141” in Redfield, NY) that occurred east of Lake Ontario, shown in Fig. 6b. The synoptic environment (Fig. 5) during this event sets up this type of banded precipitation as a previous study by Campbell and Steenburgh (2017b) has suggested with the formation of land-lake breezes due to long-lake-axis parallel large scale geostrophic flow, shoreline geometry, and differential surface heating and roughness creating single banded precipitation on the right shoreline and extending downstream. These land-lake breezes create low-level convergence, ascent, and snowband formation near the mid-lake axis as seen in Fig. 6a. Other previous studies also suggest that minimal directional shear and a cold airmass overriding relatively warmer lake waters further destabilize the atmosphere along with the other favorable conditions occurring to allow for significant snowfall (Niziol 1995, Campbell and Steenburgh 2017a, 2017b, Saslo and Greybush 2017).

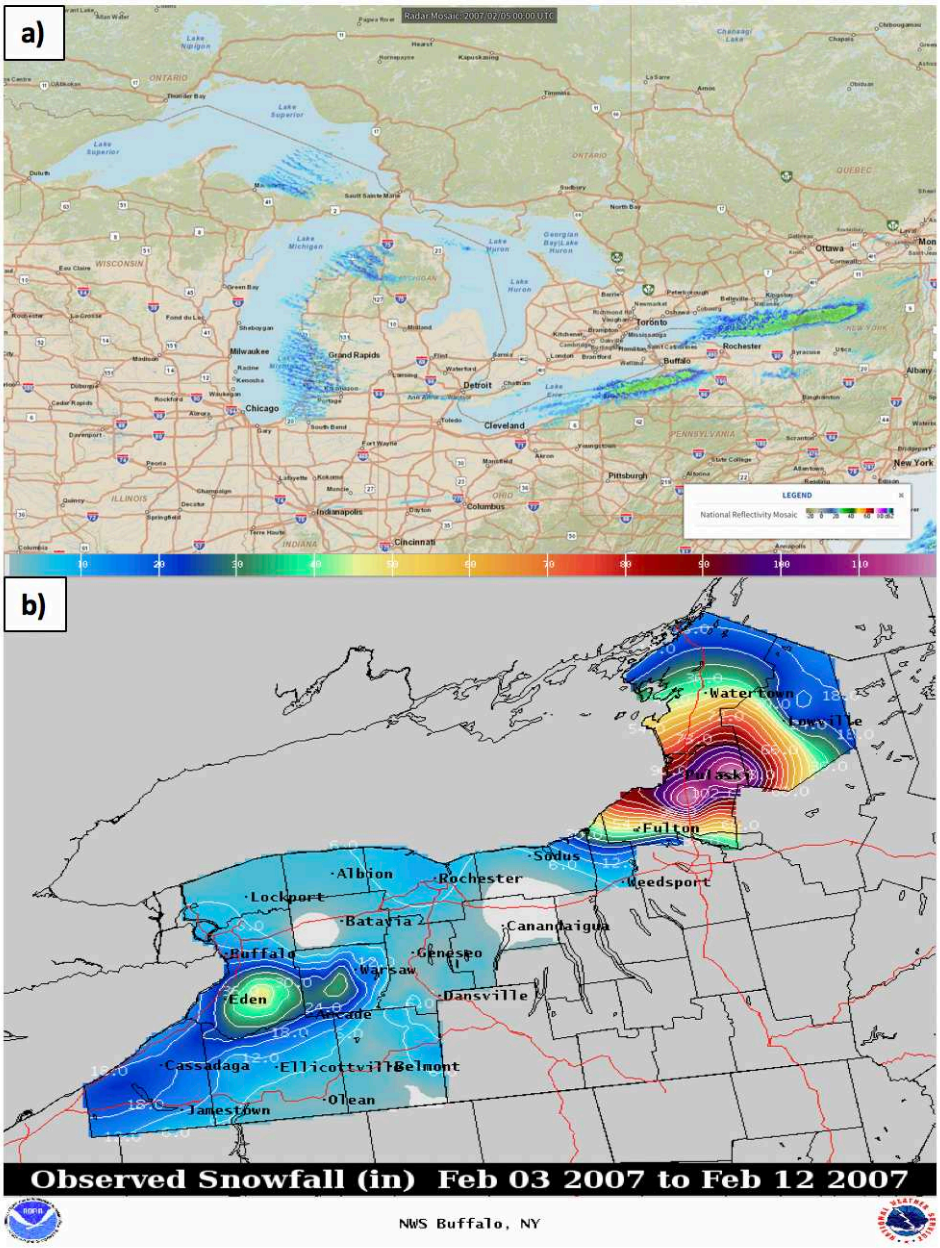

Figure 6: (a) Radar mosaic at 0 UTC on 5 February 2007, and (b) observed snowfall totals from the National Weather Service during the period of 3 February 2007 to 12 February 2007.

To provide information on how well the event was captured in the WRF CONUS simulations, averaged differences and accumulations were computed for several different variables which covered the time from 0 UTC on 1 February 2007 to 0 UTC on 15 February 2007. Figure 7 shows the accumulated SWE over the Great Lakes region for the CTRL and PGW simulations, their differences, and ERA-Interim reanalysis. The CTRL simulation demonstrates that the WRF model is indeed capturing the event in question with maximum SWE occurring over the Tug Hill Plateau region, located just east of Lake Ontario (Fig. 7a). The PGW simulation shows a similar pattern in SWE and a clear increase in SWE over the Tug Hill Plateau (Fig. 7b). Furthermore, the difference between the CTRL and PGW (PGW-CTRL) simulations (Fig. 7c) shows increases in lake-effect snowfall (represented by SWE values) downstream of many of the Great Lakes, with decreases to the south of the region. Comparing SWE between

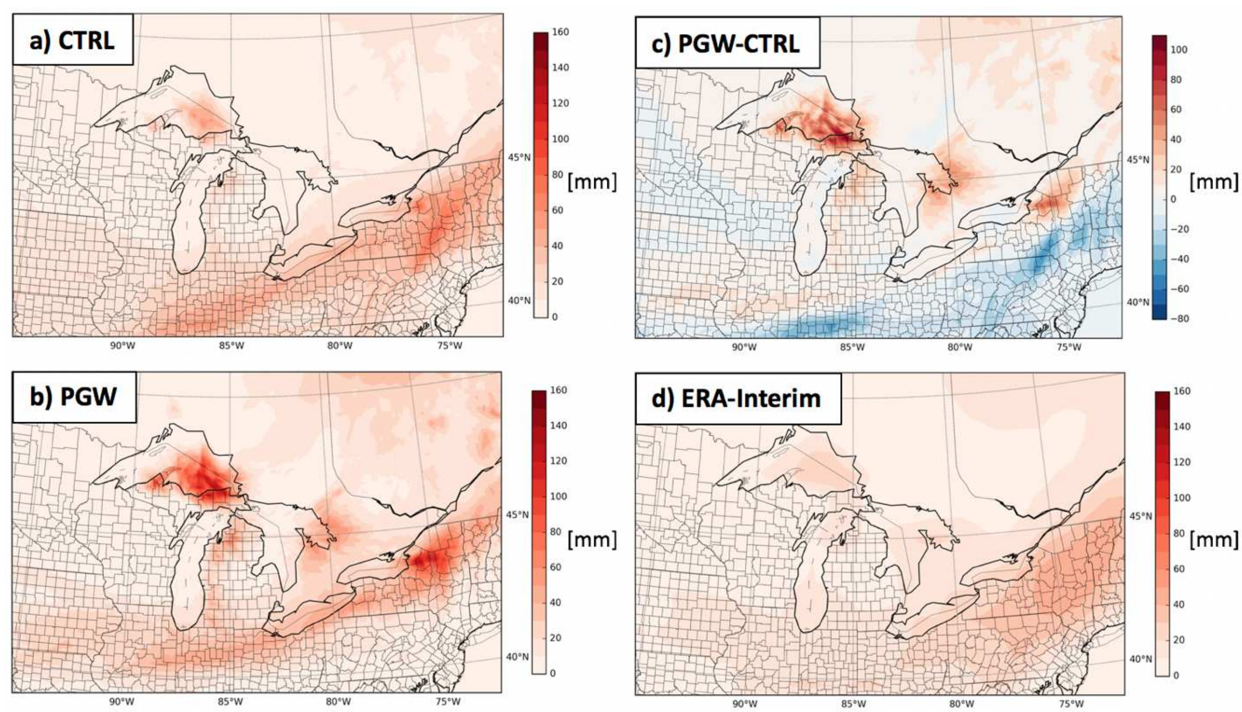

Figure 7: Accumulated snow water equivalent (SWE) [mm] over the Great Lakes domain from 1 February 2007 through 14 February 2007 for the (a) CTRL, and (b) PGW simulations. The difference between the PGW and CTRL simulations (PGW-CTRL) is shown in (c) and (d) is ERA-interim data for the same time period.

Figs. 3a-c and 7 demonstrates that this case study is capturing a similar pattern of lake-effect snow, providing confidence that the case study generally represents the processes leading to the

13-year results (Fig. 3). In addition, we hypothesize that in the region to the south, decreasing SWE is likely due to a combination of warmer temperatures and decreasing fraction of frozen precipitation, as seen previously in Figure 1d, but for the 13-year simulations. The ERA-interim data (Fig. 7d) is presented to further verify the integrity of the model and appears that it does a good job once again, despite the difference in resolution (WRF at 4 km vs ERA-I at 0.7 degrees, or approx. 77 km). WRF is higher in magnitude than ERA-I but the ERA-I reanalysis still captures the overall synoptic event in the region.

Focusing on the Great Lakes region, Figure 7c reveals ~70 mm differences (PGW-CTRL) of SWE values over the Tug Hill Plateau region. The range of lake-effect snow to liquid ratios are typically from 8:1 to 20:1[4] and can be greater than 50:1 at times, as suggested by Niziol et al. (1995). It is outside the scope of this study to examine the lake-effect snow to liquid ratio for this case, however an increase of 70 mm of SWE using an 8:1 ratio is 22.05 inches of more snowfall and using a 20:1 ratio is 55.12 inches of more snowfall. Therefore, regardless of the density of the snow impacting the region, the projections for future climate environments demonstrate a dramatic increase of lake-effect snowfall, particular later in the season, as shown in the 13-year average simulations of SWE (Fig. 3).

Building on the hypothesis that enhancements in lake-effect snowfall impacting the Great Lakes region in a future climate are due to a combination of (1) warmer temperatures, (2) more frequent ice-free conditions, (3) enhanced sensible and latent heat fluxes from ice-free lake regions, and (4) stronger mesoscale circulations associated with the lake-land breeze over an ice-free lake, a closer examination of these processes in the case study is necessary. The averaged difference between the CTRL and PGW simulations (PGW-CTRL) of surface skin temperature, albedo, latent heat flux, and sensible heat flux are shown in Figure 8. The surface skin

[4] http://glisa.umich.edu/climate/snow-great-lakes-past-and-future

temperatures increase everywhere in the region with the lake skin temperature increasing more than the land regions surrounding them (Fig. 8a). The albedo decreases specifically over the Great Lakes, suggesting that there is less ice coverage over Lake Ontario and all the other Great Lakes (Fig. 8b), which is consistent with our hypothesis above. Associated with the greater extent of ice-free conditions in the PGW simulations, both the latent and sensible heat fluxes increase over Lake Ontario and the other Great Lakes (Figs. 8c, d). The increases in surface heat fluxes further support that the decreases in albedo are a direct result of the amount of lake ice (Figs. 3 and 4). This information is particularly important as increasing amounts of ice cover reduces the amount of heat and energy available to the overriding airmass (Niziol 1987). Thus, in a future climate, these simulations suggest that more frequent ice-free conditions will result in greater sensible and latent heat fluxes and will provide additional energy and moisture to the atmosphere to enhance lake-effect snow downstream of the Great Lakes.

To further examine the characteristics of the lake surface in a current and future climate, hourly averages of the surface lake temperature in the CTRL and PGW simulations are compared for the same 14-day period over Lake Ontario (Fig. 9). In the CTRL run, after the cold air associated with the cold front reaches the region, the lake appears to be completely frozen around hour 96 and it stays frozen for the rest of the event. In the PGW run, the lake cools off dramatically once the cold air mass reaches the region, but the lake is not frozen at the same time. It does, however, oscillate between becoming frozen and unfrozen states for many days, but remains unfrozen during most of the event and significantly warms later in the period. For this reason, instead of looking at the temperature difference between the lake temperature and 850 mb, which is used as a forecasting parameter, analysis of the low-level atmospheric

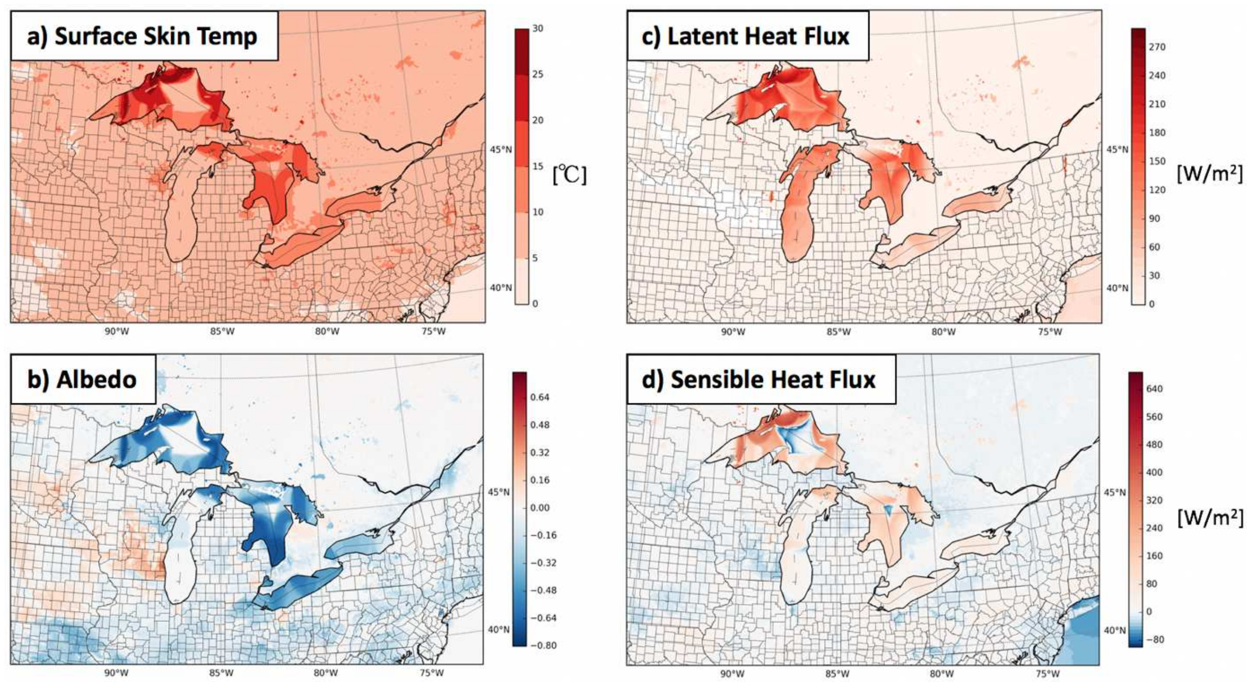

Figure 8: Differences between PGW and CTRL simulations (PGW-CTRL) of the (a) surface skin temperature [°C], (b) albedo, (c) latent heat flux [W/m^2], and (d) sensible heat flux [W/m^2] are shown over the Great Lakes domain from 1 February 2007 through 14 February 2007.

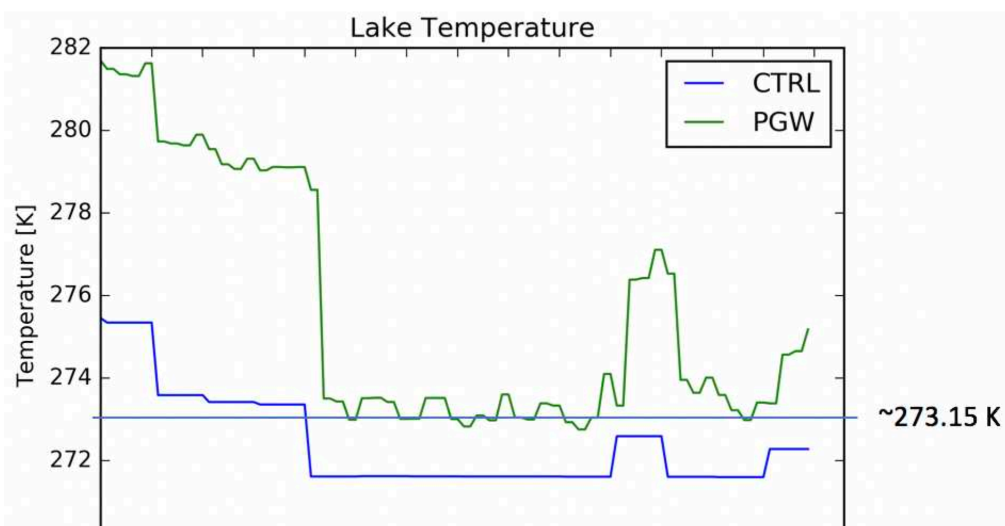

Figure 9: Lake temperature [K] of the CTRL simulation in blue, and PGW simulation in green from 1 February 2007 through 14 February 2007 given in hours from starting at 0 UTC on 1 February 2007 to ending at 23 UTC on 14 February 2007. The lake temperature at any given time is an average over the entire lake. Note that 0 UTC on 5 February 2007 is at 96 hours, and 6 UTC on 5 February 2007 is at 102 hours.

thermodynamic conditions will instead examine the temperature differences between the 2-meter and 850 mb levels over the lake only (Figure 10). This modification provides relevant information related to commonly-used lake-effect forecast metrics, but allows for analysis in both frozen and unfrozen conditions. It is important to note that unfrozen lake conditions in the

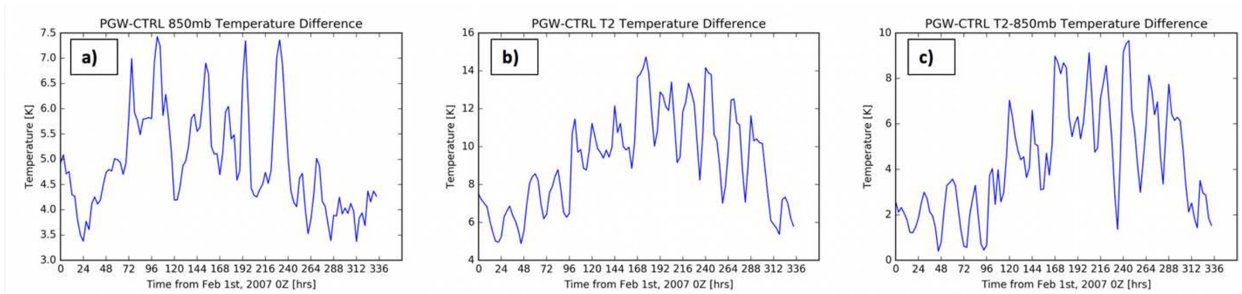

Figure 10: Differences between the PGW and CTRL simulations (PGW-CTRL) of the (a) 850 mb temperature [K], (b) 2-meter air temperature [K], and (c) 2-meter air temperature minus the 850 mb temperature [K], from 1 February 2007 through 14 February 2007 given in hours from starting at 0 UTC on 1 February 2007 to ending at 23 UTC on 14 February 2007. These differences at any given time area averages over the entire lake.

PGW simulation shows about a 6 degree increase in lake temperature compared to the CTRL simulation during periods before the cold airmass moves in and about a 2 degree increase after (Fig. 9). The temperature difference between the two simulations at 850 mb are shown in Fig. 10a. This level is warmer in the PGW simulation throughout the entire event by ~3.5-7.5 degrees. Fig. 10b is the temperature difference between the two simulations at 2-meters and is also warmer in the PGW simulation throughout the event, but with much warmer temperatures (between 5 and 15 degree increases). Using the commonly-used lapse rate of 13°C to identify lake-effect snow conditions in forecasts, with the modifications described above, it is clear that steeper lapse rates are present in a future climate over Lake Ontario (Fig. 10c). The increase in this temperature difference demonstrates more favorable conditions for lake-effect snow in a future climate (Figs. 3 and 7) and supports our overall hypothesis.

Two specific times during this lake-effect event were chosen to compare simulated radar reflectivity, albedo, hydrometeor concentrations, and dynamics. These times were chosen when there was a clear banded feature over Lake Ontario in the PGW simulation, as shown in the radar observations for this case (Fig. 6a). Figure 11 shows the composite radar reflectivity and albedo

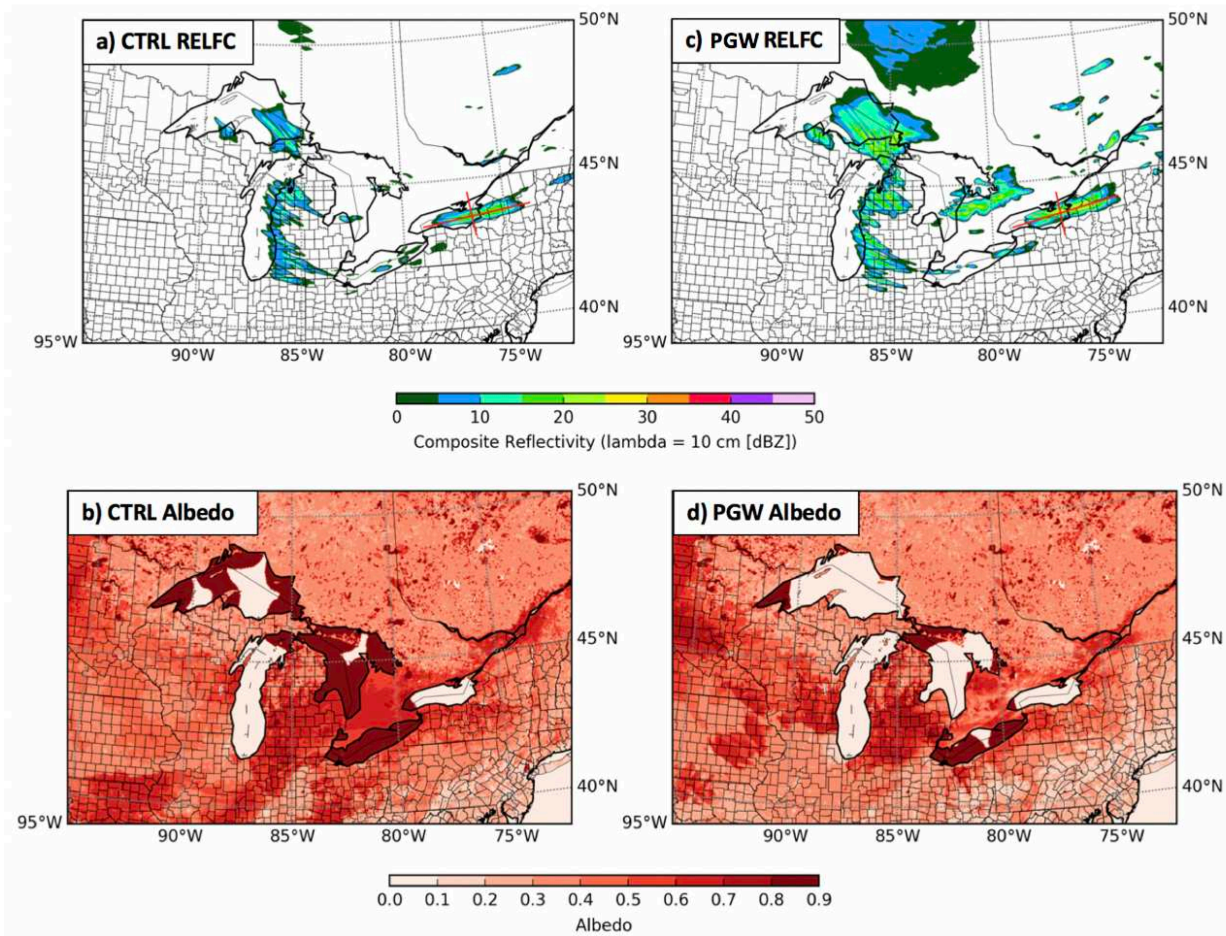

Figure 11: The CTRL simulation (a) composite radar reflectivity, and (b) albedo are compared with the PGW simulation (c) composite radar reflectivity, and (d) albedo at 0 UTC on 5 February 2007 over the Great Lakes domain.

for the CTRL and PGW simulations at 0 UTC on 5 February 2007. At this time, a lake-effect snow mesoscale band is present in both the CTRL and PGW simulations, with the PGW band appearing to be slightly stronger (Figs. 11a, c). This type of mesoscale banded feature over Lake Ontario has been well-studied in the literature as was previously described (Niziol 1995, Campbell and Steenburgh 2017a, 2017b, Saslo and Greybush 2017). To examine our hypothesis that the ice or ice-free conditions of the lake relates to the intensity of lake-effect snow events in a future climate, albedo is presented in Fig. 11b and d. The albedo maps show that the ice coverage on Lake Ontario is similar between the CTRL and PGW simulations. However, despite these similarities, the mesoscale band in the PGW simulation shows higher reflectivity values that suggests higher snow intensity relative to the CTRL simulation. A further examination of the vertical distributions of hydrometeor concentrations and water content along the E-W cross-section shown as a red line in Figs. 11a and b are shown in Figure 12, it is clear that there is a

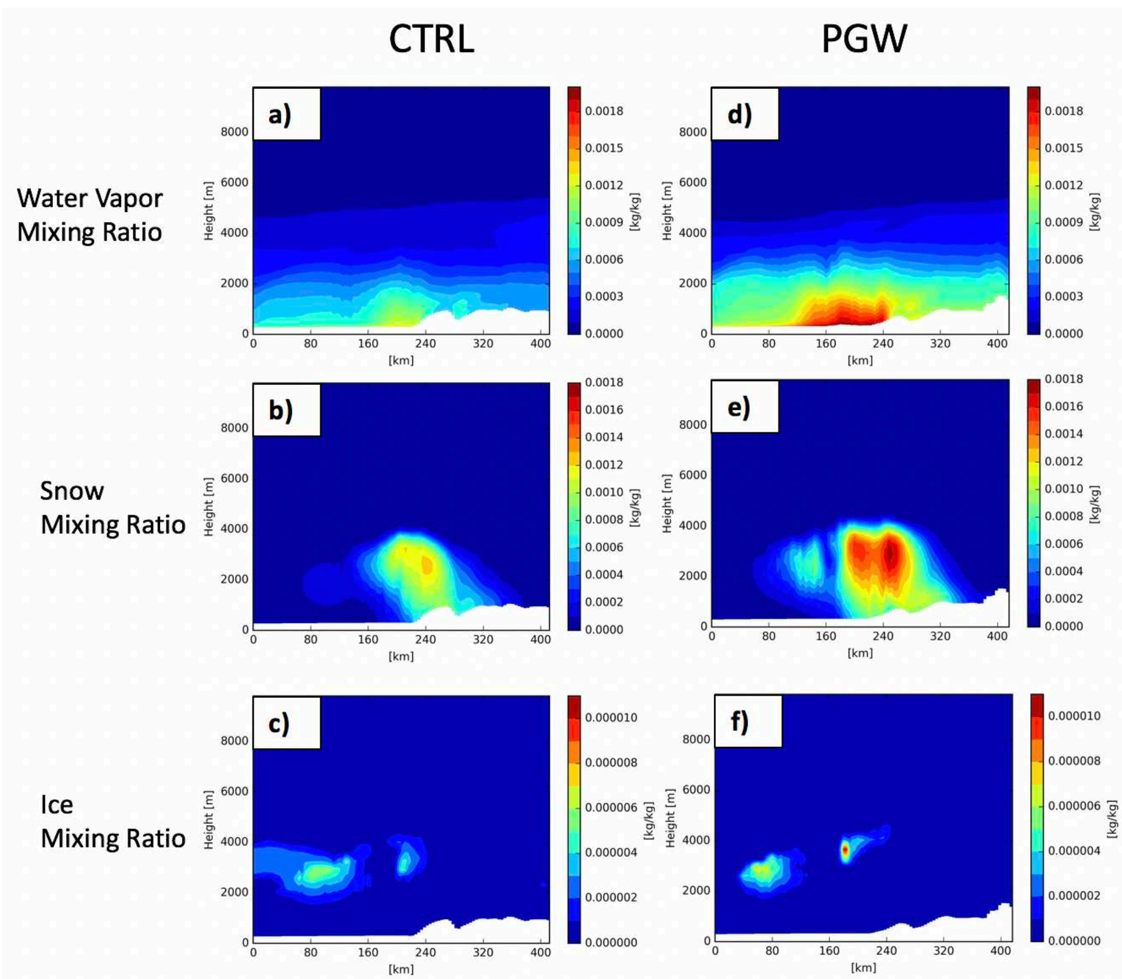

Figure 12: The CTRL simulation (a) water vapor, (b) snow, and (c) ice mixing ratios [kg/kg] are compared with the PGW simulation (d) water vapor, (e) snow, and (f) ice mixing ratios [kg/kg] at 0 UTC on 5 February 2007 for the west-east cross sections shown in Fig. 11 as a red line. The differences plot is not shown as the two cross sections are not the same.

considerable increase in the amount of water vapor and snow and ice hydrometeors in the PGW simulation. This is most likely due to a warmer atmosphere and warmer lake temperatures providing more moisture and energy to the atmosphere above the lake as presented in Figure 8.

Results shown in Figure 12 suggest that the circulations associated with the mesoscale snow band in the PGW simulation may be stronger compared to the CTRL simulation. With warmer lake temperatures associated with the synoptic flow as seen in this case, based on previous studies (Niziol 1995, Campbell and Steenburgh 2017a, 2017b, Saslo and Greybush 2017), stronger surface convergence could be expected resulting in stronger vertical velocities and a stronger lake-effect snow band. To examine this specific mechanism in the CTRL and PGW simulations, Figure 13 shows the horizontal divergence at 900 mb and 750 mb. Both simulations show convergence near the surface in the center of Lake Ontario and divergence aloft at 750 mb. However, the PGW simulation features stronger convergence near the surface and stronger divergence aloft creating enhanced mesoscale dynamics to further organize the band across the lake. As mentioned previously, this band of convergence near the surface is likely due to the land-lake breeze shown in Campbell and Steenburgh (2017). In a future climate, warmer surface temperatures and even warmer lake temperatures (Fig. 8) may result in a stronger lake-land breeze that acts to enhance near surface convergence and associated mid-level divergence. In addition, there appears to be stronger meridional flow over the lake and deeper vertical circulations in the PGW simulation, shown in N-S cross-sections in Fig. 14c, d, compared to the CTRL simulation (Fig. 14a, b). This particular time was chosen to investigate the effects of a future climate on a particular snow band without a noticeable change in albedo over Lake Ontario. Thus, even with no change in albedo between the CTRL and PGW simulations, lake-effect snow bands can be expected to be stronger and produce more snowfall in a future climate.

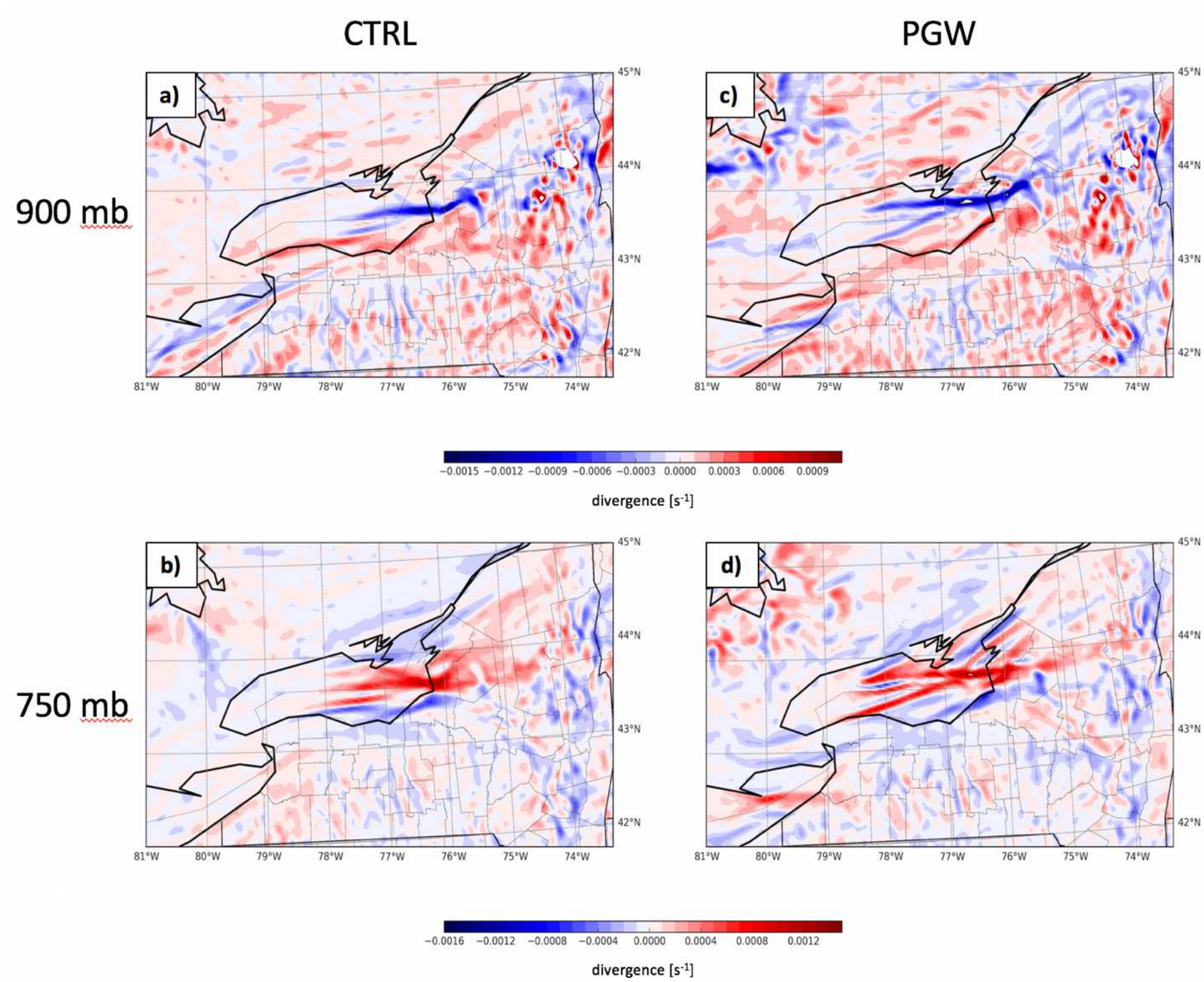

Figure 13: The CTRL simulation (a) 900 mb, and (b) 750 mb divergence [s^{-1}], are compared with the PGW simulation (c) 900 mb, and (d) 750 divergence [s^{-1}] at 0 UTC on 5 February 2007 over the Lake Ontario domain. Convergence is shown in blue and divergence in red.

This appears to be predominantly due to warmer lake temperatures, more available moisture, and advection of energy and moisture from the upwind Great Lakes.

It has just been shown that even without noticeable albedo changes between the CTRL and PGW simulations, banded precipitation becomes stronger. In order to see how much change in banded precipitation could be expected when there is a considerable difference in albedo between the two simulations, another time was chosen where this was the case. Composite radar reflectivity and albedo for the CTRL and PGW simulations at 6 UTC on 5 February 2007 is

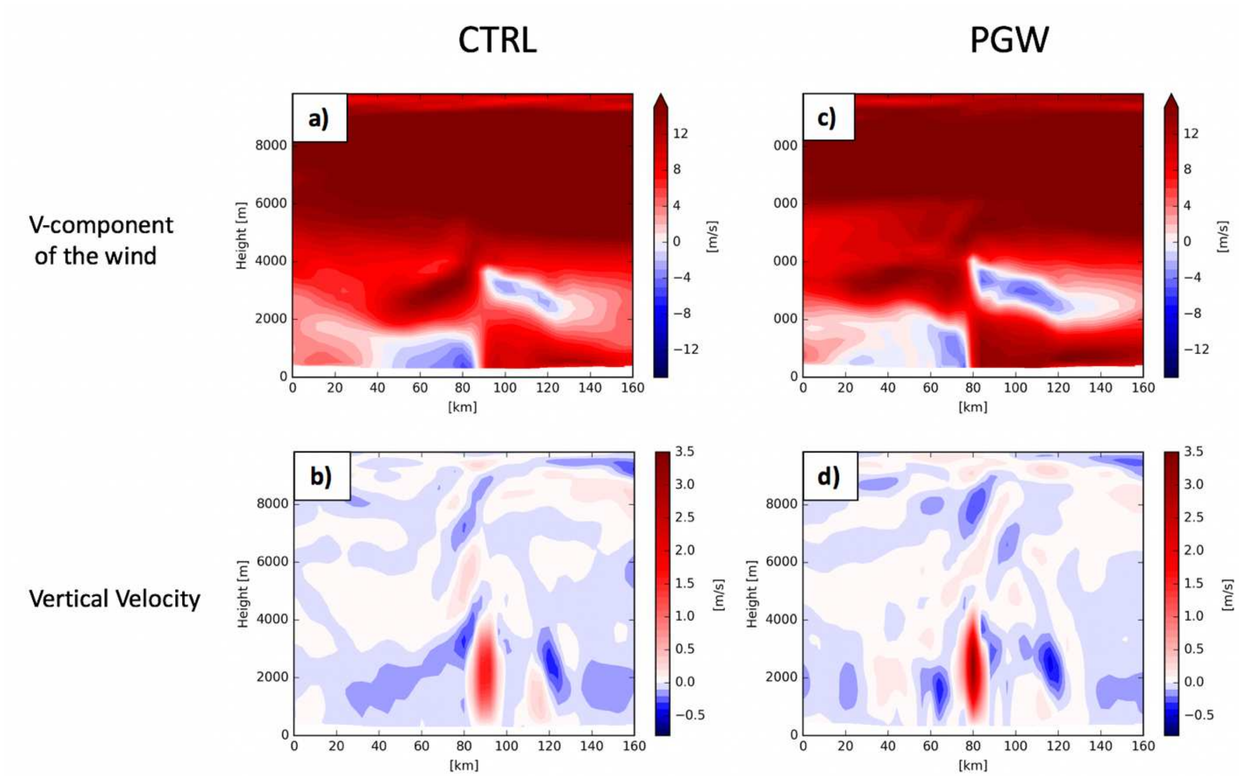

Figure 14: The CTRL simulation (a) v-component of the wind [m/s], where red is northward moving air and blue is southward moving air, and (b) vertical velocity [m/s], where red is upward moving air and blue is downward moving air, are compared with the PGW simulation (c) v-component of the wind [m/s], and (d) vertical velocity [m/s] at 0 UTC on 5 February 2007 for the north-south cross section shown in Fig. 11 as a red line.

shown in Figure 15. Unlike the previous time studied, there is no banded precipitation in the CTRL simulation, but a robust band of precipitation is present in the PGW simulation. Also unlike the previous time studied, we see a higher albedo in the CTRL simulation suggesting that this case involves a frozen lake in the CTRL simulation and an unfrozen lake in the PGW simulation. Figure 16 shows east-west vertical cross-sections (represented by red lines in Fig. 15a, c) of the CTRL and PGW simulations and their differences in the hydrometeor concentrations similar to Figure 12. Significant increases in water vapor and snow mixing rations along with modest increases in the ice mixing ratio are observed in the PGW compared to the CTRL simulation (Fig. 16g, h, and i). This is most likely due to similar reasons as seen in the 0

UTC case, but the differences are more pronounced at this time due to the absence of ice coverage in the PGW simulation compared to more ice coverage in the CTRL simulation allowing for additional latent and sensible heat fluxes off of the lake. The modest changes seen in the ice mixing ratios are likely just due to an upward shift of the location of ice due to stronger vertical mesoscale circulations.

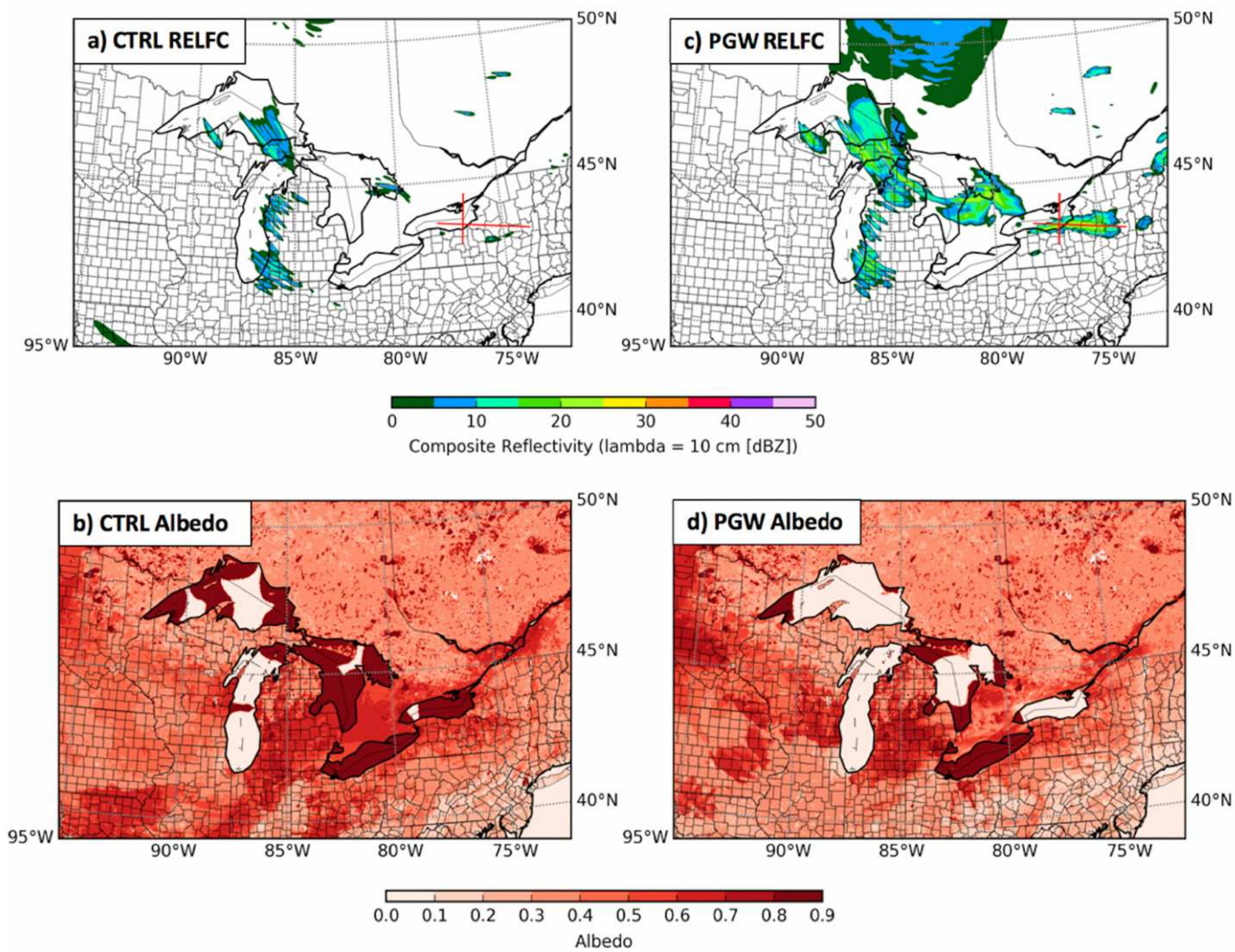

Figure 15: The CTRL simulation (a) composite radar reflectivity, and (b) albedo are compared with the PGW simulation (c) composite radar reflectivity, and (d) albedo at 6 UTC on 5 February 2007 over the Great Lakes domain.

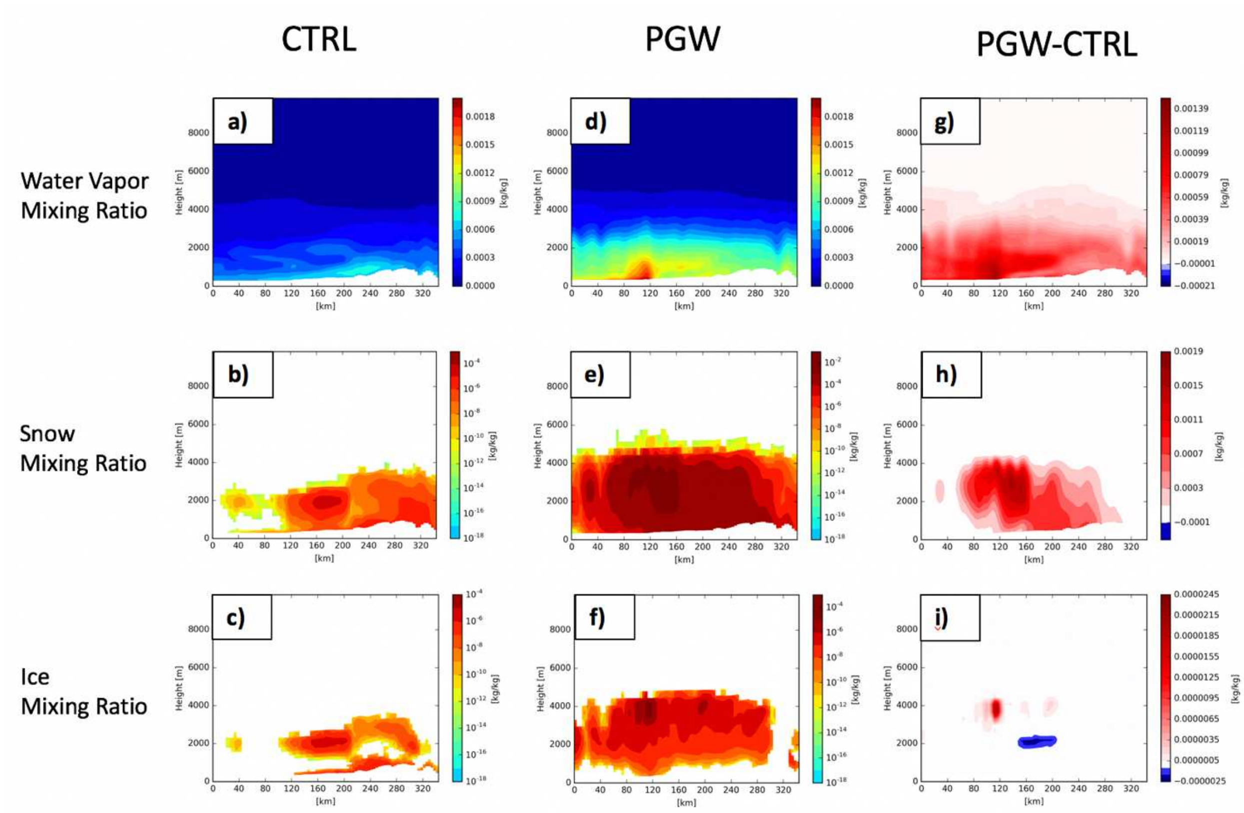

Figure 16: The CTRL simulation (a) water vapor, (b) snow, and (c) ice mixing ratios [kg/kg] are compared with the PGW simulation (d) water vapor, (e) snow, and (f) ice mixing ratios [kg/kg]. The differences between the two simulations (PGW-CTRL) of (g) water vapor, (h) snow, and (i) ice mixing ratios [kg/kg] are also shown at 6 UTC on 5 February 2007 for the west-east cross section shown in Fig. 15 as a red line. The CTRL and PGW simulation figures for the snow and ice mixing ratios are shown on a logarithmic scale for comparison.

In order to examine the dynamical effects of future lake-effect snow bands, the horizontal divergence at this time period at 900 mb and 750 mb is shown in Figure 17, as in Figure 13 for the previous time. A notable lack of organized divergence/convergence fields in the CTRL simulation (Fig. 17a) suggests that the frozen lake leads to an insignificant temperature difference between the lake and surrounding land regions that suppresses the lake-land breeze at this time. However, in the ice-free conditions in the PGW simulation, a robust lake-land breeze with associated near surface convergence and mid-level divergence is clearly shown in Fig. 17c and d. This strong mesoscale circulation is likely providing the vertical forcing for the

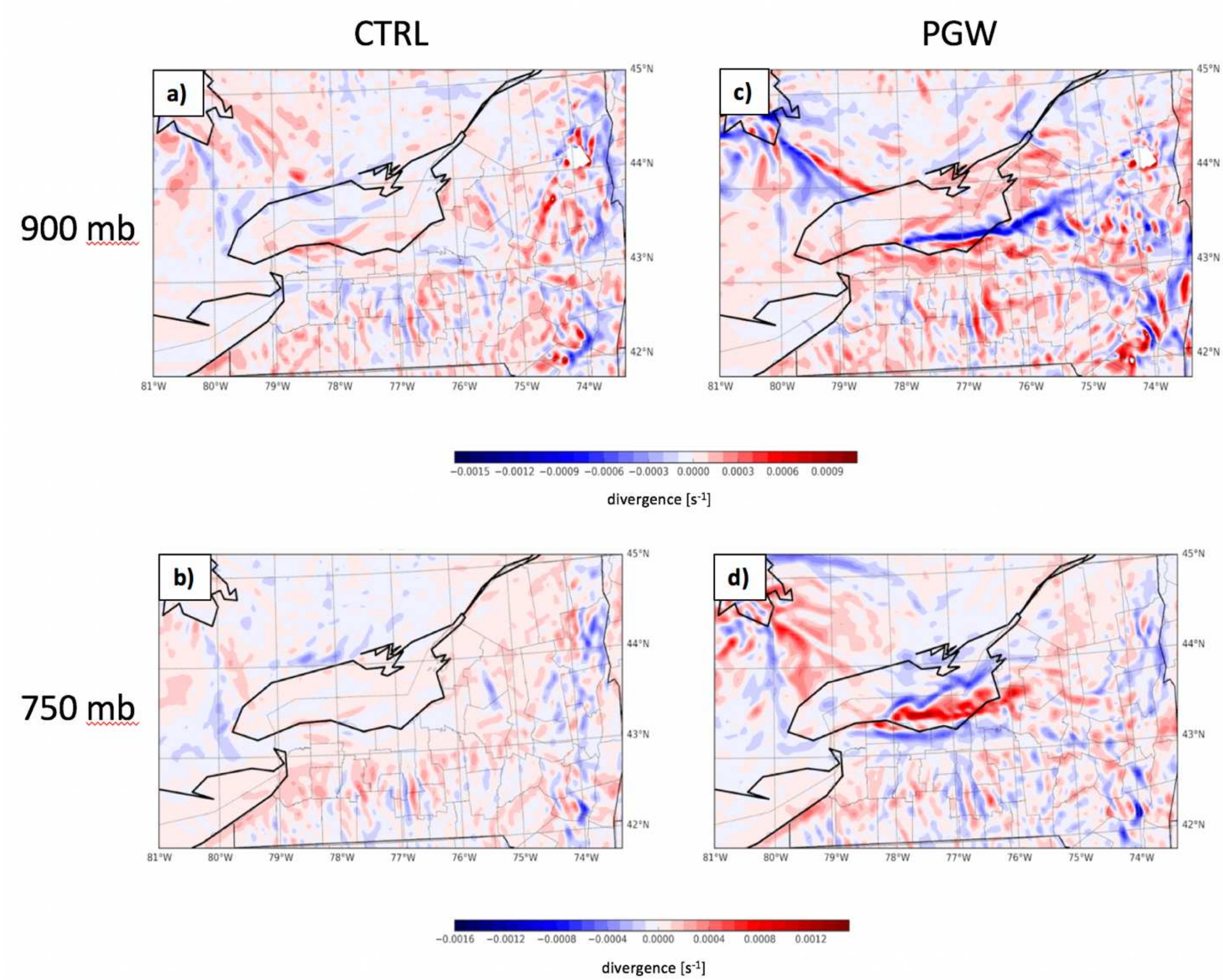

Figure 17: The CTRL simulation (a) 900 mb, and (b) 750 mb divergence [s^{-1}], are compared with the PGW simulation (c) 900 mb, and (d) 750 divergence [s^{-1}] at 6 UTC on 5 February 2007 over the Lake Ontario domain. Convergence is shown in blue and divergence in red.

mesoscale band development in the PGW simulation (Fig. 15c). As a result of the divergence fields shown in Fig. 17, as well as the likely presence of a land-lake breeze in the PGW simulation, stronger meridional flow converging over the center of the lake is present in the PGW simulation (Fig. 18c) compared to the CTRL simulation (Fig. 18a). Associated with these meridional wind patterns, a deep vertical circulation is visible in the PGW simulation (Fig. 18d) compared to the absent vertical circulation in the CTRL simulation (Fig. 14b). Examining a time such as this when there is a significant change in albedo between the two simulations suggests

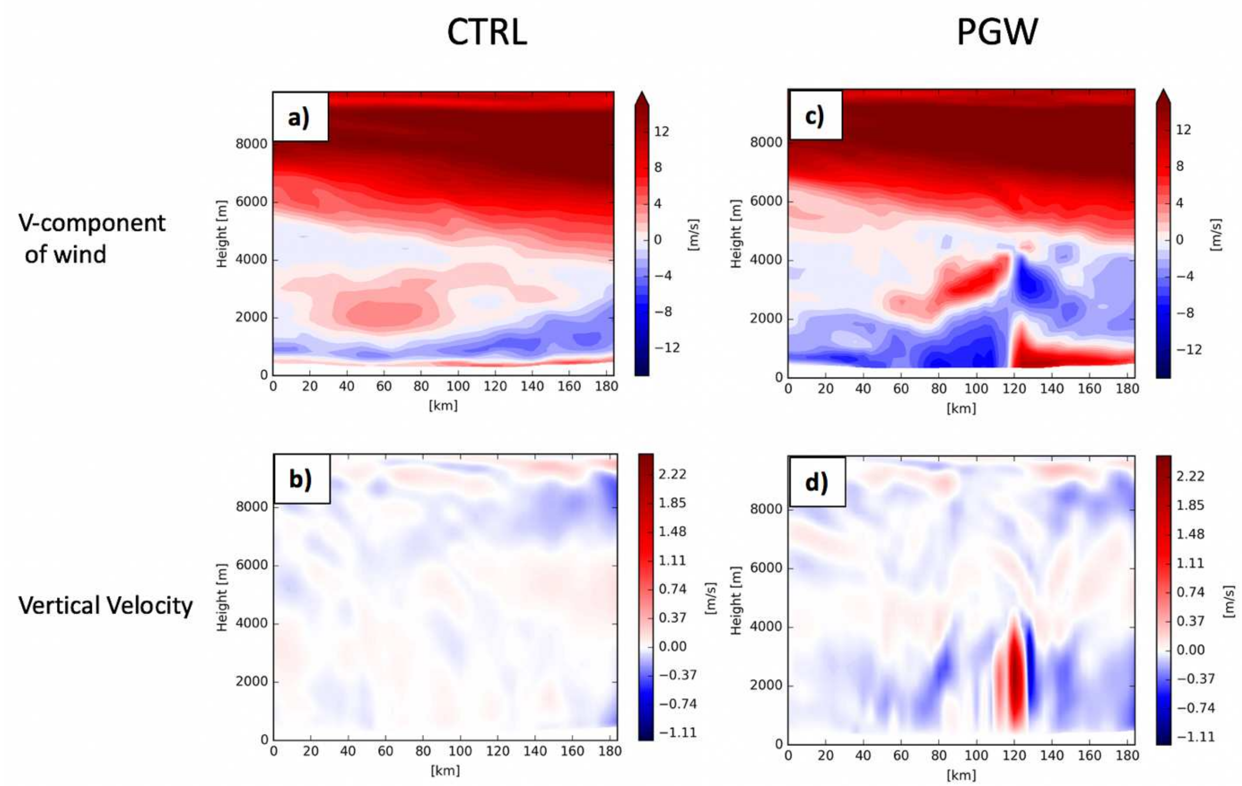

Figure 18: The CTRL simulation (a) v-component of the wind [m/s], where red is northward moving air and blue is southward moving air, and (b) vertical velocity [m/s], where red is upward moving air and blue is downward moving air, are compared with the PGW simulation (c) v-component of the wind [m/s], and (d) vertical velocity [m/s] at 6 UTC on 5 February 2007 for the north-south cross section shown in Fig. 15 as a red line.

that in a future lake-effect snow event, banded precipitation not only gets stronger, but would be organized for longer durations and during times when it would otherwise be subdued due to diurnal changes in ice coverage.

Warmer temperatures in a future climate have many significant effects on the atmosphere. It has been shown that during the winter months, more frequent ice-free conditions over the Great Lakes modify the overlying atmosphere by providing enhanced sensible and latent heat fluxes. These surface fluxes, along with land-lake temperature contrasts, produce stronger mesoscale circulations associated with the lake-land breeze over an ice-free lake and therefore producing significantly more lake-effect snowfall over the region. These results confirm the hypotheses presented in Chapter 1.

Chapter 4 - Conclusion

The dynamical and thermodynamical changes in a future climate are examined to understand changes in the frequency and amount of lake-effect snowfall in the Great Lakes region. Two novel high-resolution convection-permitting regional climate simulations are used to examine changes in future extreme wintertime precipitation events compared to the current climate across the CONUS and more specifically in the Great Lakes region during the months of December, January and February. The two simulations are as follows: (1) 13-year continuous retrospective control simulation forced by ERA-Interim reanalysis every 6 h (CTRL), and (2) 13-year continuous PGW simulation forced by ERA-Interim reanalysis plus a 19 CMIP5 model monthly mean climate perturbation every 6 h (PGW). Comparing these two simulations provides a unique perspective on how wintertime precipitation and lake-effect snowstorms may change in a future climate. The results found from this study can be applied to many areas of expertise such as snow hydrology, city planning, forecasting, emergency management, and many other important areas.

Analysis of the average monthly differences (PGW-CTRL) for DJF showed increases of precipitation and SWE particularly downwind of the Great Lakes. There are also substantial increases in water vapor, cloud liquid water and ice and snow content concentrated around the Great Lakes and the decreases in fraction of frozen precipitation reaching the ground was strongest over and around the Great Lakes. To investigate how a warmer and moister climate state may change wintertime storms, composite reflectivity from the CTRL and PGW simulations was used to calculate the frequency of occurrence in six reflectivity ranges. Differences between the CTRL and PGW results show a widespread decrease in weak echoes over the continental U.S., particularly in the northern Rockies and over the Great Lakes region.

Increases in moderate echoes are located over the northern U.S. and are most prominent over the Great Lakes region. These results suggest an increase in the frequency and amount of lake-effect snow and is the primary focus of the study. Thus, due to the association with the strongest changes in many of the variables examined being collocated with the Great Lakes, this region was chosen to be further examined in greater detail.

Focusing on the Great Lakes region, the average monthly differences in snow water equivalent (SWE) and albedo are examined for each winter month (December, January and February). Regions downstream of the Great Lakes, where lake-effect snow is expected, shows a clear increase in the amount of SWE. Corresponding decreases in albedo differences throughout the season suggests that increases in lake-effect snow could be a result of from less lake ice coverage in a future climate. The 13-year DJF average difference in latent heat suggests that the decreases in albedo result in enhanced latent heat fluxes off of the lakes that promotes increased SWE downwind of the Great Lakes. Thus, the primary hypothesis of this study is enhancements in lake-effect snowfall impacting the Great Lakes region in a future climate are due to a combination of (1) warmer temperatures, (2) more frequent ice-free conditions, (3) enhanced sensible and latent heat fluxes from ice-free lake regions, and (4) stronger mesoscale circulations associated with the lake-land breeze over an ice-free lake.

A detailed analysis of a record-breaking lake-effect snow event from 3-12 February 2007 over Lake Ontario is used to test the hypothesis derived from the 13-year analyses described above. The synoptic scale setup with cold air, long-fetch winds parallel to the lake axis, and multiple short waves for the duration of the event is a classic lake-effect snow scenario. Over 141 inches of snow fell in Redfield, NY and classic lake-effect mesoscale bands were seen during the duration of the event. Comparing the accumulated snow water equivalent for the event shows that significantly more snowfall occurs in the PGW simulation, with approximately 70 mm of more SWE in the future. In addition, surface skin temperatures increase everywhere, with a higher increase in temperature over the lake. Decreases in albedo and increases in both latent and sensible heat fluxes are also seen over the Great Lakes in the PGW simulation, which are all consistent with the 13-year results and the driving hypothesis for the study. A time series of surface lake temperature for the CTRL and PGW simulations shows that during this event, the lake is frozen for most of the event in the CTRL simulation, but in the PGW simulation, temperatures are warmer and the lake does not fully freeze during the event. A time series of the 850 mb temperature and 2-meter temperature differences between the two simulations and their differences show that in the PGW simulations the thermodynamic structure supports a much steeper lapse rate from 2-meters to 850 mb. The steeper lapse rates support deeper and more intense lake-effect snow.

In order to examine the dynamic forces that may be different in a future climate, two specific times were selected to compare a scenario when there was and was not a noticeable change in albedo over Lake Ontario between the two simulations. The results from 0 UTC on 5 February 2007, when there was no noticeable change in albedo with both simulations having a mesoscale banded precipitation feature over Lake Ontario, showed significant increases in the water vapor, snow, and ice mixing rations along with stronger convergence at the surface and stronger divergence aloft resulting in deeper vertical motion. These results verify that more snowfall can be expected in a future climate even without a change in ice coverage over Lake Ontario most likely due to the additional available moisture from a warmer atmosphere, advection of moisture from the upwind lakes which did show decreases in albedo, as well as stronger dynamical forces at play from the land-lake temperature contrasts. The results from 6 UTC on 5 February 2007, when the CTRL simulation showed high albedo with no banded precipitation and the PGW simulation showed low albedo with banded precipitation over Lake

Ontario, showed significant increases in the water vapor and snow mixing ratios, a shift of the ice mixing ratio upward and the presence of a land-lake breeze in the PGW simulation compared to no convergence field in the CTRL simulation which contributed to strong vertical motion. Accumulated snow water equivalent was looked at, but not shown, for these two times and the one hour additional accumulation differences between the CTRL and PGW simulations for 0 UTC and 06 UTC were approximately 1.3 mm and 3.2 mm, respectively; a significant amount for a one hour time period difference.

Given that the entire atmosphere warms in the future simulations (Liu et al. 2016) with the most warming occurring at and near the surface, among other changes, forecast parameters for lake-effect snow may need to be adjusted as the dynamics near the surface and the thermodynamics of the atmosphere changes. One possible required change is in the standard 13-degree difference between the lake temperature and 850 mb temperature forecasting metric. The 850 mb temperature increases in a future climate and it may increase more than the water temperatures are increasing, especially when the lakes are closer to freezing, resulting in lower lapse rates and a demand in a change in this forecasting metric. Hourly differences in the simulations (PGW-CTRL) for the 14 days of a) 850 mb temperature, b) 2-meter temperature, and c) the difference between the 2-meter temperature difference and the 850 mb temperature difference (Fig. 10) showed these lapse rates increased. However, when comparing the lake temperature changes (Fig. 8) with the 850 mb temperature changes (Fig. 10a) the lapse rates decrease in instances when the lake was frozen in the CTRL simulation versus the PGW simulation but increases in instances when the lake was not frozen in either simulation (not shown). Water vapor also increases throughout the atmosphere (Liu et al. 2016, Rasmussen et al. 2017), which could result in changes in the amount and types of hydrometeors. Advection of moisture and energy from upwind lakes is also a contributing factor to increases in lake-effect snow events downstream as suggested in their changes in albedo and future composite reflectivity values (Figures 3d, 3e, 3f, 11c, and 15c). Previous studies also suggest that upwind lakes could be a contributing factor to enhance lake-effect snow processes over Lake Ontario by advecting moisture and energy downwind (Sousounis and Mann 1999, Vavrus et. al 2012). It is also likely that lake-effect snow events will occur for a longer seasonal period allowing for them to occur during parts of the season when they have not been typically forecasted as suggested by the change in albedo over the lake as seen (Figure 3).

Examining the differences between the CTRL and PGW simulations during a time that has a frozen lake compared to an unfrozen lake suggests that in the future we will see the presence of a land-lake breeze more often which can provide enhanced support for mesoscale banded precipitation along the lake more frequently. This supports the hypothesis that lake-effect snow increases in the future. The frequent presence of the land-lake breeze in the PGW simulations is an important factor in the formation and sustainability of the mesoscale banded snow mode for long duration of the events.

This study examines how wintertime precipitation and, more specifically, lake-effect snow events may change in a future, warmer climate. The results demonstrate the difficulty in forecasting lake-effect snow given the sensitivity to many different factors. High-resolution convection-permitting regional climate models provide an excellent tool to investigate how a warmer and moister future climate will change the characteristics of precipitating systems in the winter season. Enhanced understanding of the thermodynamic and dynamic changes leading to different environmental conditions for lake-effect snow events in the future will provide forecasters with the necessary information required to forecast future lake-effect snow storms. Their mesoscale nature is what makes snow events very difficult to forecast and requires such high-resolution modeling. Using high-resolution convection-permitting models to predict future changes in the weather due to changes in the climate is important to provide information on the physical mechanisms and processes that may shift, and more clearly and accurately communicate future changes in the water cycle to city planners, emergency management teams, and hydrologists for enhanced public safety.

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