FUTURE HYDROCLIMATE VARIABLES AND LAKE LEVELS FOR THE GREAT LAKES

using data from the Coupled Model Intercomparison Project Phase 5

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Key points:

- The general patterns of the change of hydroclimate variables experienced in the Great Lakes over the past few decades are projected to continue, these include increasing overall over-lake precipitation and increasing over-lake evaporation
- The levels of the Great Lakes are projected to increase their variability resulting in both more extreme high and low water levels under a changing climate
- The most extreme projected changes to the hydroclimate variables and lake levels occur under higher emissions scenarios, which will depend on the adaptation and mitigation measures that are put in place globally.
- There are various sources of uncertainty in any study of the future climate, these range from high level socio-economic assumptions on emissions and modelling uncertainties to more regional scale assumptions about how the basin would react under some of the more extreme climate scenarios

Executive Summary

This report summarizes the work done by the National Hydrological Service of Environment and Climate Change Canada as part of the Wetlands working group of the Great Lakes Protection Initiatives for a project designed to assess and enhance the resilience of Great Lakes Coastal Wetlands. A critical component of this study was to identify the amount and rate of climate change to which wetlands are likely to be exposed. A key role of NHS was to project future water levels of the Great Lakes from various simulations of the future climate as input to a wetlands response model. While the focus of this effort was on the response of wetland vegetation to changes in climate, it is recognized that many other interests within the Great Lakes basin will also have an interest in the results.

The data used in the current study came from the North American component of the Coordinated Regional Downscaling Experiment (CORDEX-NA). These data are based on dynamically downscaled future climate simulations from Regional Climate Models (RCMs) driven by Global Climate Models (GCMs) from the Coupled Model Intercomparison Project Phase 5. A total of 13 RCM-GCM combinations were used in this study.

In order to calculate the future lake levels, the Net Basin Supply (NBS) components (lake precipitation, lake evaporation, and runoff into the lake) were extracted from the RCMs. Initially, a bias adjustment was performed on these individual components and the NBS was calculated using the component NBS method. As a second approach, the raw component data were combined to calculate the NBS on a monthly basis for each lake and a bias adjustment was performed based on the residual NBS. Bias-adjusted NBS values using both of these methods were then used to model the future lake levels of the Great Lakes.

In the past few decades, there has been a pattern of general increases in the over-lake precipitation and the over-lake evaporation. The future climate projections found in this study show that these patterns of increases could continue, but also the range of high and low values could expand. This would lead to certain future time periods experiencing both higher high values and lower low values for these variables.

The results of this study have the same general message as previous water level studies, which is that although the projected future average water level may be higher or lower, the range and variability of water levels are expected to expand with more extreme highs and lows possible in the future. It is also evident, that more extremes are expected with the Representative Concentration Pathway (RCP) 8.5 scenario (high-emissions, business as usual) than the RCP 4.5 scenario (a middle of road path with some emission mitigation).

When examining the resulting water levels it must be considered that they are based on the current understanding of the climate system and assumptions made about the future behavior

of society that will result in the amount of anthropogenic emissions of greenhouse gases and aerosols put into the atmosphere. There are many uncertainties and assumptions that are inherent in these projections, such as, future population growth, per capita energy usage, emerging energy technologies, global mitigation initiatives, other uncertain socioeconomic conditions and the random natural variations in the climate system. The results are most useful in showing the general trends of what could happen in the future.

It is also important to note that these projections are not predicting exactly what the water levels will be for a certain year. Instead, they represent a range of possible values that the actual values should come from. The important final message of this study is that this range of possible values grows as the climate changes, with more extreme values for the lake levels becoming possible with greater changes in the global mean temperature. But it should be stressed that it does not necessarily mean that all of these conditions will be seen in the future.

These water level projections serve as input to wetland response models to identify potential impacts and potential vulnerability in order to help plan for adaptive actions for wetlands. But their use can extend beyond wetlands. For those living, working or recreating around the lakes, the projections for increases in the range of water level on both the high and low end may be a more important consideration than any general increase in the average water level. This is because the most servere impacts on the interests around the lakes are usually associated with extreme high or low levels. An appreciation that the extremes that have been observed in the past may be exceeded under a changing climate may help in the planning of future developments and activities within the Great Lakes basin.

This study was not designed to be a basis for risk assessment for all projects and interests. It will be left to any user of this data to determine their own risk tolerance for the path of the future climate characteristics (for example the amount of future climate change mitigation) and the resulting probabilities of the projected lake levels.

1 Introduction and scope of this study

The Great Lakes are important sources of drinking water, transportation, hydropower, and recreation opportunities such as fishing, boating, swimming, hunting, and wildlife watching. These activities create jobs and provide goods and services. However, climate change is causing significant impacts on the Great Lakes Basin (McDermid et al., 2015; ELPC, 2019). Many impacts projected under a changing climate are likely to be more extreme manifestations of environmental stressors already of concern, such as degraded water quality and loss of ecosystem health. As such, there is recognition of the need to anticipate, plan for, and act on the implications of future climate impacts on Great Lakes resources.

Coastal wetlands are particularly sensitive to changes in climate given their location at the land-water interface. Specifically, wetland structure and function is highly dependent on the variation in lake levels, temperature, precipitation, and ice cover (Acreman et al., 2009; Mortsch, 2006). Through the Great Lakes Protection Initiative (GLPI), Environment and Climate Change Canada is taking action to confront the adverse effects of climate change by assessing the vulnerability of Great Lakes coastal wetlands, and by identifying adaptive measures to enhance their resilience. This program, entitled 'Assessing and Enhancing the Resilience of Great Lakes Coastal Wetlands' (2017 – 2022) contributes to the long-term conservation of coastal wetland ecosystems and to Canada's commitments under the Canada – United States Great Lakes Water Quality Agreement (GLWQA) and the Canada – Ontario Agreement (COA) on Great Lakes Water Quality and Ecosystem Health. The objectives of this program are to understand coastal wetland vulnerability, identify best adaptation approaches to enhance wetland resilience, and to engage the Great Lakes conservation community to share knowledge, improve awareness, and begin to build consensus on priorities and actions for climate change adaptation.

This report summarizes the modelling conducted by the National Hydrological Service (NHS) of Environment and Climate Change Canada (ECCC), which was designed to assess the climate exposure component of the vulnerability assessment and to project future water level scenarios for each of the Great Lakes from various simulations of the future climate. These data will then be used in a separate component of the overall project that uses ecohydraulic modelling (Morin et al., 2006) which simulates wetland response to future climate information, including changes in Great Lakes water levels.

To determine projected water levels in the Great Lakes under future climate scenarios, this report focuses on the following hydroclimate variables: over-lake precipitation, over-lake evaporation, and runoff from the watersheds into the lakes. Future studies could examine changes in other variables that are produced by the models used in this study (ie. streamflow, soil moisture, snow water equivalent, etc.). There are various interests within the basin that would benefit from projections of the changes of these hydroclimate variables in the future climate, but as stated, they are not assessed in this report.

The current state of knowledge of the future climate and how it will affect the hydroclimate and lake levels of the Great Lakes is presented here. However, this knowledge is constantly evolving and as a result the most recent scientific literature should also be considered.

2 Background

There has been an evolution of the modelling of future Great Lakes water levels over the past 20 years, with modelling done in the 1990s suggesting a large drop of the water levels that in some studies was on the order of metres (Croley, 1990, Hartmann, 1990, Smith, 1991, Mortsch and Quinn, 1996). However, these studies generally did not incorporate dedicated lake models. This was an important limitation as: (a) the lake surfaces make up a large proportion of the basin areas and (b) there was no calculation of lake dynamics and thus the evolution of lake ice and consequently the lake evaporation would not have been realistically simulated. An overestimation of the rate of change of lake evaporation may possibly explain these projected large drops in lake levels.

Later studies used climate projections done for the Coupled Model Intercomparison Project Phase 3 (CMIP3) that were based on the Global Circulation Models (GCMs) as part of the Intergovernmental Panel on Climate Change fourth assessment report (Hayhoe et al., 2010, Angel and Kunkel, 2010, MacKay and Seglenieks, 2013). These GCMs are mathematical models based on atmospheric, oceanic, and land processes. They use input data from simulations of scenarios based on different possible time series of the amount of greenhouse gases and aerosols in the atmosphere as society develops until the end of the current century.

The climate models used for the Great Lakes in these more recent studies started to incorporate basic lake models that captured some of the large lake dynamics. The results of these studies generally showed an overall reduction in lake levels, although much smaller than the previous studies. However, it should also be noted that some model runs also showed a slight increase in average lake levels in the future. In general, the models agreed that there would also be a greater range of lake level extremes (higher highs and lower lows) projected to occur in the future (MacKay and Seglenieks, 2013).

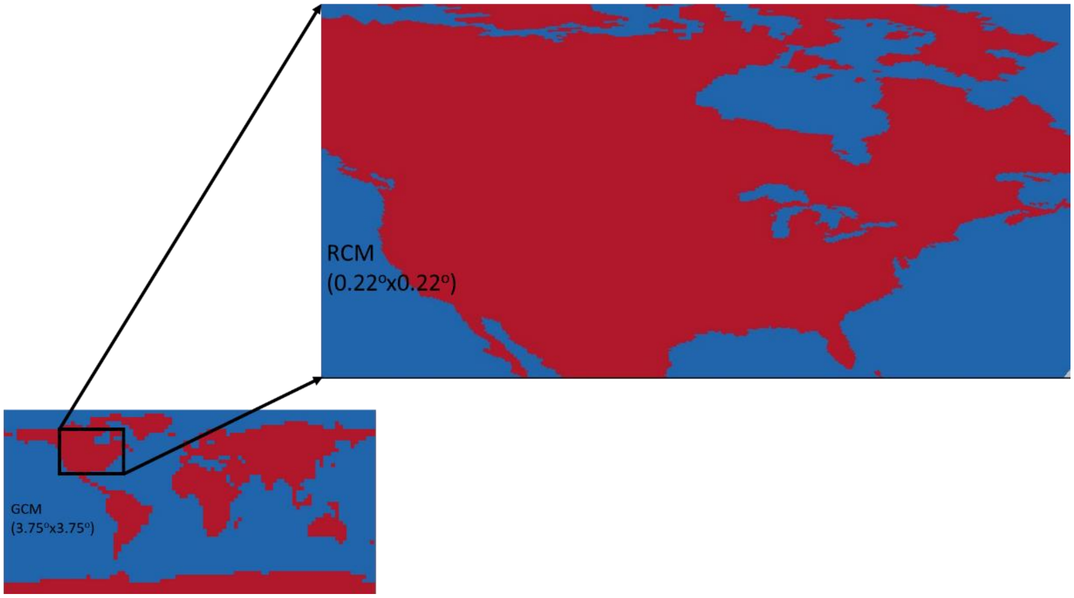
The data sets used in the current study came from the North American component of the Coordinated Regional Downscaling Experiment (CORDEX-NA), which is a program sponsored by the World Climate Research Program (Giorgi, et al., 2009). These datasets are based on dynamically downscaled future climate simulations driven by GCMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). As well, additional datasets for the Canadian Regional Climate Model 5 (CRCM5) model (Martynov et al., 2013) were generated and supplied by Ouranos, a consortium on regional climatology and adaption to climate change.

For CMIP5, scenarios were defined as Representative Concentration Pathways (RCPs) that result in specific radiative forcings by 2100, compared to the pre-industrial period (1850-1900). The runs from CORDEX-NA have focused on the RCP4.5 scenario (a middle of road path with some emission mitigation) and the RCP8.5 scenario (business as usual). Both of these scenarios result in very similar changes to the radiative forcings up until around 2050. It is only then that the RCP8.5 scenario starts to diverge and by the end of the century there are very significant changes in the radiative forcings between the two scenarios.

A difficulty in using GCMs directly is that their spatial resolution is typically on the order of hundreds of square kilometers. At this resolution, even features as large as the Great Lakes cannot be adequately represented (Figure 1). The surfaces areas of the lakes account for a large percentage of the overall Great Lakes watershed, thus it is critical for any simulations to explicitly include models of the lakes.

For this reason, it is necessary to downscale the data from the GCMs. This study used results from dynamical downscaling, which involves running Regional Climate Models (RCMs) at higher resolutions as compared to the GCMs on a regional sub-domain using outputs from the GCMs as boundary conditions. At the typical resolutions of RCMs (on the order of tens of square kilometers), the Great Lakes can be resolved, as well many RCMs also include some representation of lake dynamics.

The CORDEX-NA project utilized seven RCMs and the output of nine GCMs for scenarios RCP4.5 and RCP8.5. There were a total of 27 RCM-GCM-scenario combinations available for use. However, lake evaporation – a critical piece of information for this work – was only available in 13 of the 27 data sets. These 13 data sets formed the basis of the study presented here and included data from three different RCMs and five different GCMs. A summary of the RCMs, driving GCM, RCP scenario, resolution, and lake model used in the study are summarized in Table 1. Note that for each data set, the smallest available resolution data were used for consistency. At the time of this study, the CORDEX-NA experiment was the only known source of multiple GCM-RCM data that was publically available and contained adequate data to calculate the future lake levels for the region of interest.



The lake model used by most of the RCMs in this study was FLake (Mironov, 2008). This is a freshwater lake model that predicts the vertical temperature structure and mixing conditions in lakes of various depths with time scales that vary from a few hours to many years. It uses a two-layer parametric representation of the temperature profile and integral budgets of heat and kinetic energy for these two layers. It has been used in many different applications including in numerical weather prediction models, climate modelling and other numerical prediction systems for environmental applications.

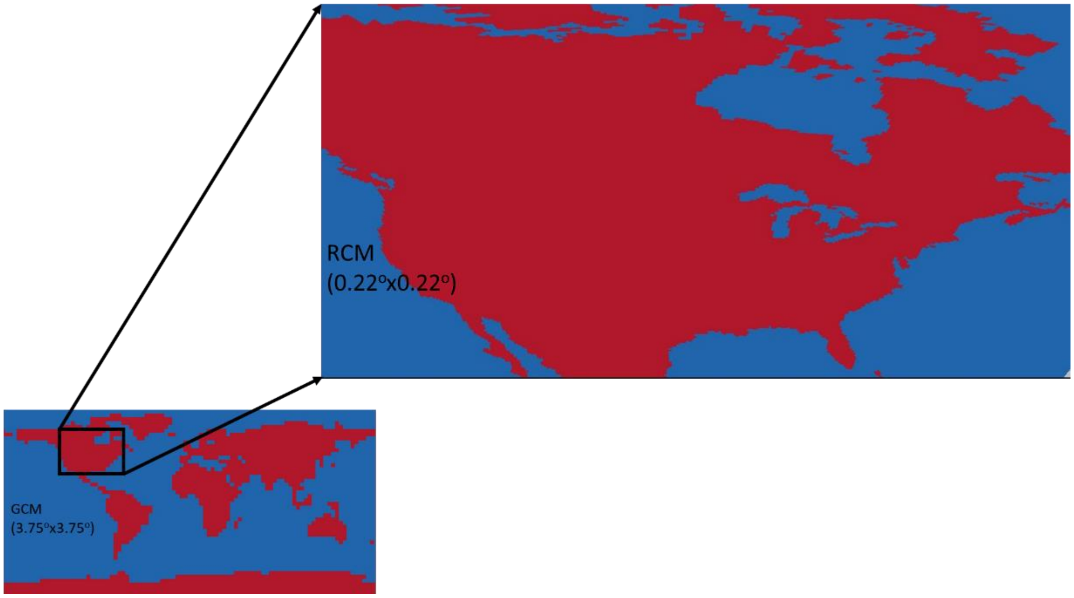


Figure 1: Land-sea masks for typical GCMs and RCMs used in this study.

Table 1: Details of the GCM-RCM combinations used in this study. For further details on these models refer to Giorgi, et al. (2009).

RCM	GCM	Scenario	Resolution	Lake model
CRCM5	CanESM2	RCP 4.5	0.22° X 0.22°	Flake
CRCM5	CanESM2	RCP 8.5	0.22° X 0.22°	Flake
CRCM5	CNRM-CM5	RCP 4.5	0.22° X 0.22°	Flake
CRCM5	CNRM-CM5	RCP 8.5	0.22° X 0.22°	Flake
CRCM5	GFDL-ESM2M	RCP 4.5	0.22° X 0.22°	Flake
CRCM5	GFDL-ESM2M	RCP 8.5	0.22° X 0.22°	Flake
CRCM5	MPI-ESM-LR	RCP 8.5	0.22° X 0.22°	Flake
CanRCM4	CanESM2	RCP 4.5	0.22° X 0.22°	None in RCM, prescribed from driving model
CanRCM4	CanESM2	RCP 8.5	0.22° X 0.22°	None in RCM, prescribed from driving model
RCA4	CanESM2	RCP 4.5	0.44° X 0.44°	Flake
RCA4	CanESM2	RCP 8.5	0.44° X 0.44°	Flake
RCA4	Earth_SMHI	RCP 4.5	0.44° X 0.44°	Flake
RCA4	Earth_SMHI	RCP 8.5	0.44° X 0.44°	Flake

3 Net Basin Supply

This study only examines the hydroclimate variables that are necessary for the simulation of lake levels. The lake level models used in section 4, utilize the hydroclimate information to calculate the lake levels, these models use the Net Basin Supply (NBS) for each lake as an input. There are two methods for calculating the NBS, component NBS (NBS_C) and residual NBS (NBS_R). The "component" method uses measurements and modelled estimates of the three main components of NBS, i.e., precipitation, runoff and evaporation; whereas the "residual" method calculates the NBS as the residual water necessary to account for the change in storage (i.e., monthly lake level change) and the measured amount of inflow and outflow from the lake via their connecting channels. Both approaches were used in this study and they are described in the following sections.

3.1 Component Net Basin Supply

The component NBS (NBS_C) consists of the summation of total precipitation on the lake surface (over-lake precipitation) and the runoff coming into the lake from the surrounding basin minus the evaporation coming off of the lake (over-lake evaporation).

$$NBS_C = P + R - E \qquad (1)$$

Where NBS_C – component NBS

P - over-lake precipitation

R – runoff entering the lake from the land surface

E – over-lake evaporation

For each lake, the precipitation, runoff, and evaporation were calculated independently and used for the NBS_C calculation. Since Lakes Michigan and Huron are hydraulically connected by the Straits of Mackinac, they will have the same water level and thus are considered one lake and, for the purposes of this study, will be referred to as Lake Michigan-Huron.

The over-lake precipitation is the amount of precipitation that falls on the surface of lake. Although this will generally be similar to the amount of precipitation on the area surrounding the lake, there can be differences based on wind patterns, local topography, and lake dynamics.

The runoff into each lake (referred to as simply runoff for the remainder of this report), is defined here as the summation of the water flowing into the lake from all the surrounding land area excluding from the river channel from the upstream lake if there is one. A majority of this incoming flow comes from the river network consisting of a combination of the direct overland flow, the sub-surface interflow, and the groundwater flow. To facilitate a direct comparison of the variables, the flow into each lake, typically expressed in units of cubic meters per second, was converted to an equivalent of mm of water over the surface of the lake based on the surface area of the lake.

The over-lake evaporation is the amount of evaporation coming from the lake surface. The seasonality of the lake evaporation is much different from the land surface as a result of the lake dynamics. For example, over-lake evaporation is also highly dependent on lake ice cover, which demonstrates the importance of having lakes models that include lake dynamics.

Both the over-lake precipitation and over-lake evaporation were taken directly from the CORDEX-NA dataset. However, the dataset only included runoff generated from each individual grid square throughout the Great Lakes basin. In order to calculate the NBS_C, the amount of runoff entering each lake is required.

In order to calculate the appropriate runoff into each lake at a monthly time scale, the land component runoff generated from each grid square must be routed down the river network to ensure proper timing of the runoff into the lake. Rather than relying on the land surface model of each of the different RCMs, this study used a widely implemented hydrological model WATFLOOD (Kouwen et al., 1993, Wijayarathne and Coulibaly, 2020) to calculate the runoff into each lake.

WATFLOOD is a semi-empirical physically based model that uses hourly temperature and precipitation as input to calculate the runoff from each grid into the river network. The runoff is separated into surface runoff, interflow and baseflow (which includes groundwater flow). The model has been successfully run over the Great Lakes for many years and a calibrated parameter set, as well as a method to calculate the runoff into each of the Great Lakes, already exists (Pietroniro et al, 2007). For this study, the raw temperature and precipitation was taken from the CORDEX-NA runs and used to calculate the flow of each of the rivers that flow into each of the lakes.

3.1.1 Historical comparison of NBS components

It is difficult to find historical datasets of the NBS components that specifically account for the lake areas of the Great Lakes. The dataset with the longest reliable record comes from the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) hydrometeorological database. This database consists of monthly values for over-lake and over-land precipitation and air temperature, runoff, and over-lake evaporation starting in 1950. The values are calculated using a combination of measured data taken across the entire basin and modelling. While the number of stations and the models used have evolved over time, every effort is made to keep the resulting data consistent throughout the time period. Details of how each of the parameters are derived can be found in Hunter et al. (2015).

The annual values for each component are presented in Figure 2 to Figure 13. The red dots show that there is a large variation in the annual over-lake precipitation, runoff, and over-lake evaporation. Such large variation makes it difficult to see overall trends in the data. Hence, in order to make it easier to identify these trends, the 10 year running average of the annual data is also shown.

There is a large annual variation in over-lake precipitation (Figures 2 to 5) where a very dry year can be followed immediately by a very wet year. Looking at the 10 year running average, the same general pattern is seen in all of the lakes with a low period in the 1960s and a period of higher over-lake precipitation throughout the 1970s and into the 1980s. From the mid-1980s into the 1990s there was an extended period of lower over-lake precipitation that gradually increased into the 2010s.

In Figure 6 to 9, the runoff coming into each lake has been converted to an equivalent of mm over the lake to allow for easier comparison to the other two components of the NBS. However, as a consequence of the smaller size of Lake Ontario relative to its drainage basin, this conversion results in much higher runoff values compared to the other lakes. Despite this, the scale of the graphs have been standardized between lakes and variables in order to allow for comparison.

As far as variations in the runoff (Figure 6 to Figure 9) are concerned, the patterns are not surprisingly very similar to the ones seen in over-lake precipitation with higher and lower patterns between decades. The variations in the over-lake evaporation (Figure 10 to Figure 13) are consistent with generally increasing decadal averages since the 1980s.

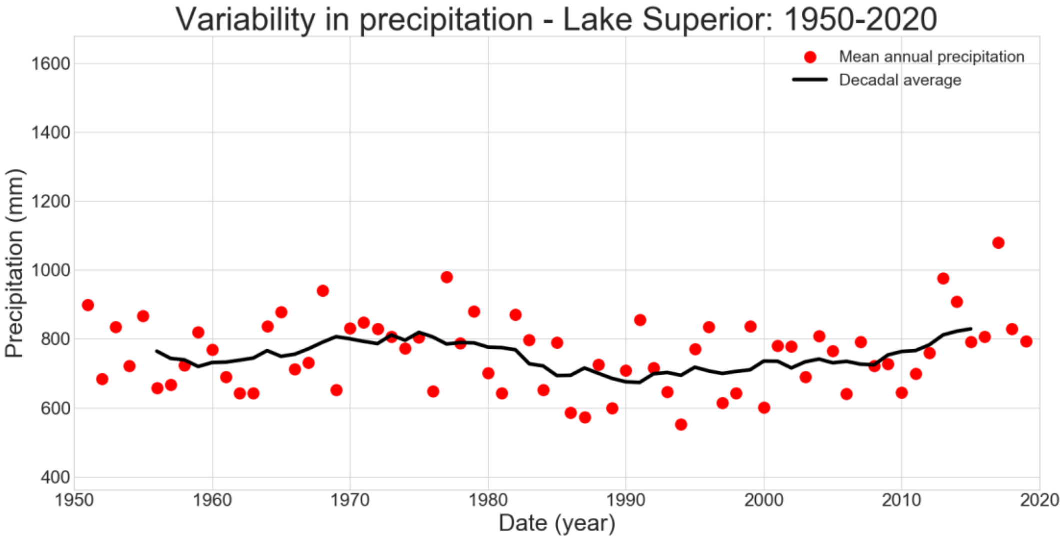


Figure 2: Variability in the annual over-lake precipitation for Lake Superior. Red dots are the annual values and the black line is the 10 year running average.

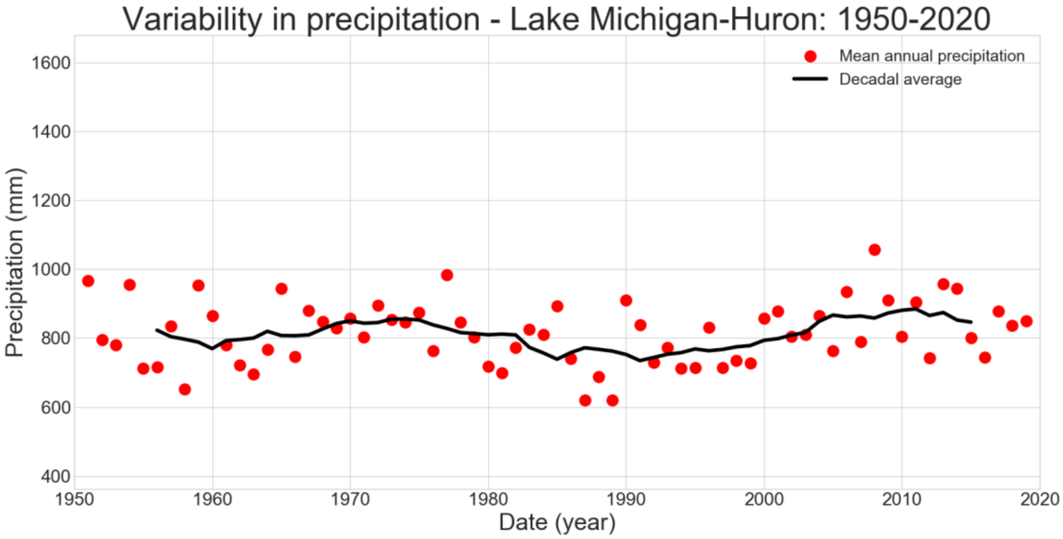


Figure 3: Variability in the annual over-lake precipitation for Lake Michigan-Huron. Red dots are the annual values and the black line is the 10 year running average.

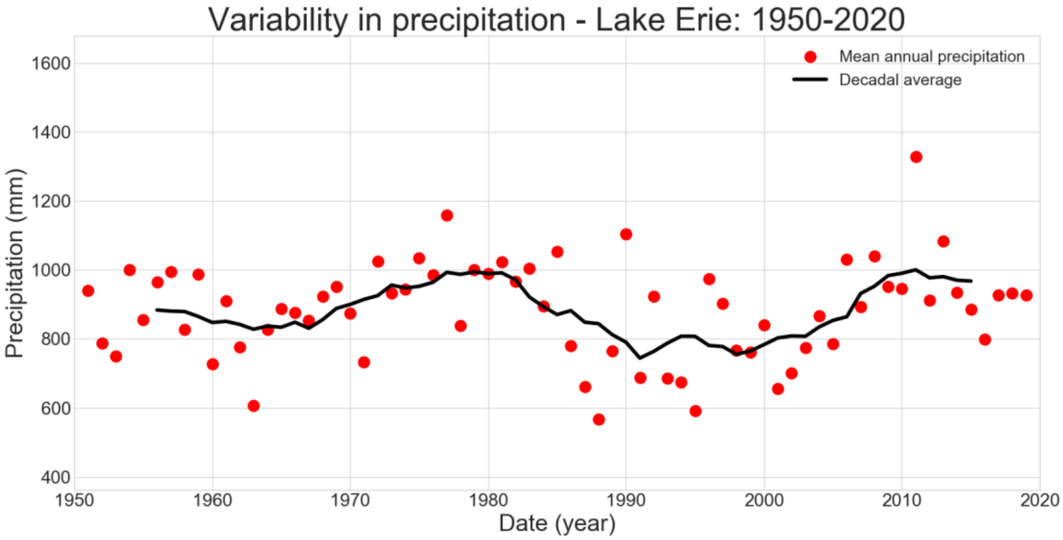


Figure 4: Variability in the annual over-lake precipitation for Lake Erie. Red dots are the annual values and the black line is the 10 year running average.

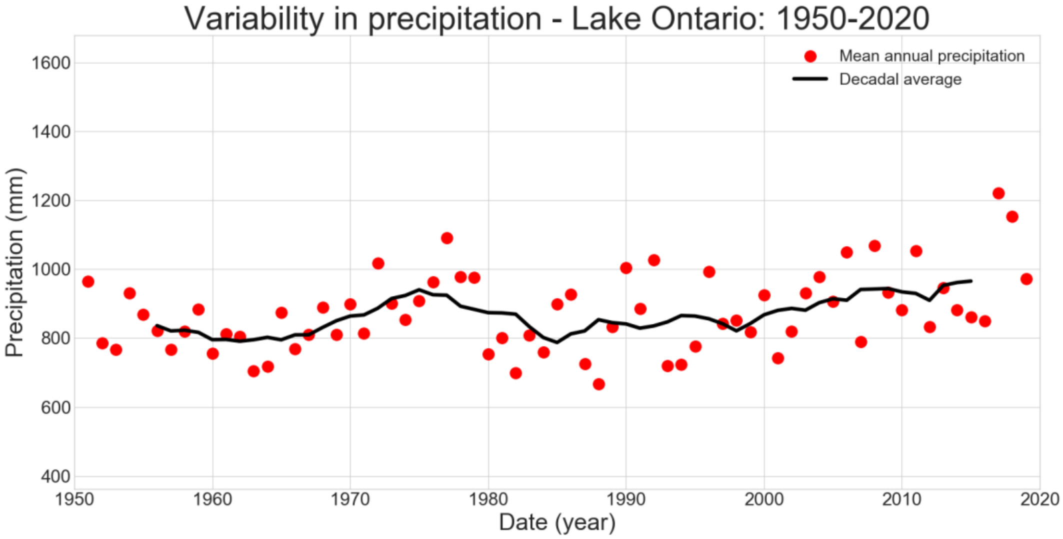


Figure 5: Variability in the annual over-lake precipitation for Lake Ontario. Red dots are the annual values and the black line is the 10 year running average.

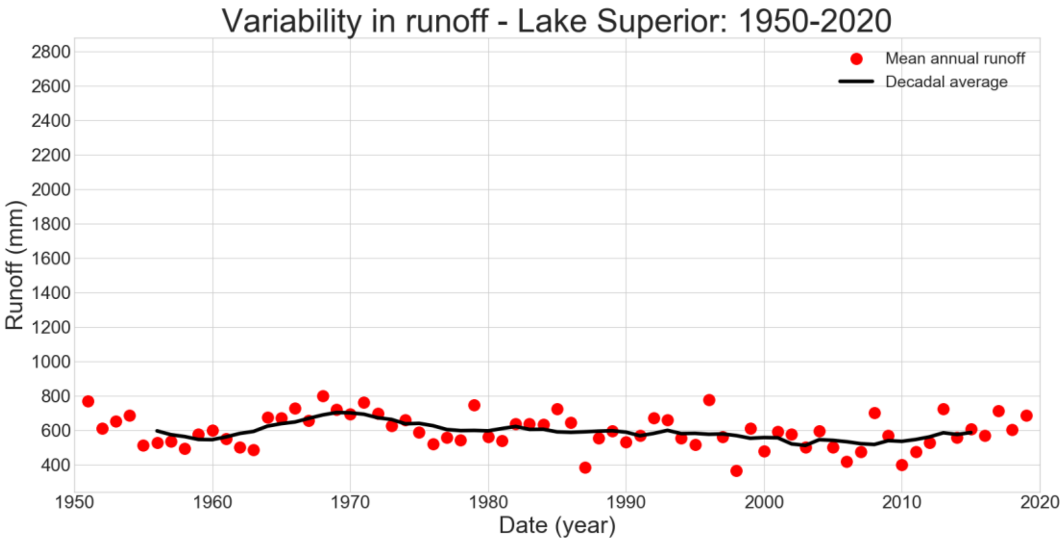


Figure 6: Variability in the annual runoff into Lake Superior. Red dots are the annual values and the black line is the 10 year running average.

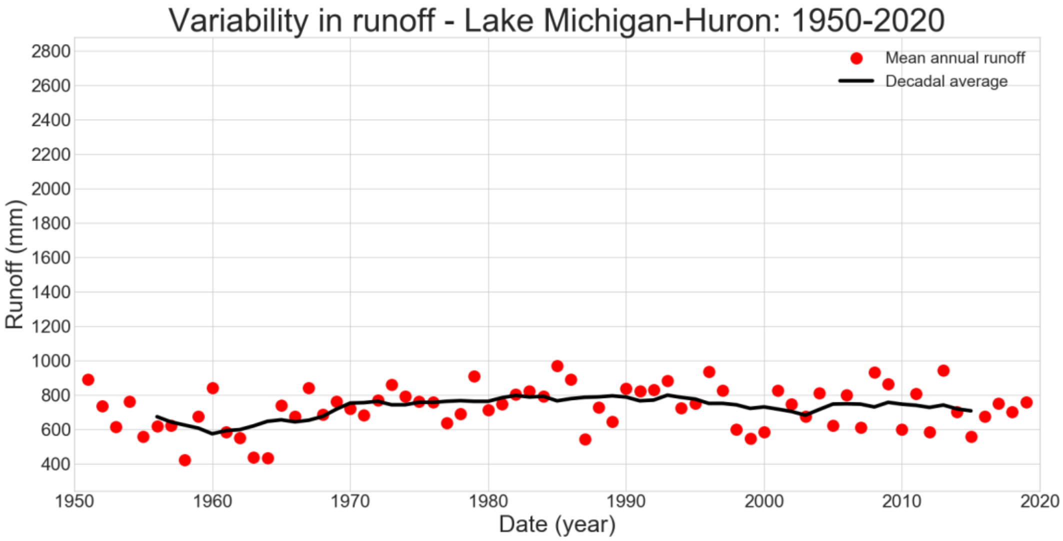


Figure 7: Variability in the annual runoff into Lake Michigan-Huron. Red dots are the annual values and the black line is the 10 year running average.

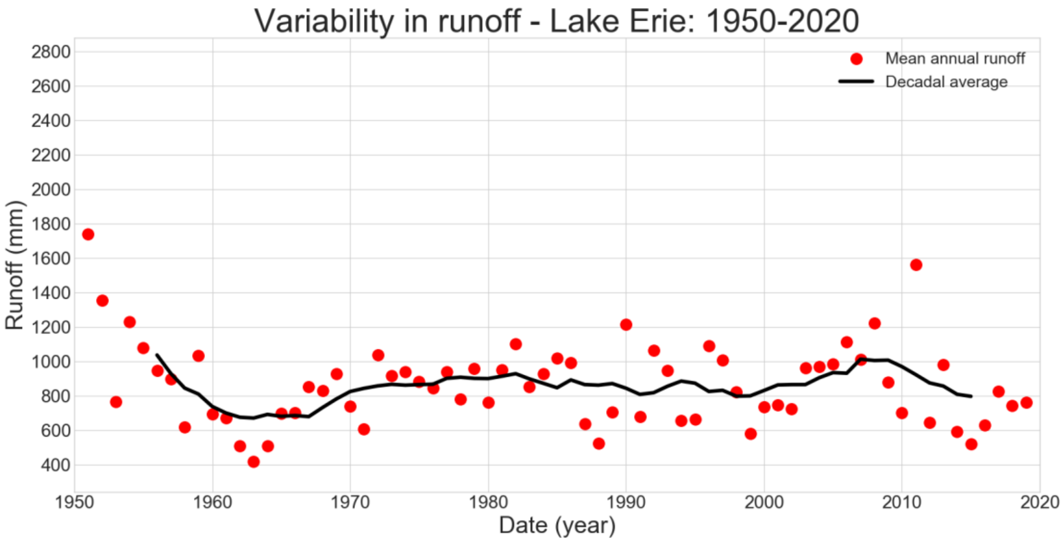


Figure 8: Variability in the annual runoff into Lake Erie. Red dots are the annual values and the black line is the 10 year running average.

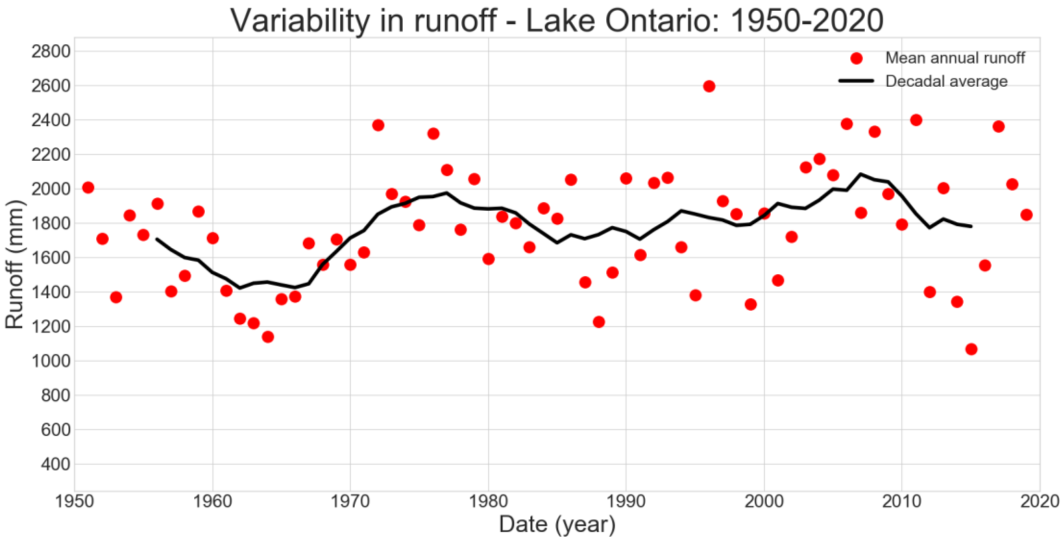


Figure 9: Variability in the annual runoff into Lake Ontario. Red dots are the annual values and the black line is the 10 year running average.

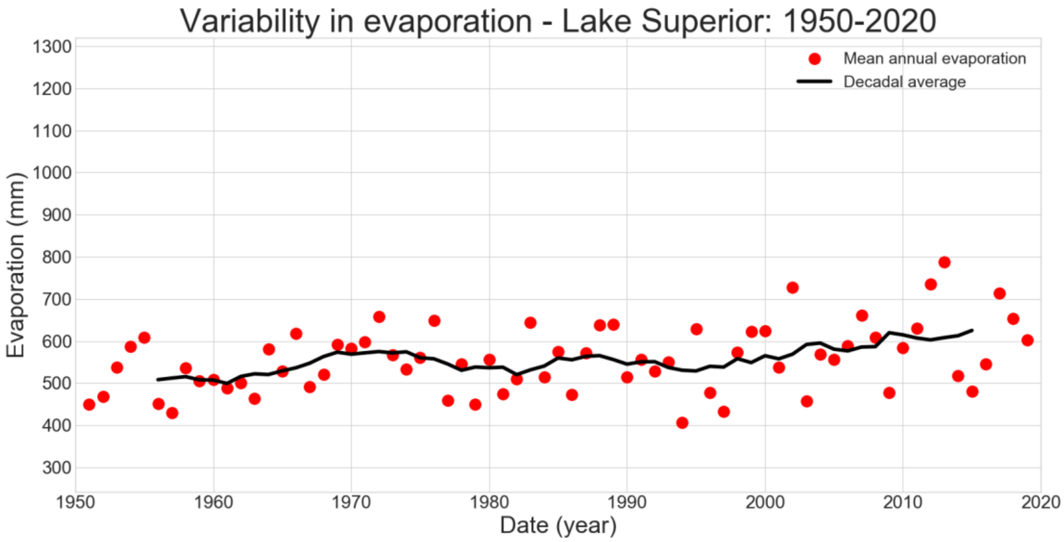


Figure 10: Variability in the annual over-lake evaporation for Lake Superior. Red dots are the annual values and the black line is the 10 year running average.

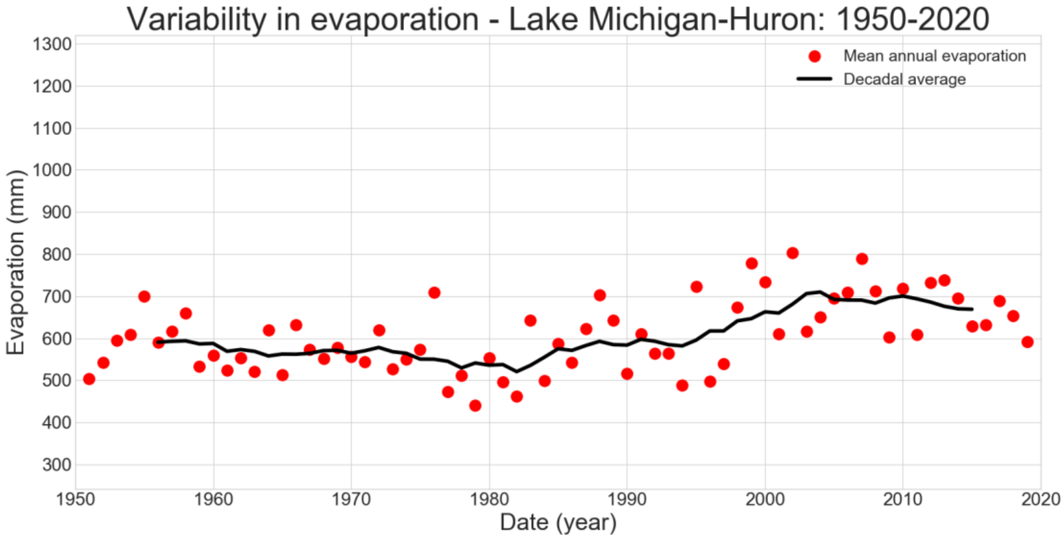


Figure 11: Variability in the annual over-lake evaporation for Lake Michigan-Huron. Red dots are the annual values and the black line is the 10 year running average.

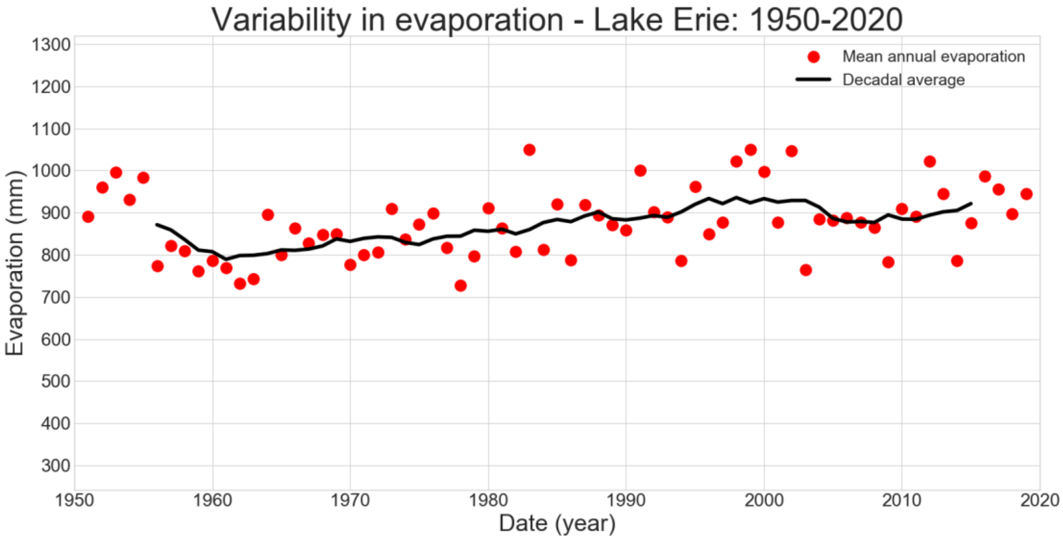


Figure 12: Variability in the annual over-lake evaporation for Lake Erie. Red dots are the annual values and the black line is the 10 year running average.

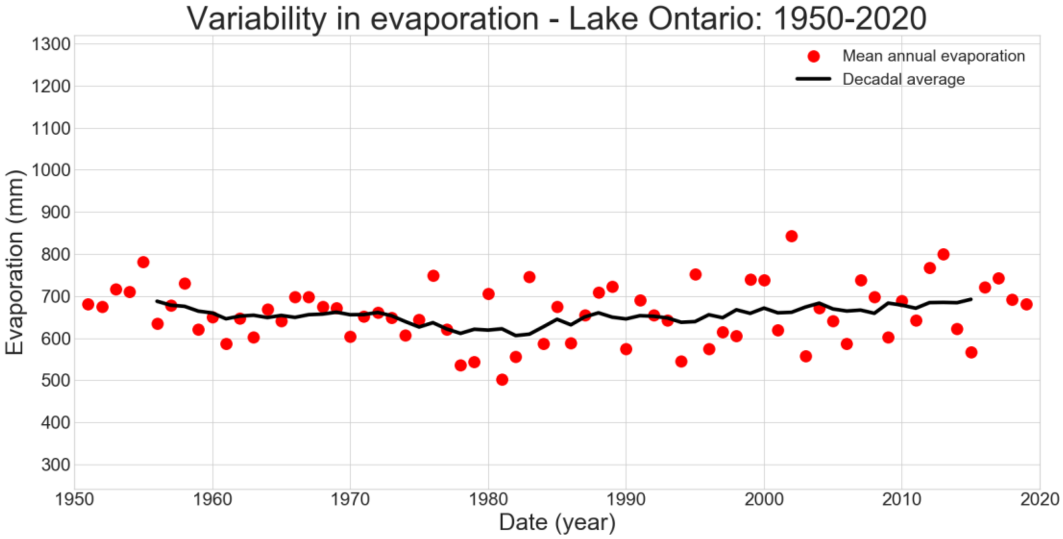


Figure 13: Variability in the annual over-lake evaporation for Lake Ontario. Red dots are the annual values and the black line is the 10 year running average.

A comparison was made of the NBS components from the GLERL Hydromet database and the current climate in the CORDEX runs. As stated earlier in section 3.1, over-lake precipitation and over-lake evaporation values were extracted from the CORDEX dataset, whereas the runoff were derived by running the WATFLOOD hydrological model, using the precipitation and temperature data from the CORDEX data set.

A direct comparison of the sequential monthly NBS component values from the CORDEX runs to the GLERL Hydromet database cannot be made. This is because the model simulations of the current climate represent possible climate outcomes that evolve differently than historical observations as result of differing initial conditions and the random nature of the climate system. Thus, the current climate comparison is made by averaging the NBS component values for each month in the 1961-2000 simulation and comparing them to the monthly average value in the GLERL Hydromet database.

For over-lake precipitation (Figure 14 to Figure 17), the RCM models did a reasonable job of representing the seasonal cycle as seen in the GLERL Hydromet database. However, all the models overestimate the over-lake precipitation, particularly for Lake Ontario.

In general, the RCM models failed to represent the seasonal variation of runoff seen in the GLERL Hydromet database (Figure 18 to Figure 21). The modelled runoff showed a delayed spring runoff peak and a slower decline to the fall and winter low flow. There are many possible causes of this poor representation, including the input data to the WATFLOOD model or the calibration of the WATFLOOD model. A full investigation was beyond the scope of this study but will be considered in the future.

The over-lake evaporation plots (Figure 22 to Figure 25) also illustrate the models' inability to capture the seasonal cycles. The RCM model simulations project higher over-lake evaporation values during the periods when the GLERL Hydromet database shows low over-lake evaporation. In particular, for Lake Erie (Figure 24), the models greatly underestimated the total over-lake evaporation. This is another avenue for possible directions of future study.

All the RCM models, in general, had difficulty representing the seasonal variation of runoff as well as over-lake evaporation for particular lakes. This demonstrates the need for the bias adjustment described in the next section.

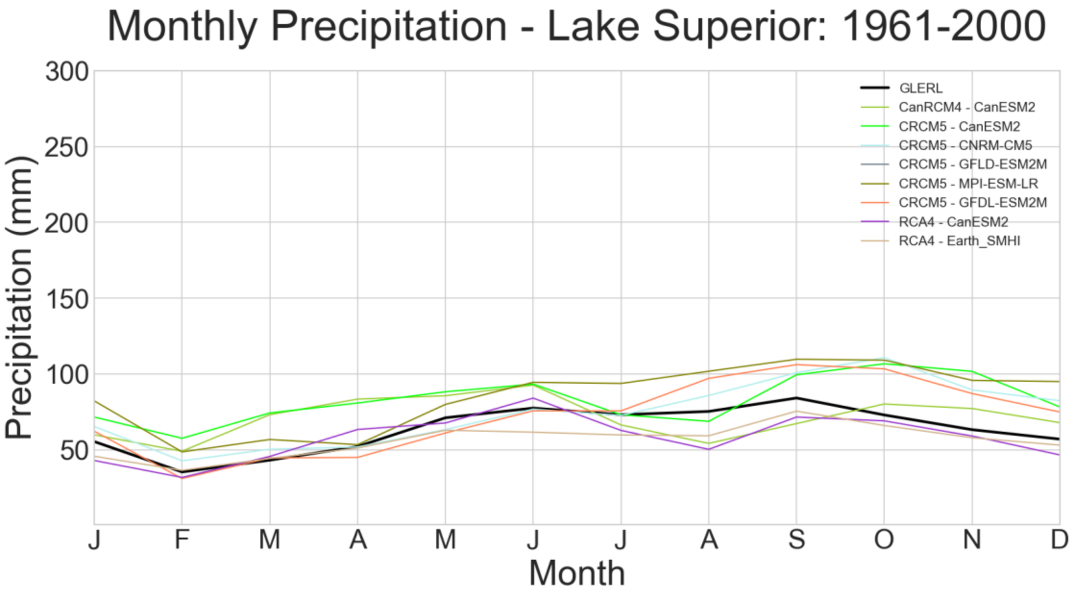


Figure 14: Comparison of monthly over-lake precipitation for Lake Superior using the GLERL hydromet database and the various RCM results for the current climate.

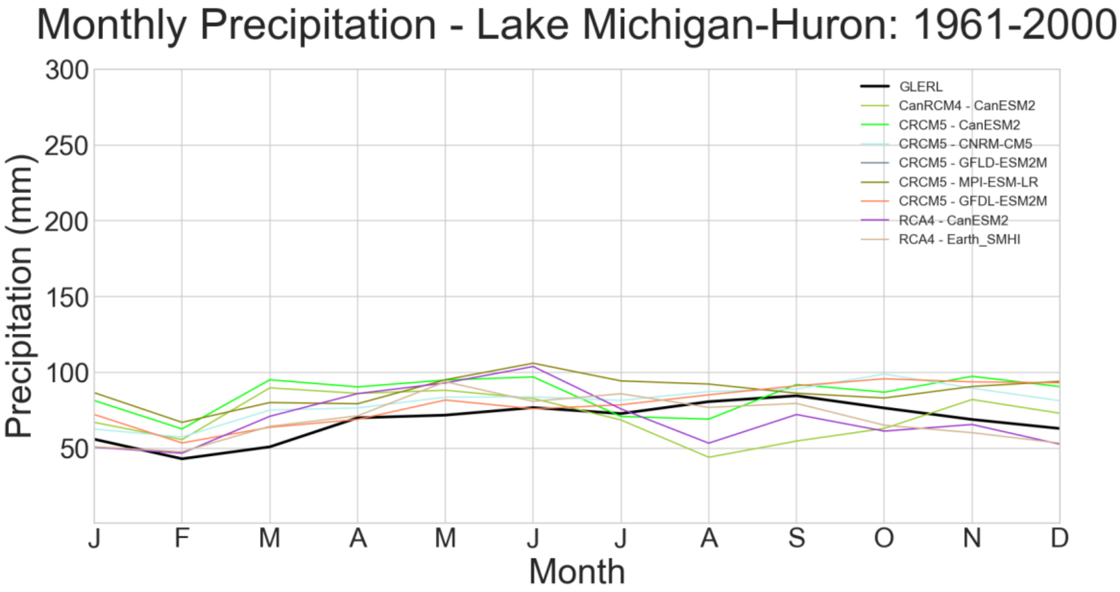


Figure 15: Comparison of monthly over-lake precipitation for Lake Michigan-Huron using the GLERL hydromet database and the various RCM results for the current climate.

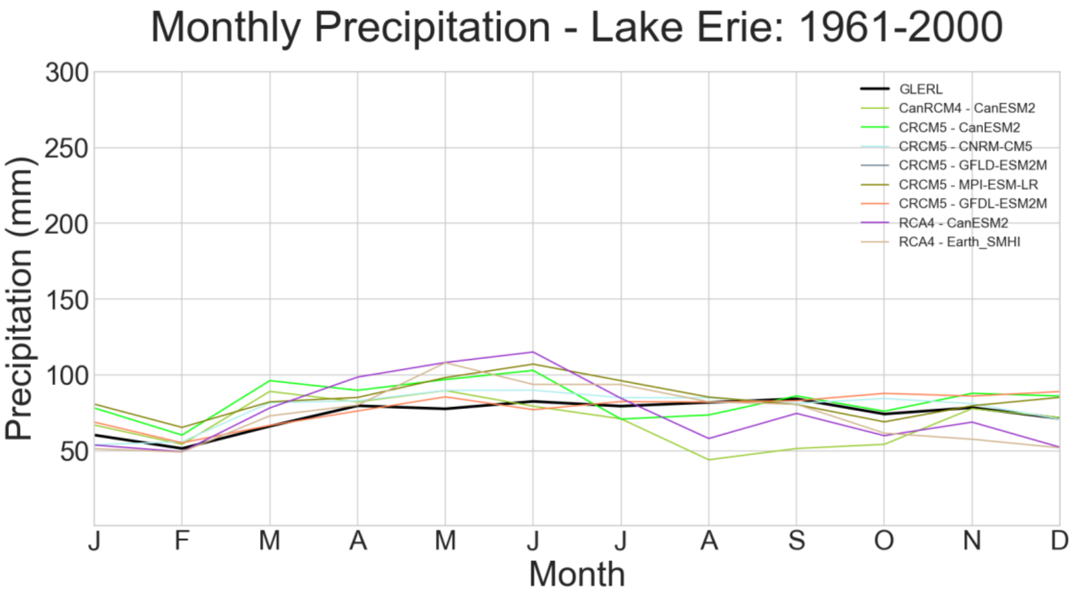


Figure 16: Comparison of monthly over-lake precipitation for Lake Erie using the GLERL hydromet database and the various RCM results for the current climate.

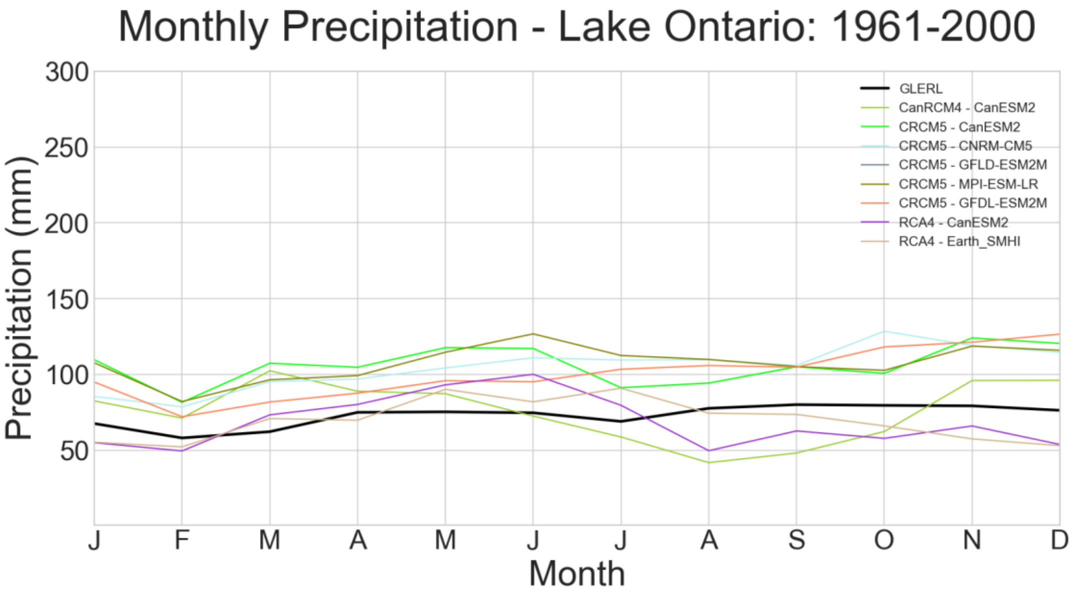


Figure 17: Comparison of monthly over-lake precipitation for Lake Ontario using the GLERL hydromet database and the various RCM results for the current climate.

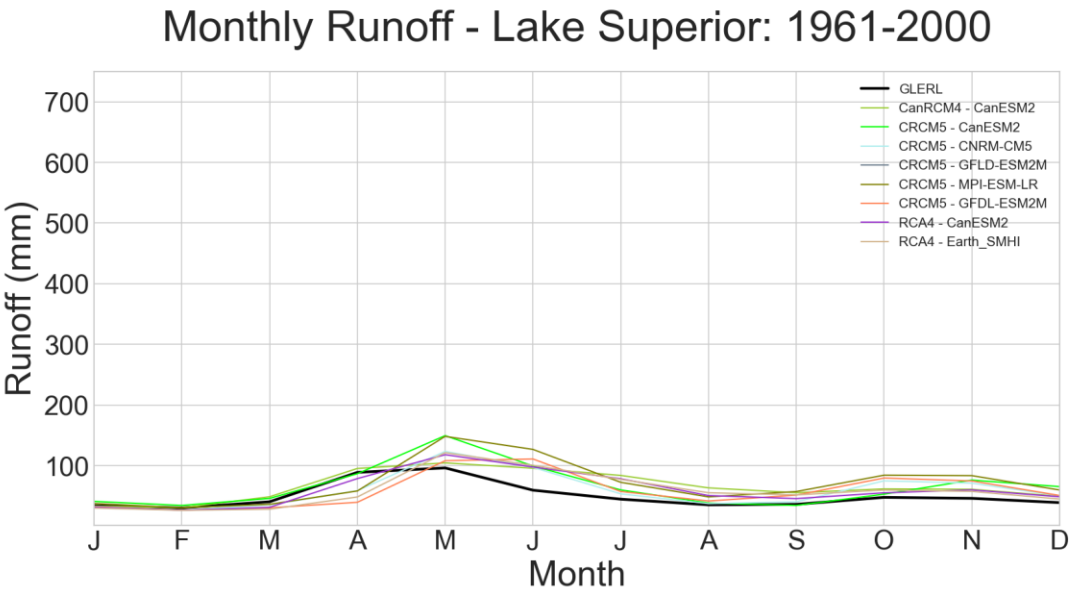


Figure 18: Comparison of monthly runoff into Lake Superior using the GLERL hydromet database and the various RCM results for the current climate.

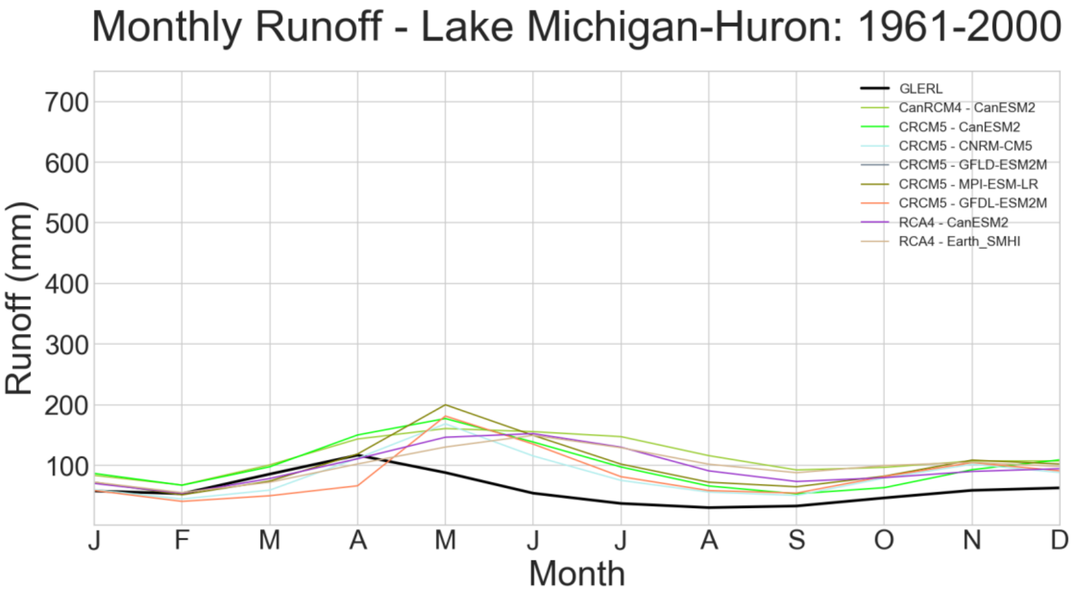


Figure 19: Comparison of monthly runoff into Lake Michigan-Huron using the GLERL hydromet database and the various RCM results for the current climate.

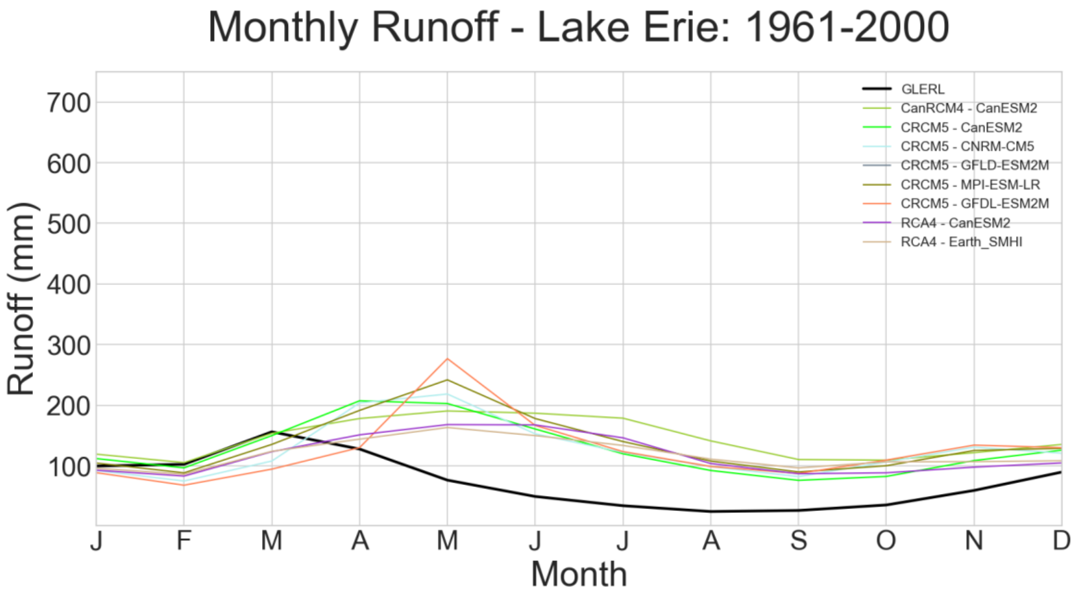


Figure 20: Comparison of monthly runoff into Lake Erie using the GLERL hydromet database and the various RCM results for the current climate.

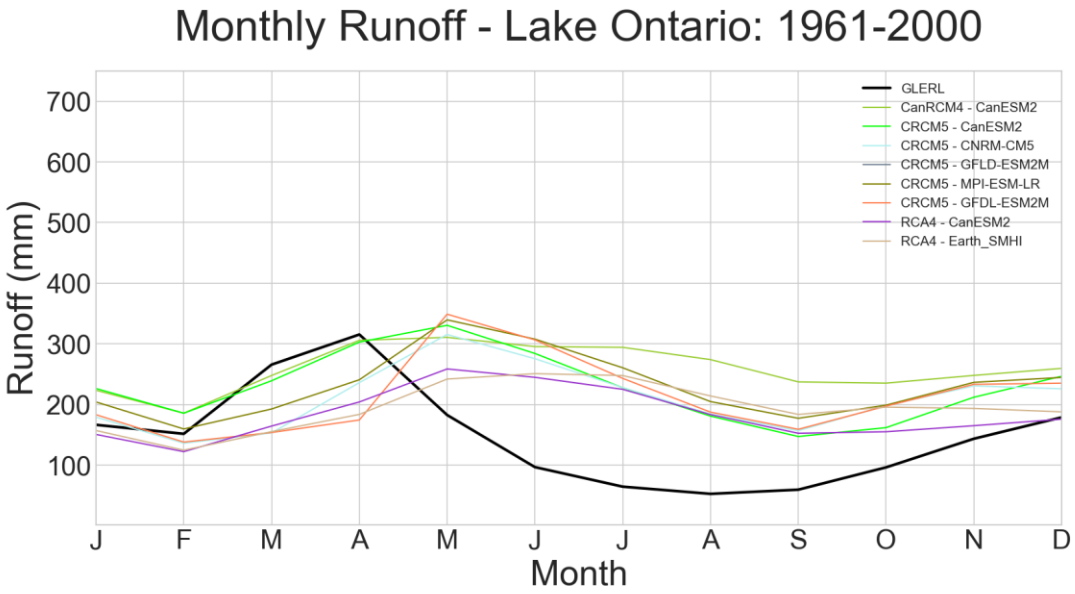


Figure 21: Comparison of monthly runoff into Lake Ontario using the GLERL hydromet database and the various RCM results for the current climate.

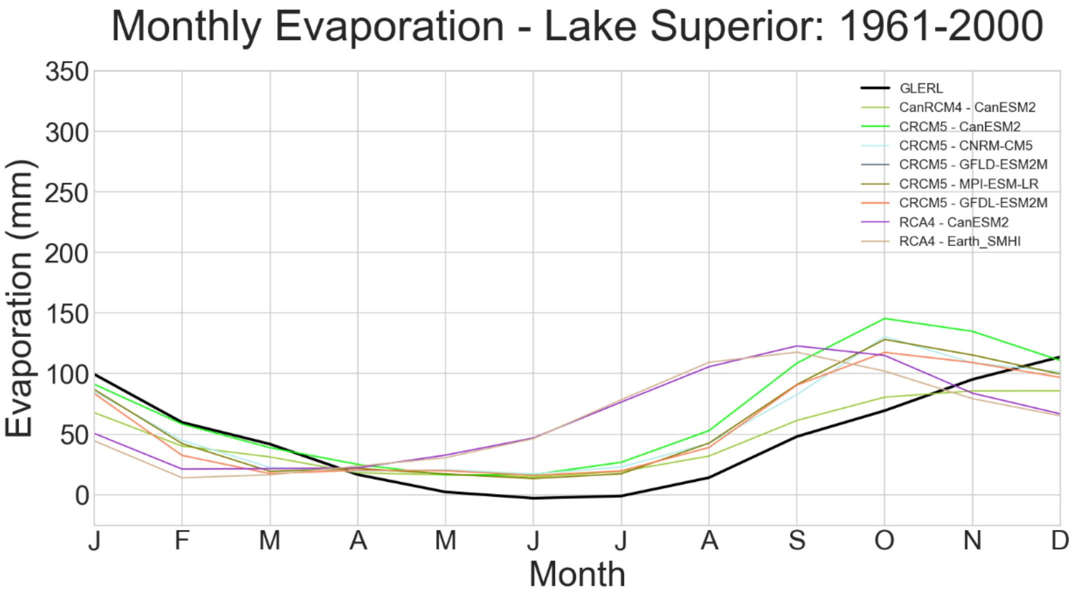


Figure 22: Comparison of monthly over-lake evaporation for Lake Superior using the GLERL hydromet database and the various RCM results for the current climate.

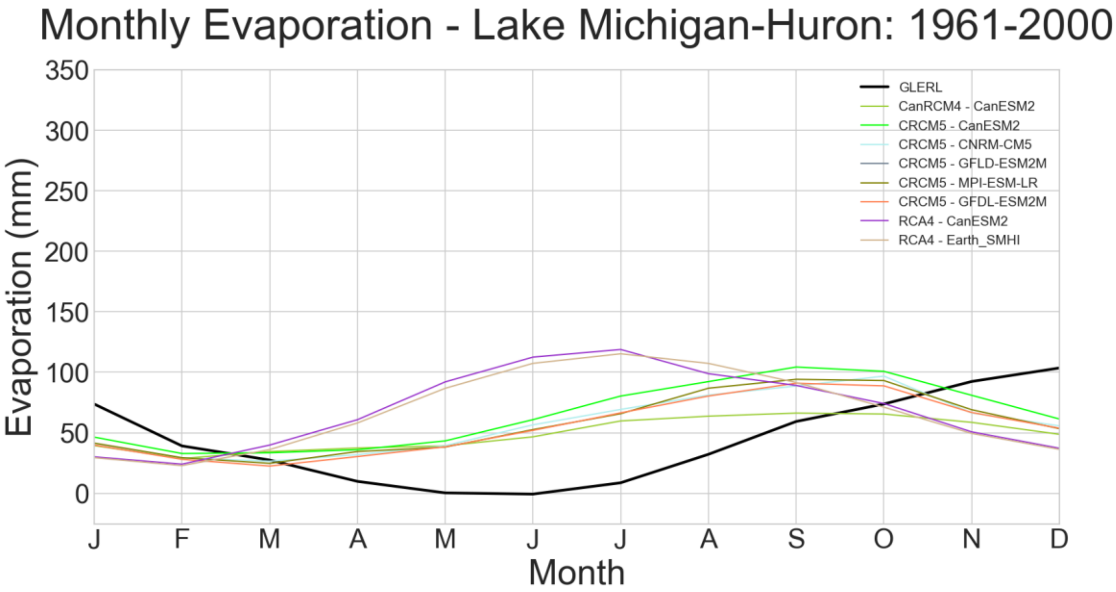


Figure 23: Comparison of monthly over-lake evaporation for Lake Michigan-Huron using the GLERL hydromet database and the various RCM results for the current climate.

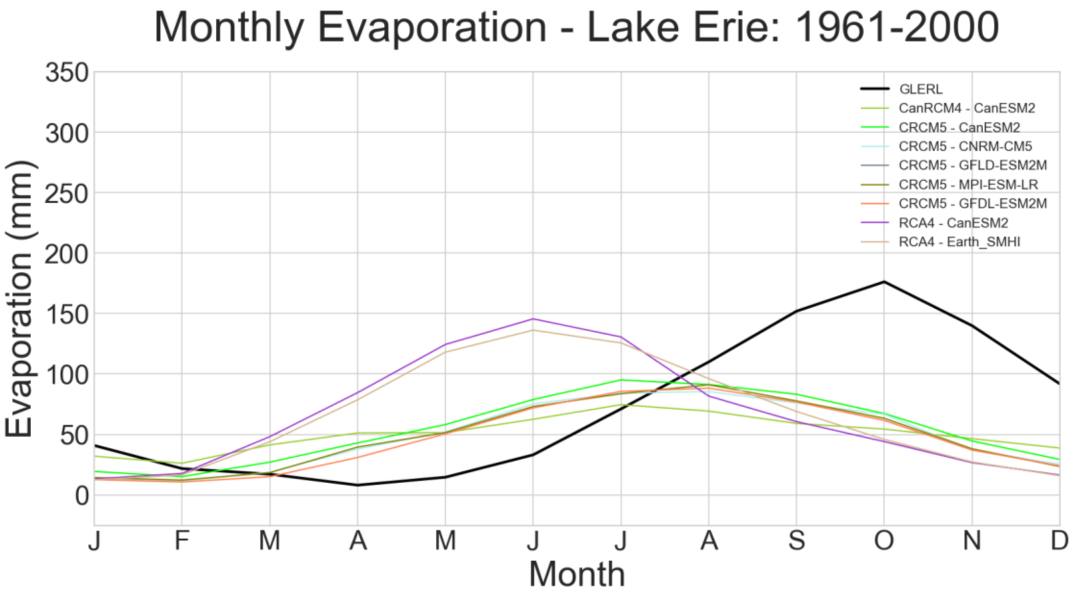


Figure 24: Comparison of monthly over-lake evaporation for Lake Erie using the GLERL hydromet database and the various RCM results for the current climate

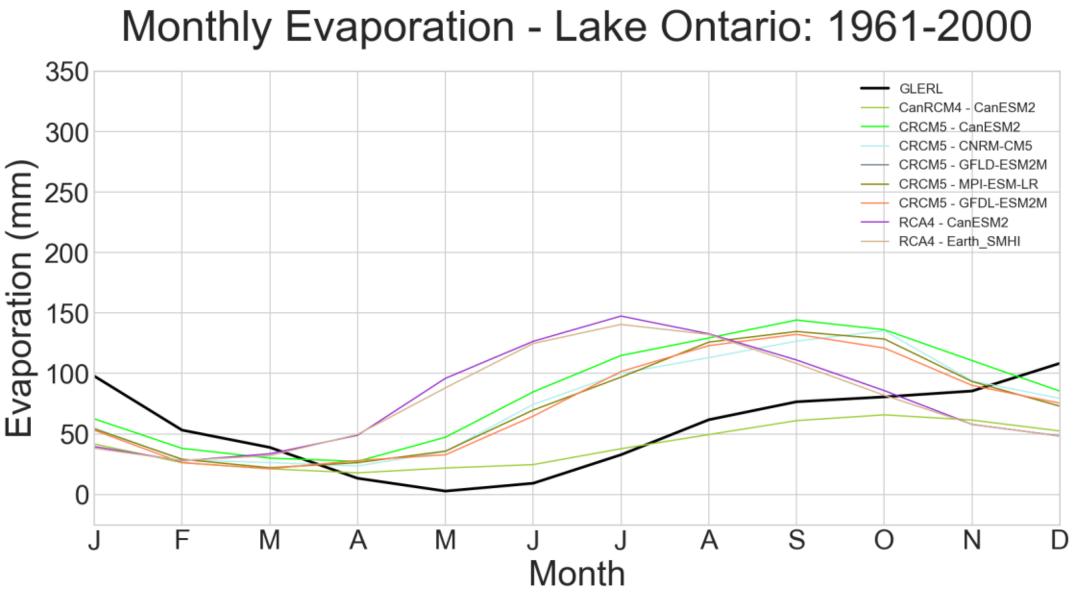


Figure 25: Comparison of monthly over-lake evaporation for Lake Ontario using the GLERL hydromet database and the various RCM results for the current climate.

3.1.2 Bias adjustment of the hydroclimate variables

As shown in the previous section, for some variables and some time periods, the RCM output does not have the same characteristics as current climate reference dataset. One of the reasons for this mismatch is the presence of non-negligible bias in RCM output. As suggested by Piani et al (2010), bias adjustment needs to be carried out in RCM output before using them for hydrological studies to obtain a more realistic output.

There are several bias adjustment techniques. A generally accepted practice is that the bias in the simulation of the current climate is assumed to be the same in the simulation of the future climate (Reichler and Kim, 2008). In this study, a multivariate bias adjustment function was used to perform the bias adjustment on the data on a monthly basis. This technique involves first choosing a reference period for which a variable has reliable measured or simulated values. The data from this reference period are then compared to the simulated values from the model for the current climate. Calculations are then made on this comparison that result in adjustments to the model output for the current climate so that they will more closely match the reference data. The same adjustments are then done to the model output for the future climate, resulting in the bias adjusted future dataset. Further details on this bias adjustment technique can be found in Cannon (2016).

All three components of the NBS_C were adjusted using the chosen bias adjustment technique using reference data from the GLERL hydromet database from the time period 1961-2000. This period captures both wet and dry conditions in the recent past while not overlapping with ramp-up periods used in the climate projections, which could have skewed the comparisons.

Figure 26 shows the bias adjustment for the 1961-2000 monthly precipitation for Lake Superior using the combination of the GCM: Max Planck Institute Earth System Model (MPI-ESM) and the RCM: Canadian Regional Climate Model, version 5 (CRCM5). The values from the GLERL database values are shown in orange and the raw results of the current climate simulations are shown in grey. It can be seen that the raw current climate simulations have overall higher values. The average for the GLERL database is 66.4 mm with a standard deviation of 28.2 mm while the simulations have an average of 84.4 mm and a standard deviation of 35.4 mm.

The bias adjusted values shown in blue match the GLERL reference data well. In general, these data better align with the reference data both in terms of magnitude and variation, with an average of 66.1 mm and a standard deviation of 27.2 mm in the bias adjusted dataset. The bias adjustment results were similar for other lakes and other NBS components.

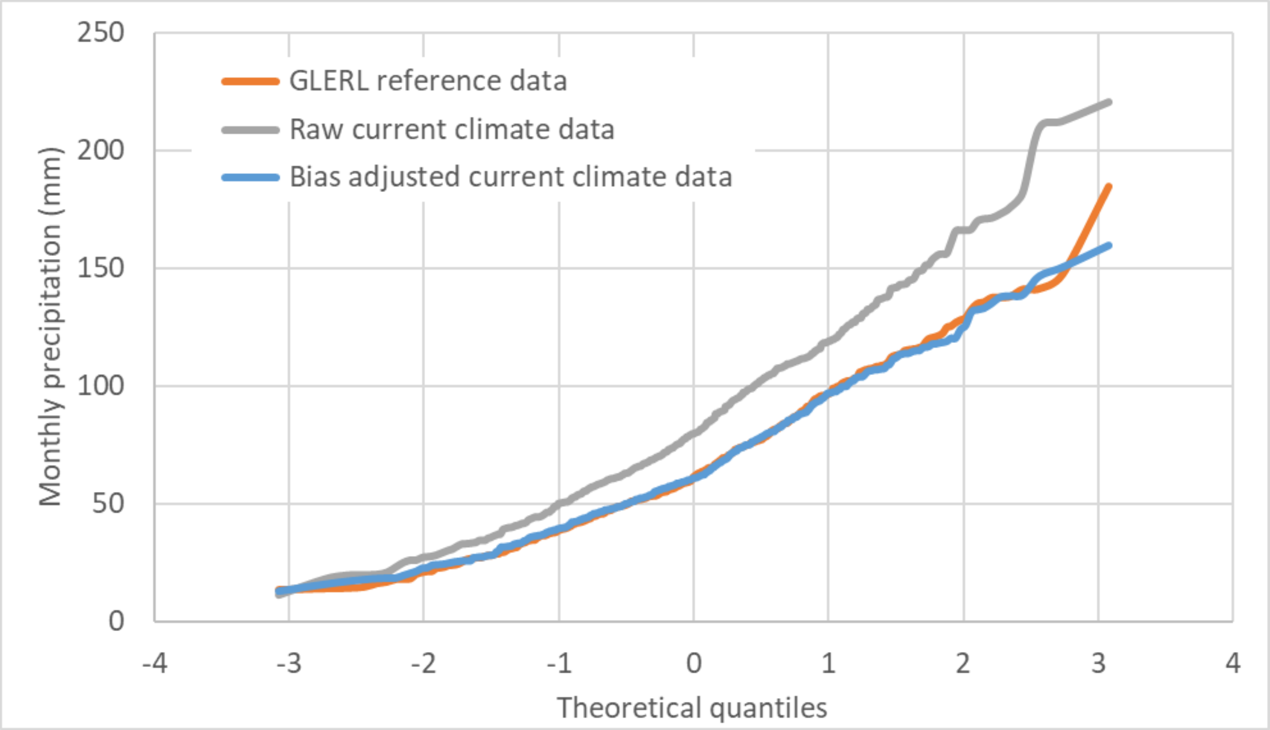


Figure 26: Quantile-quantile plot showing bias adjustment for the 1961-2000 monthly precipitation from the MPI-ESM GCM and the CRCM5 RCM.

For each individual dataset, the bias adjustment was done for the current climate, and then the same adjustment was applied for the future climate. This of course assumes that the bias observed in the current climate will be the same bias that would occur in the future climate. Although the validity of this assumption cannot be tested, it is a common procedure used in these types of studies (Christensen, 2008; Teutschbein and Seibert, 2012; Willkofer et al., 2018, Krinner et al., 2020). Consequently, the bias adjusted data are used to project future values of the hydroclimate variables, again with the assumption that the same biases would be carried forward into the future.

3.1.3 Projected future values of the hydroclimate components

To determine how the variation of the hydroclimate components in the future climate compare to the ones seen in the current climate, Figure 27 to Figure 38 show: the annual average from the GLERL Hydromet database for the current climate, the annual projected values for all of the

RCP4.5 and RCP8.5 runs, and the least squares liner fit for the RCP8.5 and RCP4.5 projected values.

For over-lake precipitation (Figure 27 to Figure 30), a majority of the future climate runs show an increasing average values in the future climate. The overall trend line shows that the RCP 8.5 runs consistently have a higher slope (and thus a great increase) than the RCP 4.5 runs. The range of the future climate projects are greater than those seen in the current climate, most of the expanded range is on the higher values, but some more extreme low values are also seen.

For the early to mid-century projections, the differences between the RCP 4.5 and RCP 8.5 are minimal. This results is expected, as the amount of greenhouse gases in the atmosphere is not that different between the pathways during these years. However, in the last 30 years of the century, the RCP 8.5 runs show higher over-lake precipitation values. In particular the CRCM5 runs using the MPI-ESM-LR and GFDL-ESM2M GCMs show much higher over-lake precipitation during this time period.

As runoff is principally driven by the precipitation dynamics, the same general patterns are seen in the future runoff data as they were in the over-lake precipitation (Figure 31 to Figure 34). The range of variation in the projected future climate is greater than that seen in the current climate database, particularly later in the century.

Over-lake evaporation show that the same general increasing trend seen in the current climate would persist in the future (Figure 35 to Figure 38). Interestingly, the trend seen in the "business as usual" RCP 8.5 pathway seems to continue the actual trend seen over the past decades, while the RCP 4.5 pathway reduces the slope of the increase.

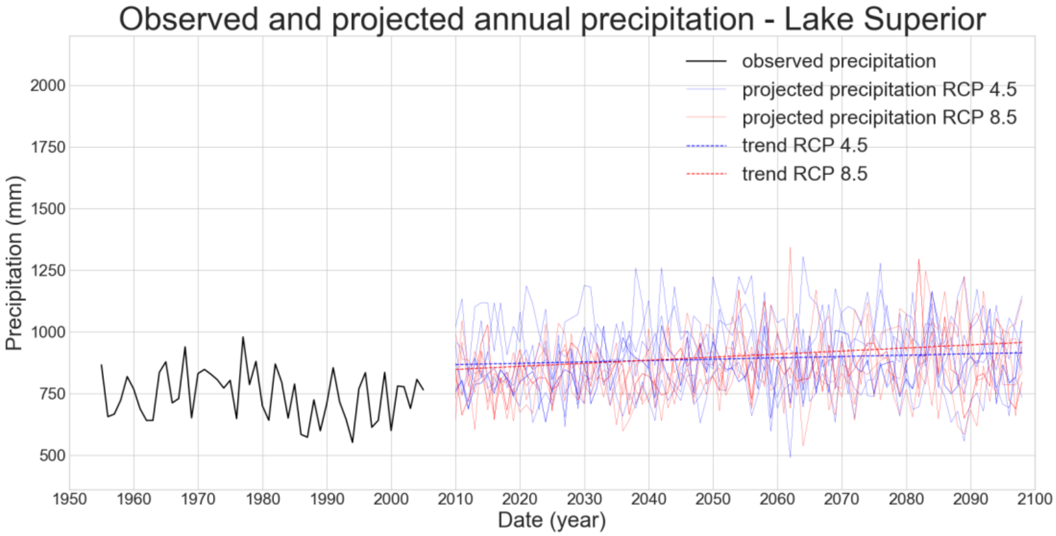


Figure 27: Variability in the bias adjusted annual over-lake precipitation for Lake Superior, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

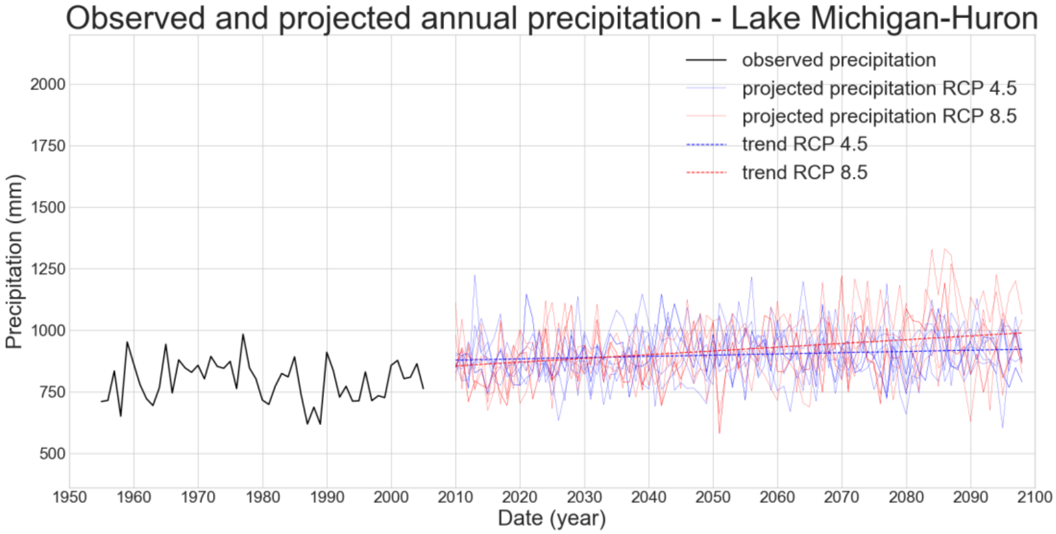


Figure 28: Variability in the bias adjusted annual over-lake precipitation for Lake Michigan-Huron, , black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

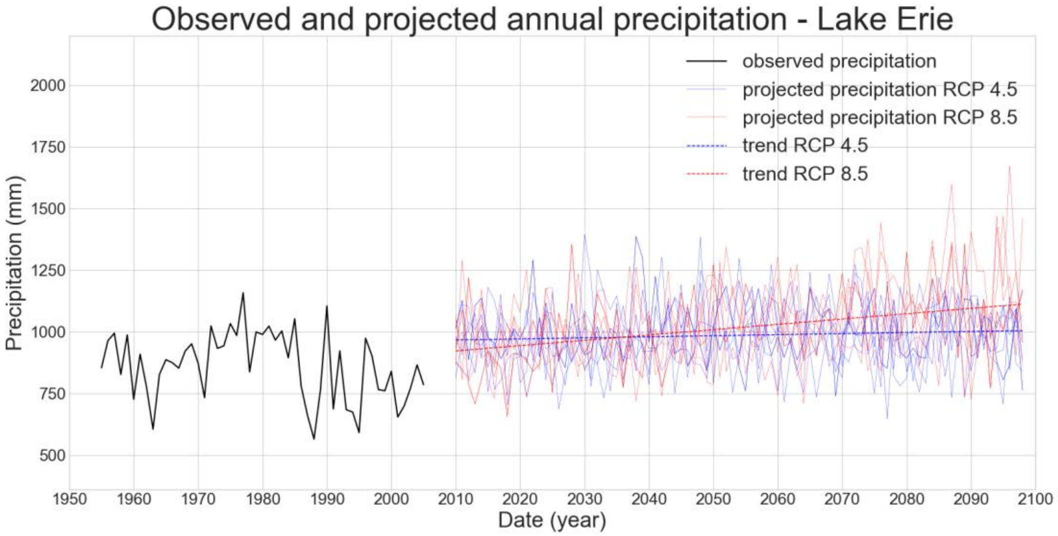


Figure 29: Variability in the bias adjusted annual over-lake precipitation for Lake Erie, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

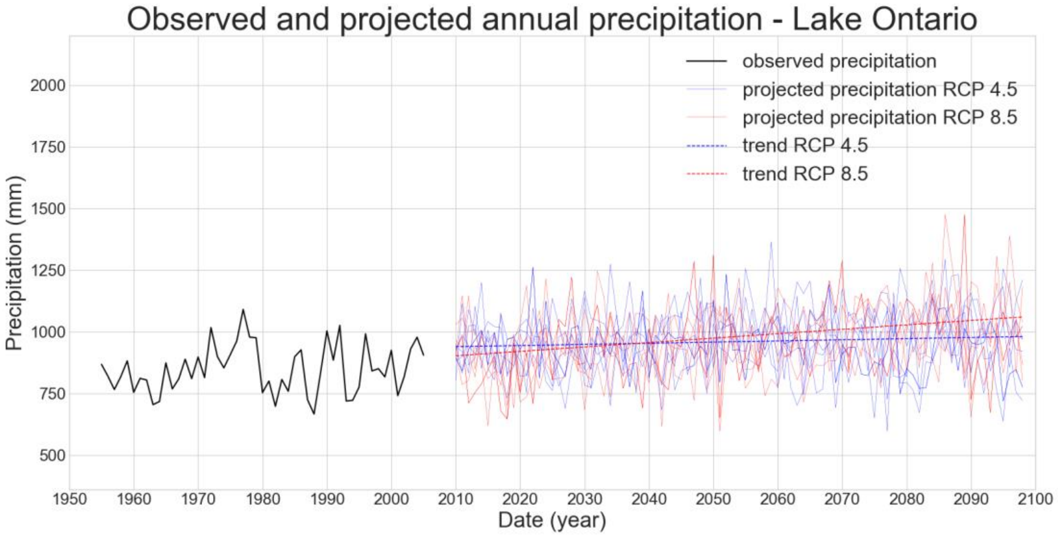


Figure 30: Variability in the bias adjusted annual over-lake precipitation for Lake Ontario, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

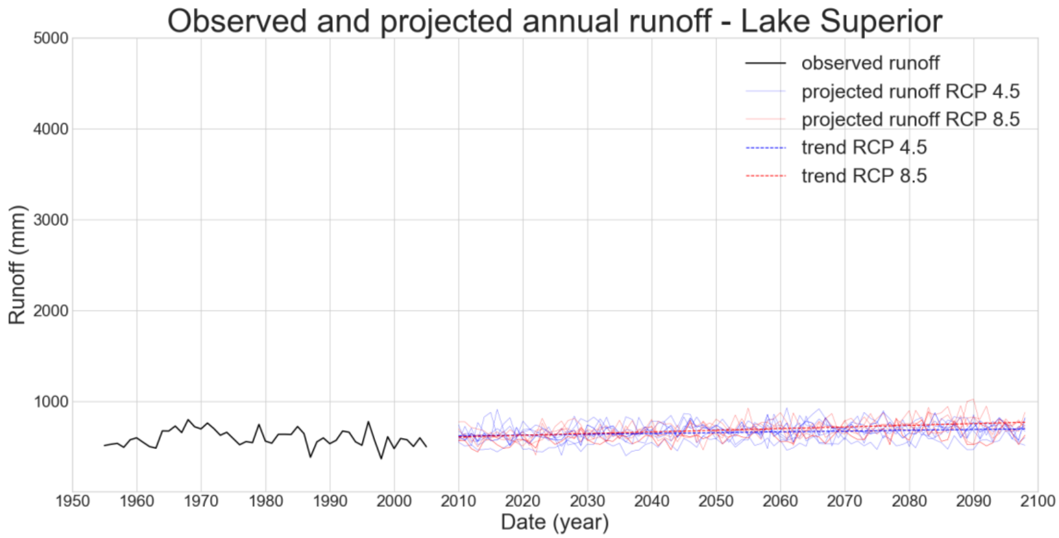


Figure 31: Variability in the bias adjusted annual runoff into Lake Superior, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

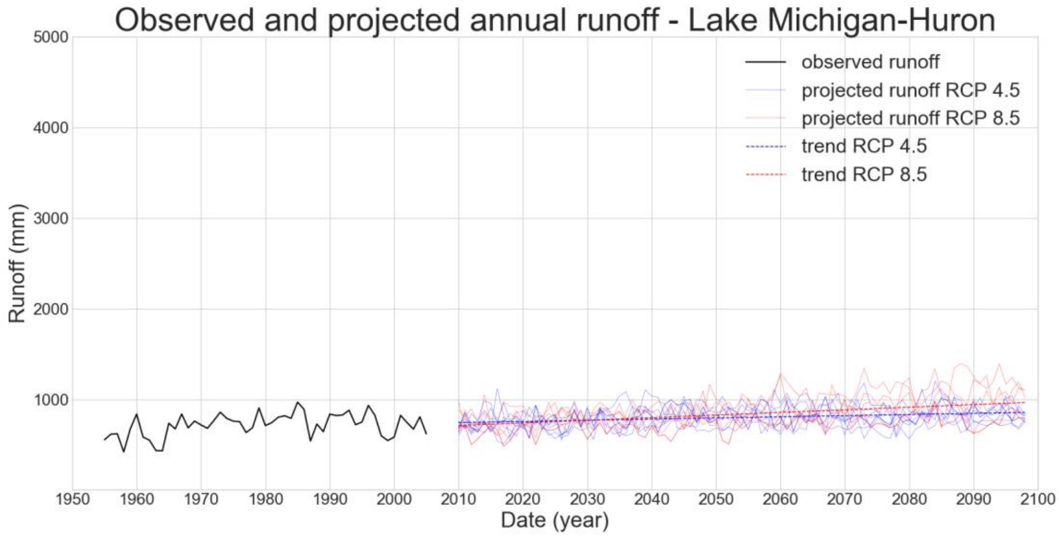


Figure 32: Variability in the bias adjusted annual runoff into Lake Michigan-Huron, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

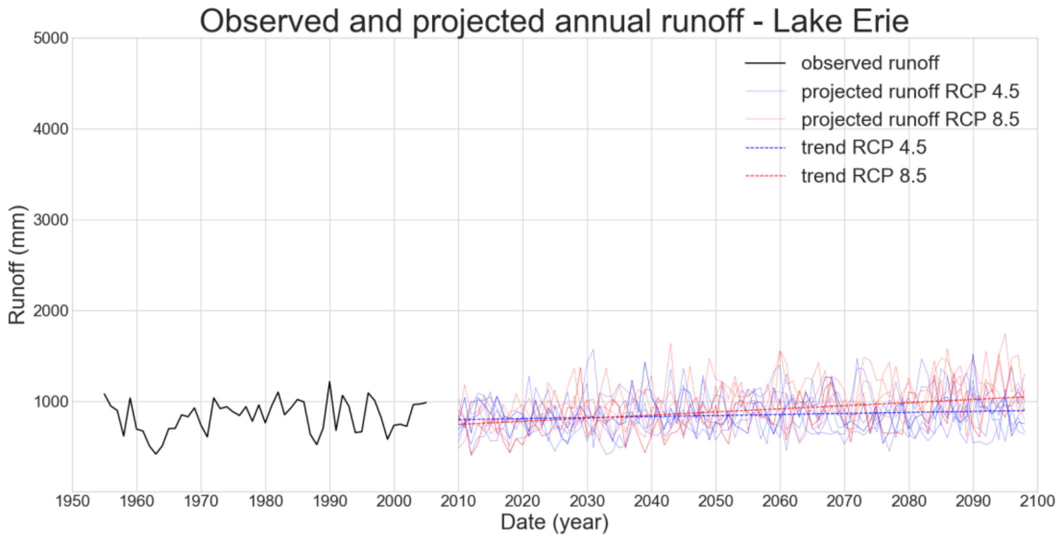


Figure 33: Variability in the bias adjusted annual runoff into Lake Erie, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

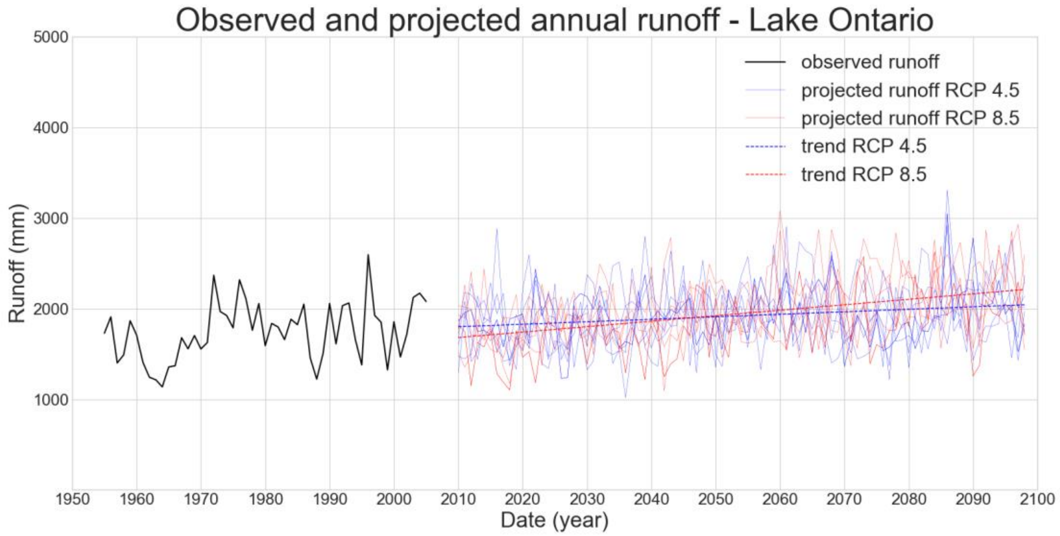


Figure 34: Variability in the bias adjusted annual runoff into Lake Ontario, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

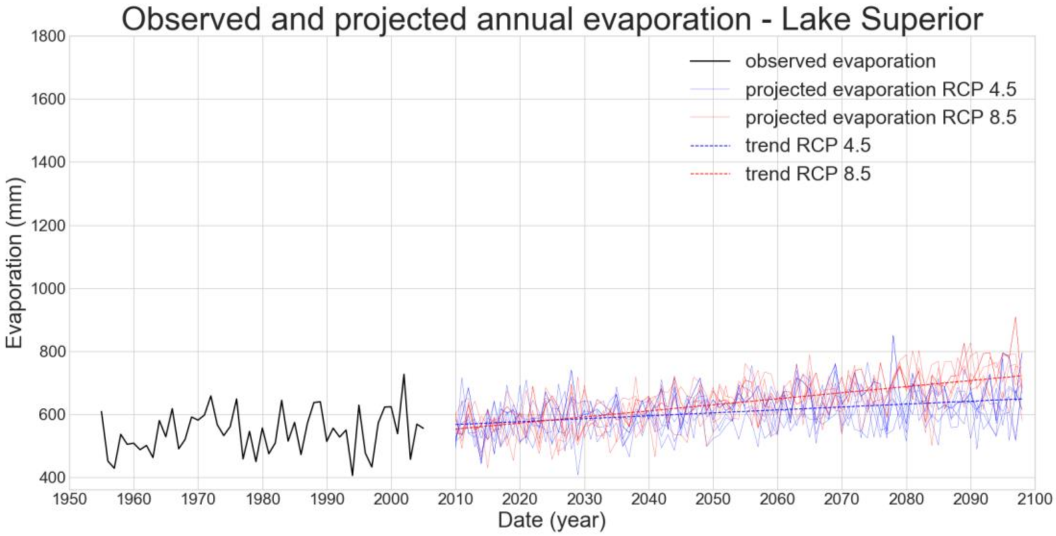


Figure 35: Variability in the bias adjusted annual over-lake evaporation for Lake Superior, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

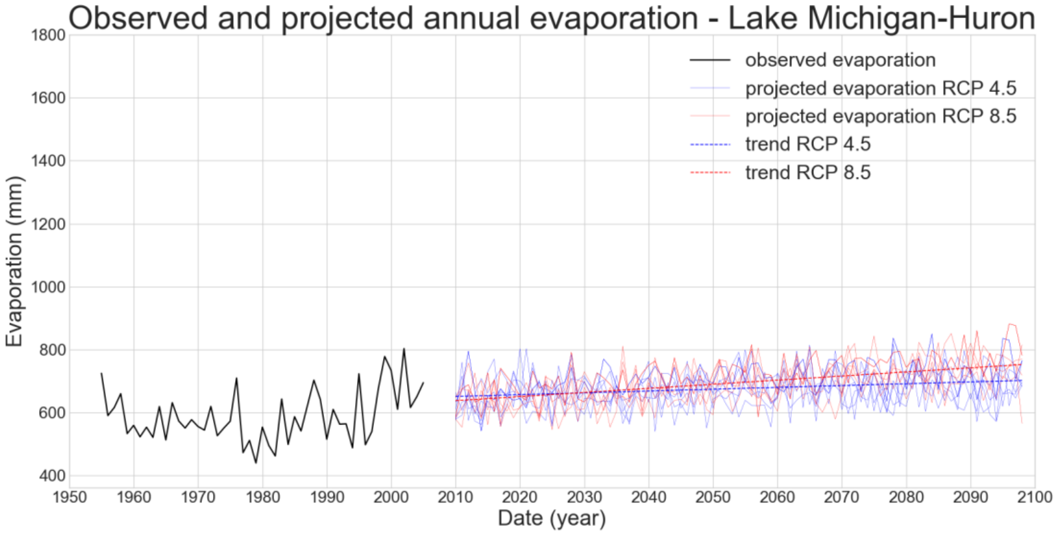


Figure 36: Variability in the bias adjusted annual over-lake evaporation for Lake Michigan-Huron, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

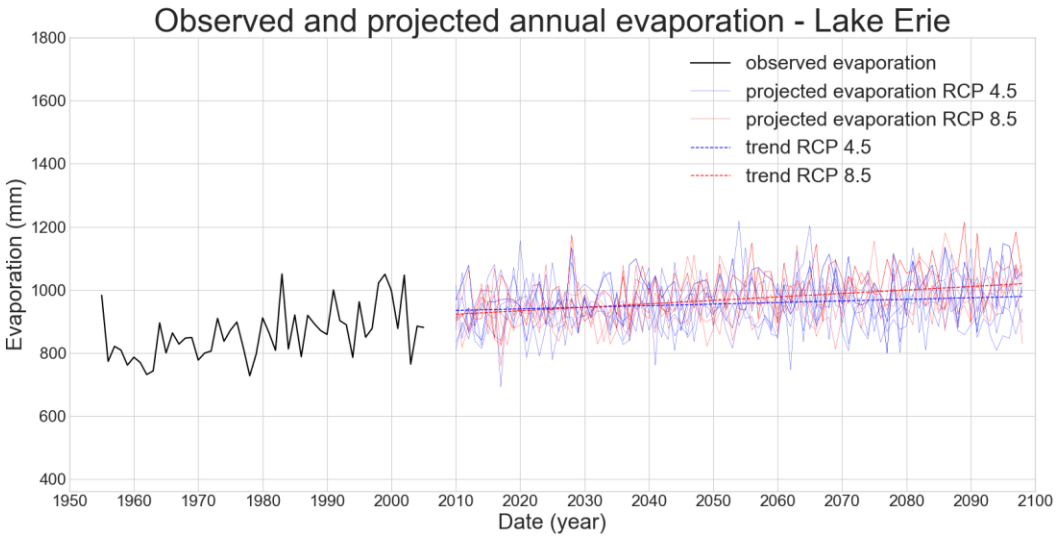


Figure 37: Variability in the bias adjusted annual over-lake evaporation for Lake Erie, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

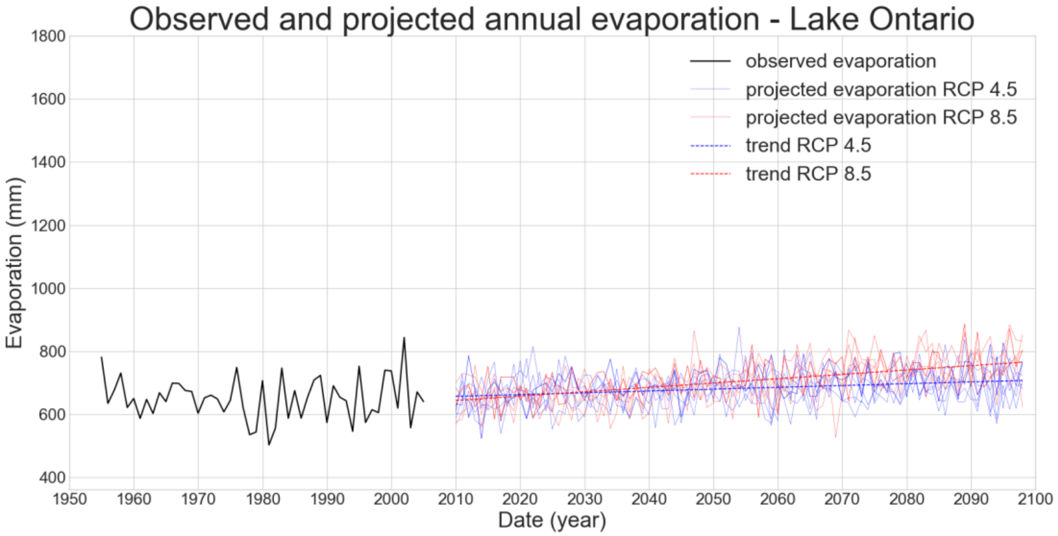


Figure 38: Variability in the bias adjusted annual over-lake evaporation for Lake Ontario, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

Examining only annual values can mask some of the future seasonal trends in the hydroclimate variables. The next series of figures show the monthly anomalies of the NBS components for 2050 time slice (2036-2065) with respect to the current climate reference period. For brevity, only the figures for Lake Michigan-Huron are shown here, the full set of figures for all the lakes are presented in Appendix A.

The time slice calculation was done by taking the average projected value for a month of a component in the future climate (for example over-lake precipitation for January 2050) and comparing it to the average of the current climate for that month (in this example the average of the over-lake precipitation for all the Januaries from 1961-2000). This results in a single anomaly value, this is then repeated for all the years in the period under examination (all the Januaries in the 2036-2065 time period in this example).

For Lake Michigan-Huron precipitation (Figure 39), positive anomalies (ie. more precipitation in the future climate) are seen in the spring while for the other lakes positive anomalies are concentrated in the early fall and winter. It should also be noted that although the annual trend in over-lake precipitation is higher for future values, there are some months (particularly in the late spring and early summer) where there is either no change or even a slight decrease.

For runoff (Figure 40), an increase in the winter and early spring period is expected. Such an increase is most likely as a result of increased precipitation during the winter as well as higher temperatures that result in more rain on snow events. This also results in lower spring runoff as these factors also reduce the spring snowpack. In all the lakes, the runoff during the summer and early fall show very minimal change.

As over-lake evaporation (Figure 41) is generally concentrated in the fall and winter, depending on the lake, it is not surprising that these are also times of year when the highest values of the anomalies are seen in the future.

Although there were small variations between the lakes, the RCP pathways, and the time slices, the results for the other lakes were similar to the graphs that are shown. The full set of seasonal anomalies are shows in Appendix A.

The results presented in this section show that the range of the NBS components is projected to increase under the future climate projections. But, although it is important to understand how each hydroclimate component might be changing into the future, in order to calculate water levels, the net basin supply (NBS) to each lake is required.

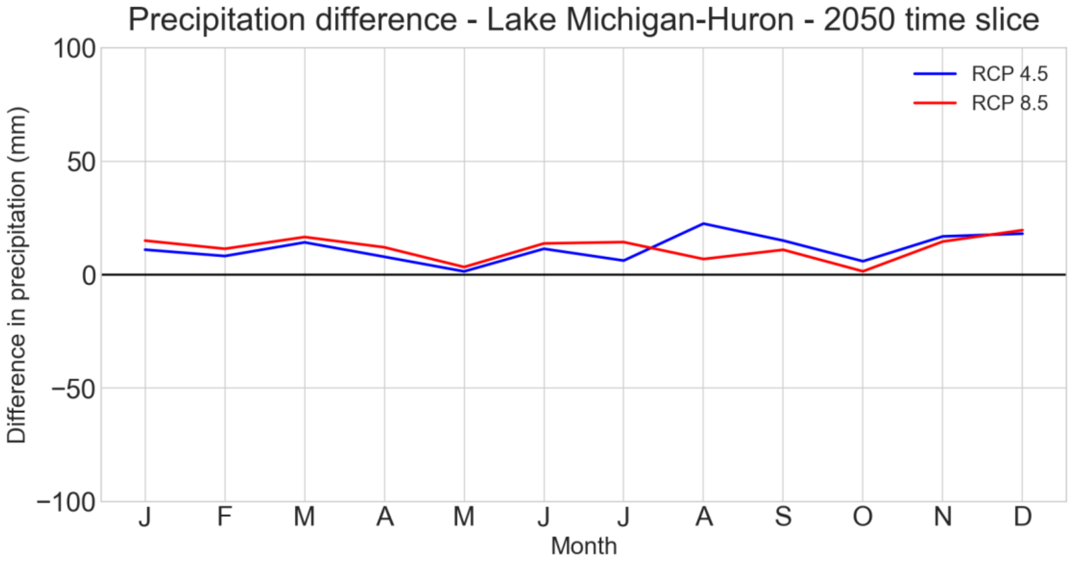


Figure 39: Monthly anomalies of precipitation between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Michigan-Huron.

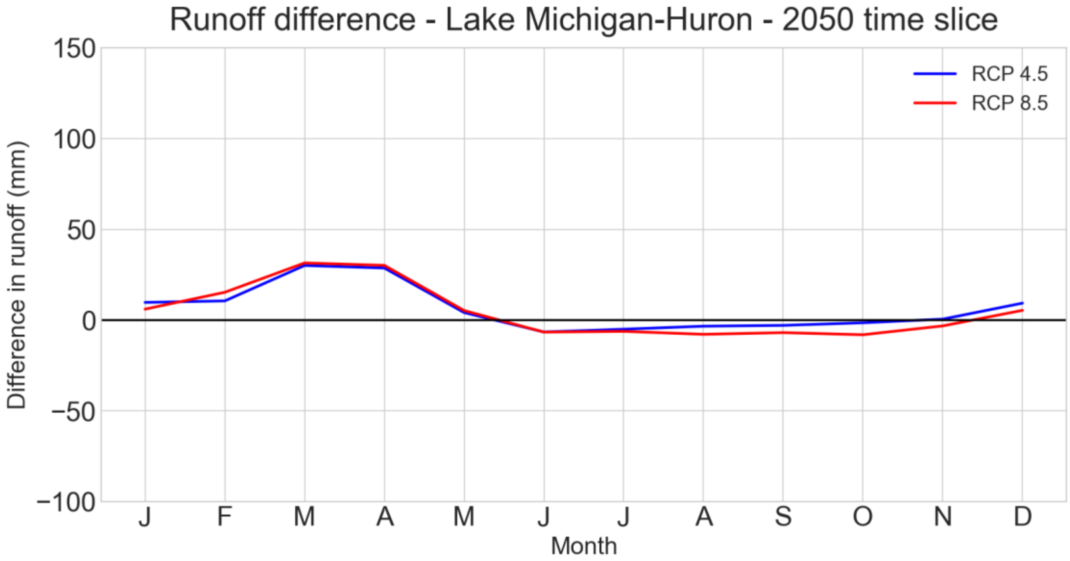


Figure 40: Monthly anomalies of runoff between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Michigan-Huron.

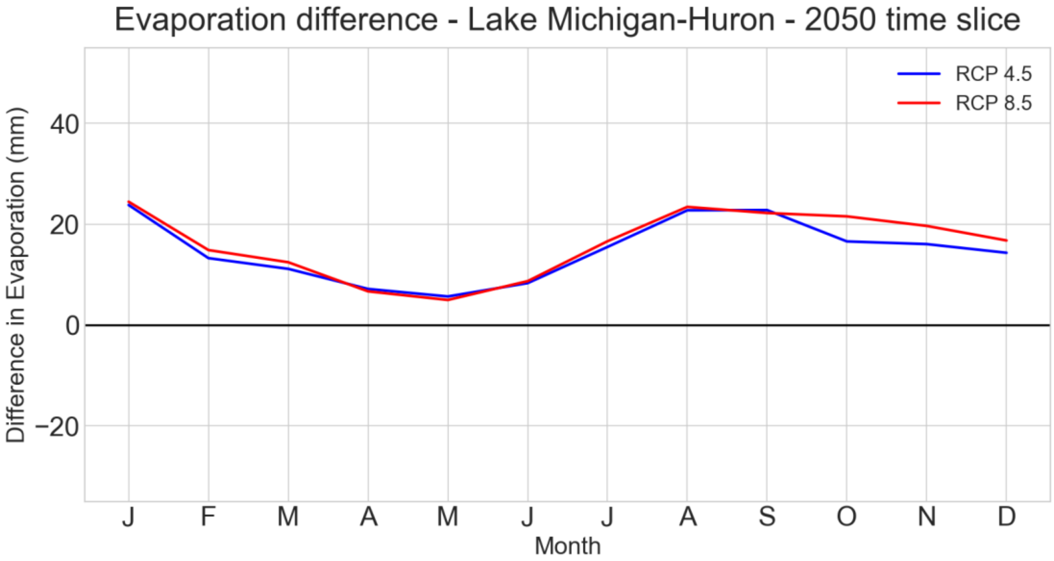


Figure 41: Monthly anomalies of evaporation between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Michigan-Huron.

3.1.4 Component Net Basin Supply analysis

As described in previous sections, the NBS is the local water supply that is entering each lake. The NBS combined with the inflow from the upstream lake and outflow to the downstream lake will determine if the water level in the lake increases or decreases. For this part of the study, the bias adjusted values of the NBS components were combined to determine the values of NBS.

The trends and variability in annual projected future NBS_C (Figure 42 to Figure 45) are similar to those of the individual NBS components discussed in the previous sections. The trends of the average of the RCP 4.5 scenarios again show less of an increase than the average of the RCP 8.5 scenarios. These results show that there are two individual RCP 8.5 scenarios that project very high NBS in the later part of the century, as a result of the very high precipitation for those scenarios.

The seasonal breakdown of the NBS for the 2050 time slice for Lake Michigan-Huron is shown in Figure 46. It can be seen that when the seasonal anomalies of the components are combined, the pattern of higher water supplies in the winter and early spring that was seen in each of the components is not surprisingly repeated for the combined component NBS_C. Then during the summer and early fall the component NBS shows a decrease in values. The seasonal anomalies for the other lakes are shown in Appendix B.

The results of the component Net Basin Supply analysis show a projected general increase in the future annual average value, with this increase being greater under the RCP 8.5 scenario. However, it is also important to recognize the increase in range of the projected future values resulting in both higher highs and lower lows.

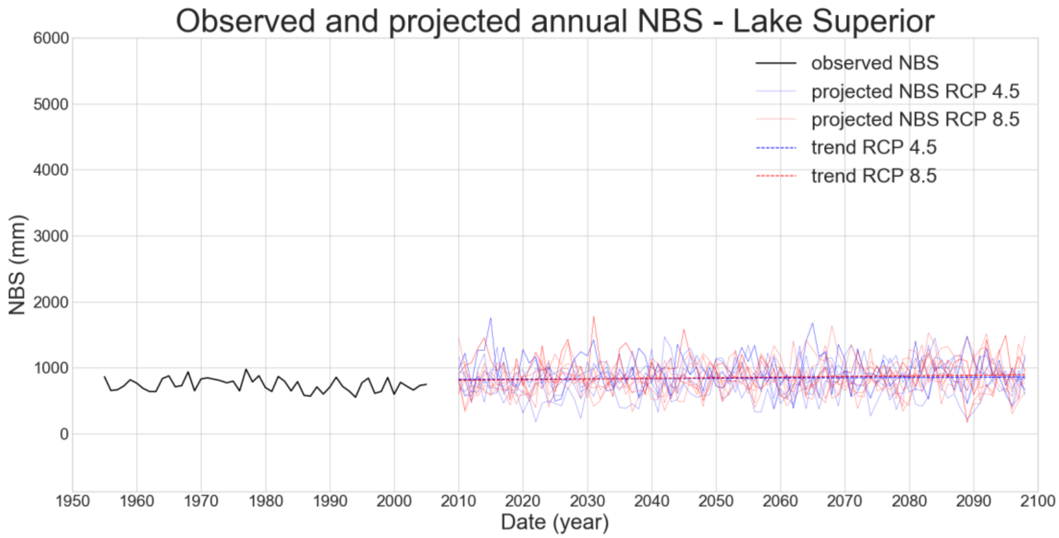


Figure 42: Variability in the bias adjusted annual component NBS for Lake Superior, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

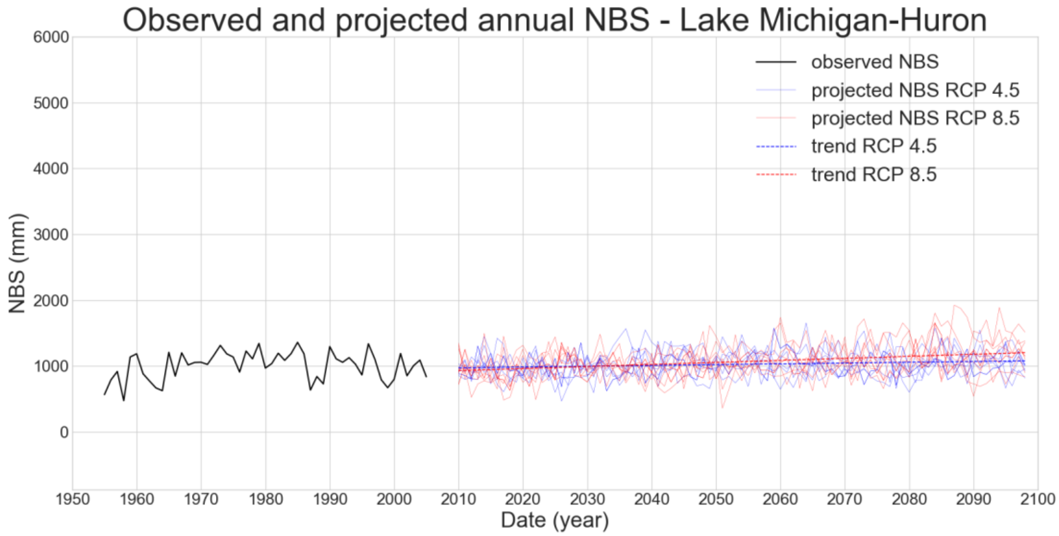


Figure 43: Variability in the bias adjusted annual component NBS for Lake Michigan-Huron, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

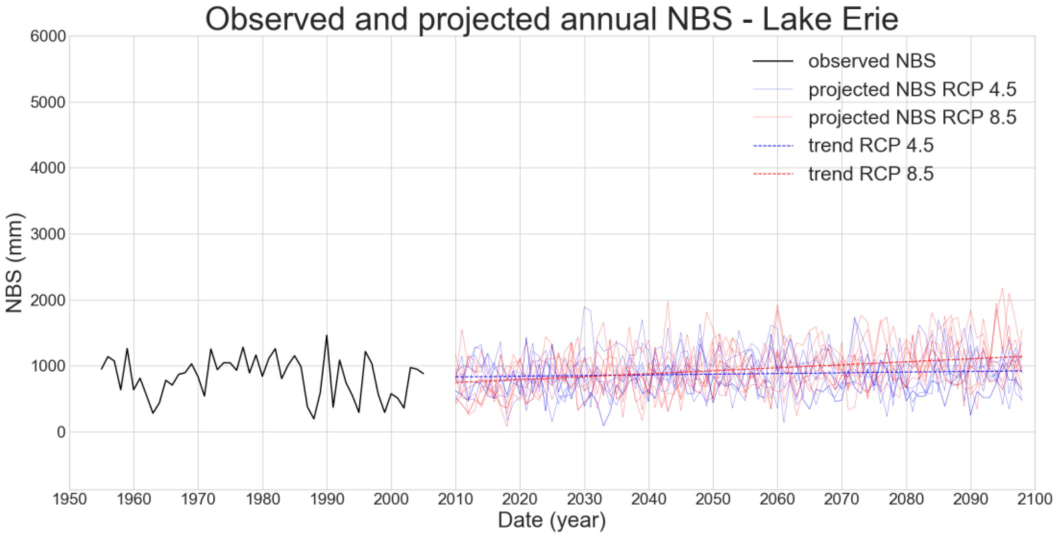


Figure 44: Variability in the bias adjusted annual component NBS for Lake Erie, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

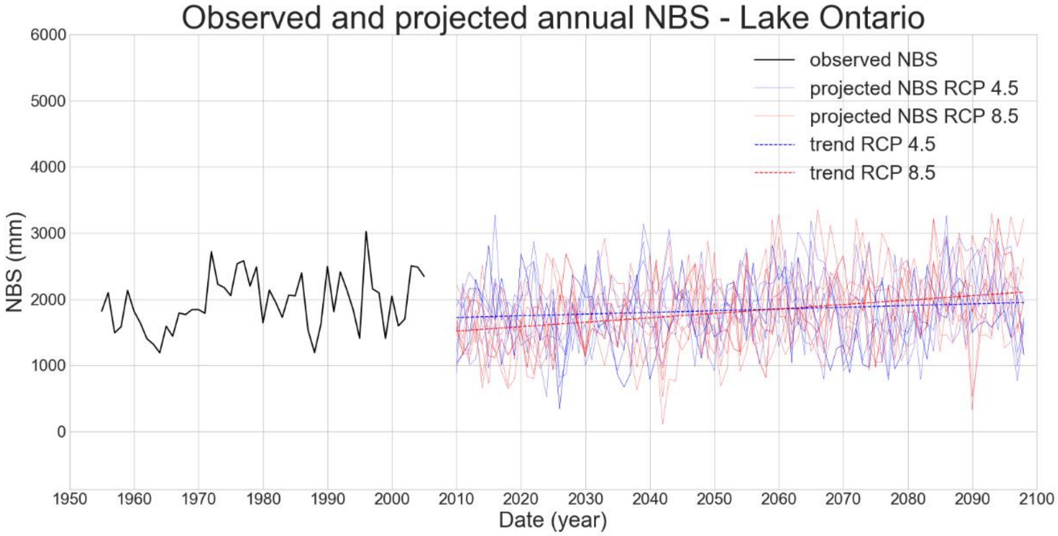


Figure 45: Variability in the bias adjusted annual component NBS for Lake Ontario, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

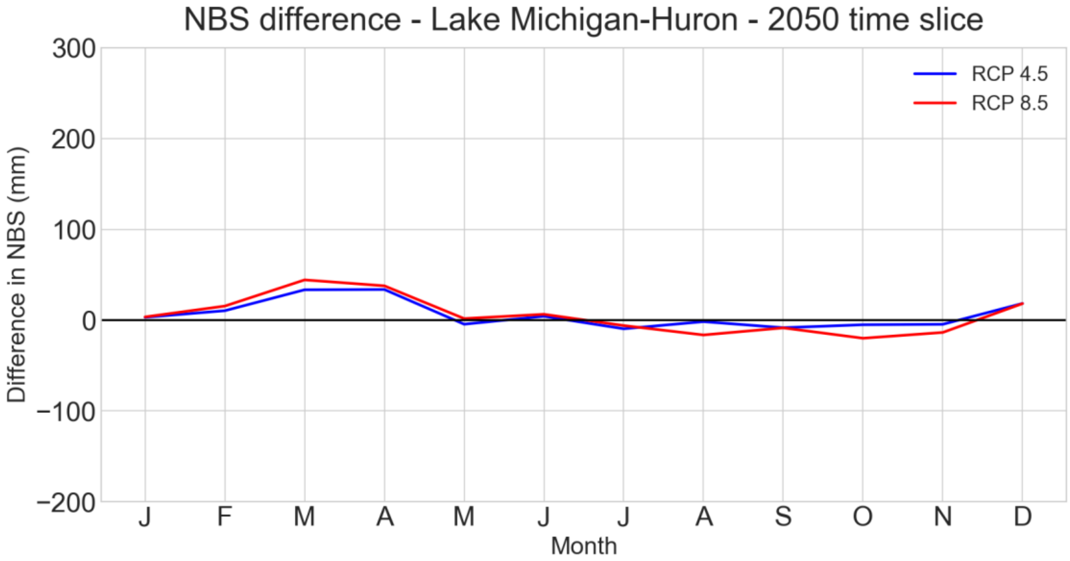


Figure 46: Variability anomalies of the component NBS between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Michigan-Huron.

3.2 Residual Net Basin Supply

Another method to calculate the NBS uses the change in water level of a lake and the difference between the incoming flow to the lake and the outgoing flow from the lake, this is called the residual NBS.

$$NBS_R = Q_{out} - Q_{in} + S \qquad (2)$$

Where NBS_R – residual NBS
Q_{out} – outflow to downstream lake through the connecting channel
Q_{in} – inflow from the upstream lake through the connecting channel (if applicable)
S – change in lake storage (based on lake level)

A residual NBS dataset has been coordinated between the US and Canada since 1900, and is available from the website of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (www.greatlakescc.org).

A new bias adjustment was performed, this time using the coordinated residual NBS as the reference dataset to bias adjust the component NBS calculated from the raw (non-bias adjusted) NBS component data (over-lake precipitation, runoff, and over-lake evaporation). As was done previously, the time period chosen for the reference data set was 1961-2000.

As with the component NBS, the values of the residual NBS for the future climate show an increase in both their average as well as the range to a differing degree depending on the individual lake (Figure 47 to Figure 50). As well, until the late part of the century, both the RCP 4.5 and RCP 8.5 runs are very similar. It is only in the later part of the century that the RCP 8.5 runs show consistently higher values.

The seasonal anomalies for the residual NBS for the 2050 time slice for Lake Michigan-Huron are shown in Figure 51. This is the difference between the future time slice and the current time slice. As with the component NBS based analysis, the largest differences are seen in the winter and early spring, with the future being wetter. During the summer months there is a tendency for the future values to be drier than the current climate, however to a lesser degree than the analysis based on residual NBS. This again shows that although overall for the year the NBS values are generally higher in the future climate projections, there are still times of the year when they can be on average lower.

The seasonal anomaly pattern for other time slices and other lakes are similar, so they are not shown here. However, they are available in Appendix C.

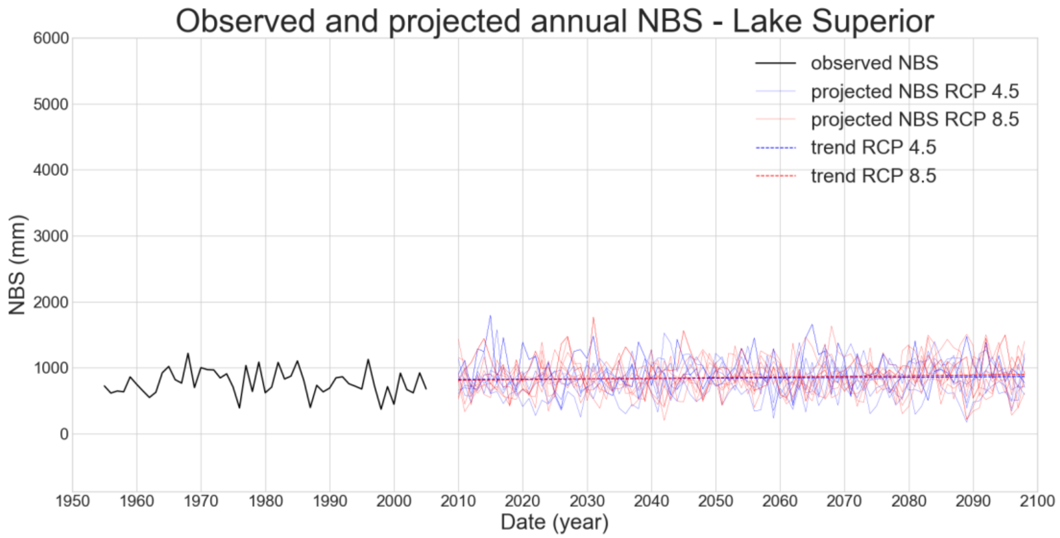


Figure 47: Variability in the bias adjusted annual residual NBS for Lake Superior, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

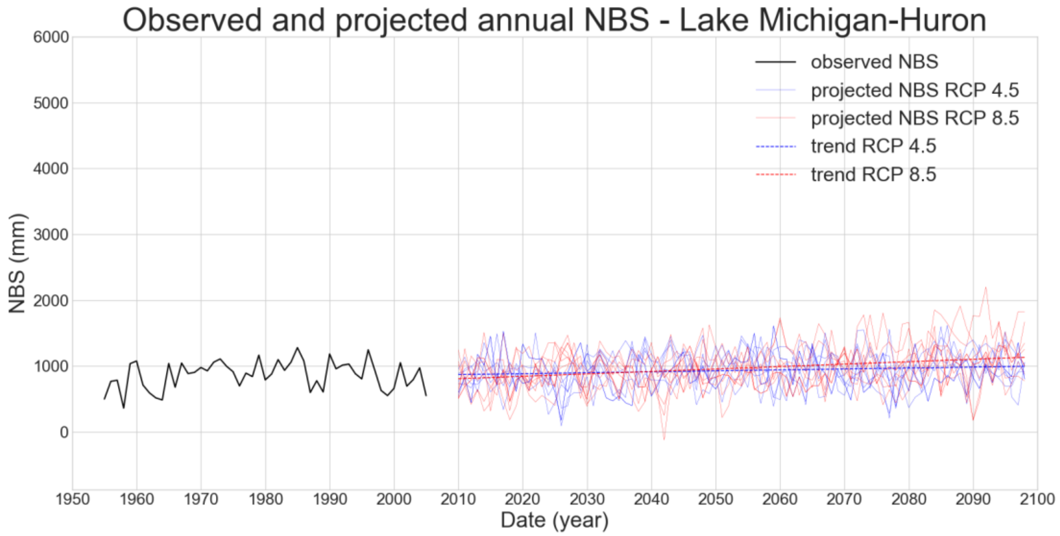


Figure 48: Variability in the bias adjusted annual residual NBS for Lake Michigan-Huron, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

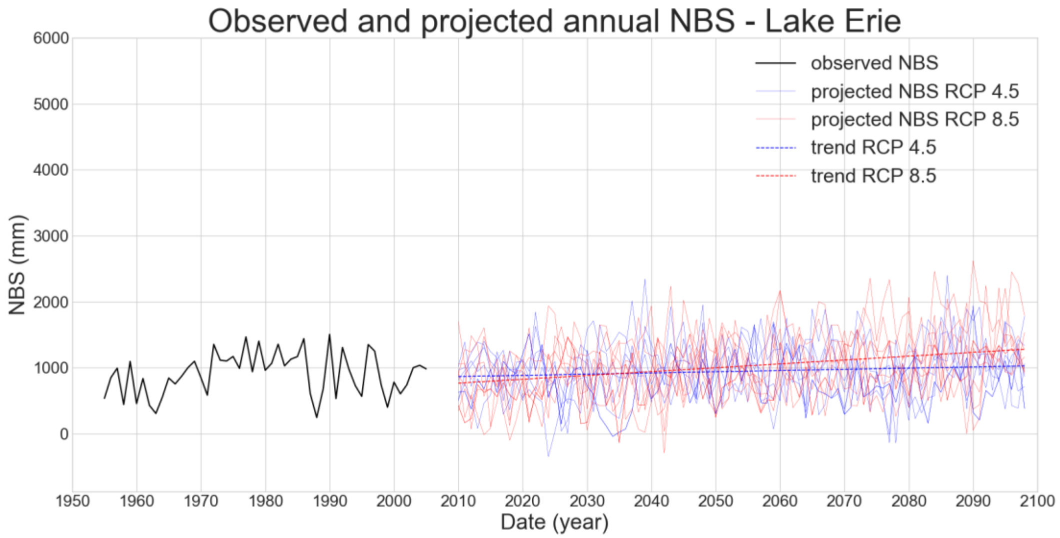


Figure 49: Variability in the bias adjusted annual residual NBS for Lake Erie, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

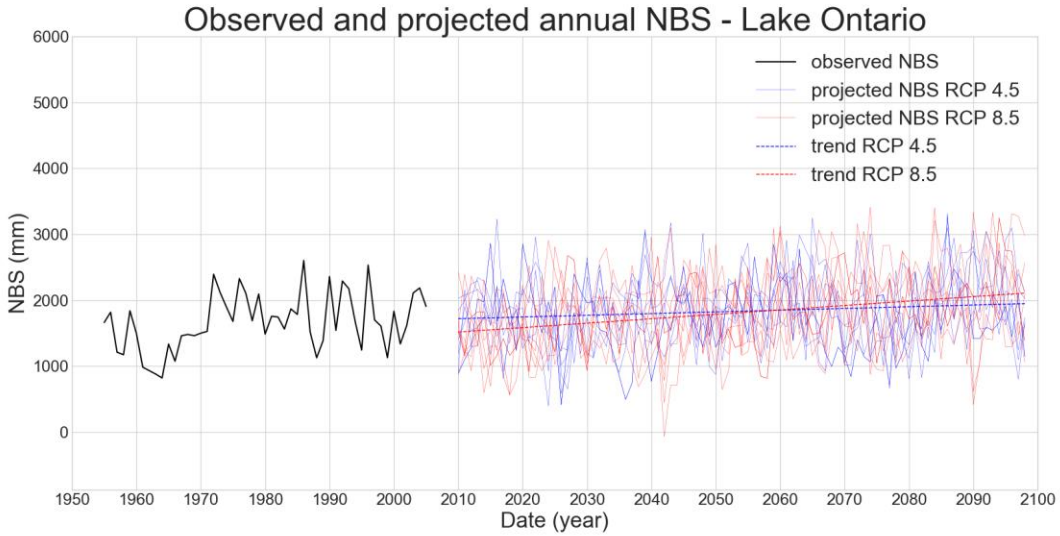


Figure 50: Variability in the bias adjusted annual residual NBS for Lake Ontario, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections.

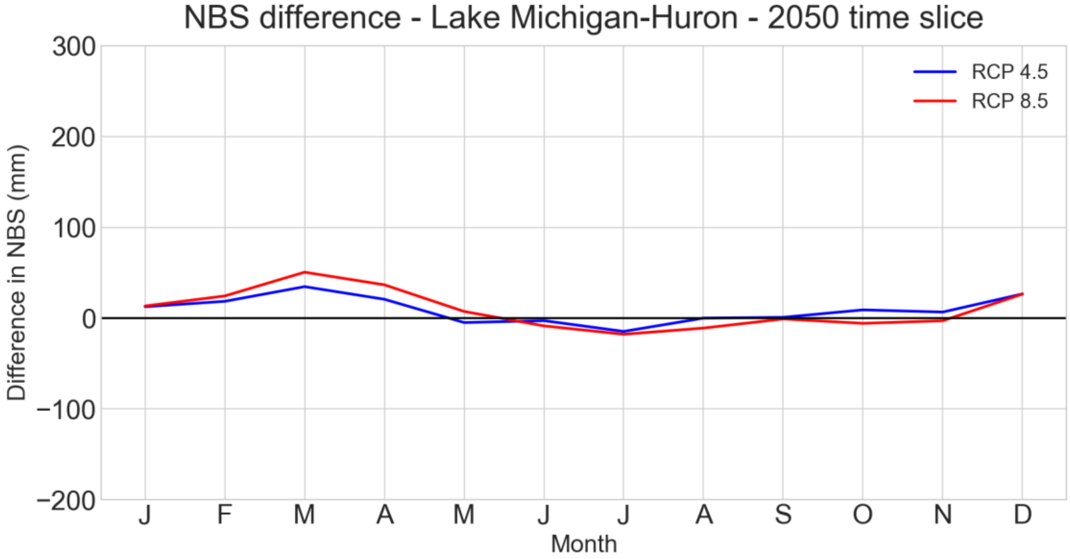


Figure 51: Variability anomalies of the residual NBS between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Michigan-Huron.

3.3 NBS comparison

A comparison was performed between the future values of the NBS computed using the component and residual NBS analysis for both the RCP4.5 and RCP8.5 scenarios. As shown in Table 2, the values for Lake Superior and Lake Ontario are quite close between component and residual NBS calculations. For Lake Michigan-Huron the component NBS analysis values were in general more than the residual NBS analysis values, while the opposite was true for Lake Erie. In all cases, the RCP 8.5 values were higher than their corresponding RCP 4.5 values. However, while the values for the 2080 time slice were always higher than the 2050 time slice in the RCP 8.5 scenario, the values are very close between the time slices in the RCP 4.5 scenario.

Table 2: Comparison of projected future average monthly NBS in mm using both the component and residual NBS analysis.

Lake Superior		Component RCP 4.5	Residual RCP 4.5	Component RCP 8.5	Residual RCP 8.5
2050 Time Slice	Average	70.4	70.5	70.5	70.4
	Standard Deviation	78.7	78.8	82.1	81.8
2080 Time Slice	Average	72.8	73.2	73.6	73.8
	Standard Deviation	79.9	80.2	85.7	85.8

Lake Michigan-Huron		Component RCP 4.5	Residual RCP 4.5	Component RCP 8.5	Residual RCP 8.5
2050 Time Slice	Average	88.3	80.2	86.4	77.4
	Standard Deviation	68.1	75.4	72.4	79.7
2080 Time Slice	Average	87.3	80.4	95.8	88.6
	Standard Deviation	68.6	75.5	78.7	86.9

Lake Erie		Component RCP 4.5	Residual RCP 4.5	Component RCP 8.5	Residual RCP 8.5
2050 Time Slice	Average	76.3	82.9	76.1	81.3
	Standard Deviation	112.4	114.9	116.6	117.8
2080 Time Slice	Average	74.3	80.3	87.6	97.3
	Standard Deviation	110.6	112.6	124.2	123.9

Lake Ontario		Component RCP 4.5	Residual RCP 4.5	Component RCP 8.5	Residual RCP 8.5
2050 Time Slice	Average	156.3	156.8	146.4	146.9
	Standard Deviation	144.4	144.5	149.8	150.1
2080 Time Slice	Average	156.4	155.5	165.7	165.6
	Standard Deviation	147.1	146.1	162.1	162.3

The general patterns seen in the future values of the residual NBS are similar to those found using the component NBS. It can also be seen that the resulting average values are generally similar when using the different techniques. The next section of this report shows how the calculated NBS was used to derive future lake levels.

4 Lake levels

The Coordinated Great Lakes Regulation and Routing Model (CGLRRM) (Clites and Lee, 1998) was used to calculate the lake levels and flow of the connecting channels for the upper lakes (Lake Superior to Lake Erie). The model considers the current regulation plan for Lake Superior (called Plan 2012) in the calculation of the connecting channel flow while the main input into the model is the NBS for each lake. The model has shown good results in simulating the historical lake levels and flows when run with historical NBS (Clites and Lee, 1998). Note that the model provides results for Lake St. Clair, although this lake has not been part of the NBS analysis, it is included in this section.

In order to calculate the connecting channel flow, the CGLRRM model makes assumptions about the conveyance of these channels. As the effects of climate change on the conveyance are not known, it was assumed that the channels would remain stable and the conveyance relationships would be constant throughout all of the simulations. As part of the conveyance calculations, the model also has parameters adjusting the flow for the effects of vegetation and ice in the connecting channels. For this study it was assumed that the vegetation and ice effects would not change throughout the simulation period. This is something that should be examined in future studies.

For Lake Ontario, a separate regulation plan simulation model was run to calculate the lake level and outflow from Lake Ontario based on the input water supplies. The model is based on Plan 2014, the current regulation plan, as well as incoming water supplies (https://ijc.org/sites/default/files/2019-04/Plan2014.pdf). It also uses as inputs the flow of the Ottawa River and other tributaries that enter the St. Lawrence River downstream of Lake Ontario. More information on the regulation of Lake Ontario is available at: https://ijc.org/en/loslrb.

As the lake levels have some persistence from month to month, the choice of a starting level in the models will affect the simulation results for a few years. Thus, the first 5 years of the water level simulations were considered as a spin up period and were not used in the analysis.

The choice of reference period for the bias adjustment affects the calculation of the projected lake levels. For example, if the reference period contains a period of low NBS, then the resulting water levels in both the current and future time periods would be lower than a reference period when the NBS was higher. However, the lake levels were calculated as a difference between the future lake levels and the lake levels from the reference period (1961-2000 in this study). Therefore, the choice of the reference period is not believed to make a difference in the final values of the future lake levels. However, more research should be done on the effect of choosing different reference periods on future lake level trends.

All elevations in this study are in reference to the International Great Lakes Datum of 1985, often referred to as IGLD85. For more information on the history of the Great Lakes Datum refer to the following website: http://www.greatlakescc.org/wp36/home/international-great-lakes-datum-update/

The projected future lake levels for all of the lakes using all of the scenarios as well as the historical lake levels are presented using the component NBS analysis in Figure 57 to Figure 61 and using the residual NBS analysis in Figure 57 to Figure 61. Note that all the figures show the same range on the y-axis to make it easier to compare the variability between the lakes.

These figures show a wide range of projected future lake levels, with some values less than then reference period and some above. In general, the range of values increase as the simulations go later into the century. As well, there is a general tendency for the average values to increase in the later portions of the projections.

A comparison of the lake levels using the component and residual NBS methods (Table 3) shows that the results using either of these methods are quite similar both in terms of average and standard deviation. As seen in the comparison of the NBS values, the most change is seen in the 2080 time slice under the RCP 8.5 scenario both for average and standard deviation.

Table 3: Comparison of monthly mean projected future lake levels using the component NBS analysis and the residual NBS analysis.

Lake Superior		Component RCP 4.5	Residual RCP 4.5	Component RCP 8.5	Residual RCP 8.5
2050 Time Slice	Average	183.8	183.5	183.7	183.5
	Standard Deviation	0.17	0.21	0.19	0.23
2080 Time Slice	Average	183.8	183.6	183.8	183.6
	Standard Deviation	0.17	0.21	0.18	0.23

Lake Michigan-Huron		Component RCP 4.5	Residual RCP 4.5	Component RCP 8.5	Residual RCP 8.5
2050 Time Slice	Average	177.3	176.8	177.2	176.7
	Standard Deviation	0.29	0.45	0.29	0.43
2080 Time Slice	Average	177.3	176.8	177.6	177.1
	Standard Deviation	0.26	0.39	0.31	0.47

Lake St. Clair		Component RCP 4.5	Residual RCP 4.5	Component RCP 8.5	Residual RCP 8.5
2050 Time Slice	Average	175.8	175.4	175.7	175.3
	Standard Deviation	0.26	0.36	0.25	0.35
2080 Time Slice	Average	175.8	175.4	176.0	175.7
	Standard Deviation	0.23	0.31	0.28	0.38

Lake Erie		Component RCP 4.5	Residual RCP 4.5	Component RCP 8.5	Residual RCP 8.5
2050 Time Slice	Average	174.8	174.6	174.8	174.5
	Standard Deviation	0.26	0.34	0.26	0.33
2080 Time Slice	Average	174.8	174.6	175.0	174.8
	Standard Deviation	0.24	0.30	0.28	0.36

Lake Ontario		Component RCP 4.5	Residual RCP 4.5	Component RCP 8.5	Residual RCP 8.5
2050 Time Slice	Average	75.3	75.0	75.3	75.0
	Standard Deviation	0.38	0.38	0.58	0.38
2080 Time Slice	Average	75.3	75.1	75.5	75.1
	Standard Deviation	0.39	0.40	0.53	0.42

As with precipitation and NBS, there are 2 projections using the RCP 8.5 scenario that result in very extreme lake levels. These are most notable in the lake projections for Lake Michigan-Huron and St. Clair.

However, it must be noted that the results in Table 3 represent the simulation from all the models, including those that show extreme changes in the future climate. Moreover, these extreme changes occur later in the century when there is higher uncertainty in the future climate projections.

For this study, all of the different future climate models were deemed as equally plausible. However, examining the future NBS components, NBS, and lake level sequences, it is obvious that there are a few very wet scenarios that skew some the results to appear to be very extreme, particularly in the later part of the century. Some of these sequences would result in water supplies that are well above the observed extremes for many consecutive years or even decades. This would be unprecedented and would result in streamflow, lake levels, and interconnecting channel flows that are not compatible with the current built infrastructure within the Great Lakes basin. However, these are only a few possible scenarios out of the many that were available for this study.

Some of the assumptions of the CGLRRM and the Lake Ontario model would most likely be violated by the extreme higher flows resulting from some of the future climate projections. These models were created based on the flow characteristics that have been observed in the past and it is not clear that the same flow relationships would be maintained under these extreme conditions.

For instance, the maximum recorded monthly flow of the Detroit River was 7680 cubic metres per second (cms) in January, 2020. The results from the CGLRRM have Detroit River flow above 9000 cms for almost 2 years and in some months it is well over 10 000 cms. The validity of the conveyance relationships in the routing and regulation model would be questionable at these flow rates outside the relationships' empirical range. In addition, the connecting channels may not respond in the same manner they have in the past. The hydraulic modelling that would be needed to assess the consequences at these higher flow rates are beyond the scope of this study. As well, this study assumes no changes to the current infrastructure between now and the latter part of the century. This should be considered when examining some of the more extreme results in some of the future climate projections.

The regulation of the outflow of Lake Superior and Lake Ontario is also an area of uncertainty as the regulation of outflows would most likely also be modified if such sustained inflows were observed. For example, the flows into Lake Ontario in some of these extreme scenarios would be higher than the maximum allowable outflow of the regulation plan for a period of months or years. As deviations from the current regulation plan were made in both 2017 and 2019 during times of elevated flows into the system, it can be assumed that under such extreme conditions, deviations would again be made from the regulation plan. Thus, the simulations done in this study based on the current regulation plans may not be valid during some of the extreme scenarios.

Consequently, not all the scenarios are presented for Lake Ontario. For instance, in the case of some of the wet RCP 8.5 scenarios, the amount of water going into the lake did not even allow for the Lake Ontario model to complete its simulation.

Based on these recent actual deviations from Plan 2014 (https://ijc.org/en/glam/report-summary-2017-great-lakes-basin-conditions-and-water-level-impacts-support-ongoing) , the criterion chosen was that levels would not be used if the 6 month average of the NBS for Lake Ontario plus the inflow from Lake Erie was greater than 9250 cms. Lake level and flow calculations after this criteria was met were not used in the analysis, note that this only affected 2 of the climate projections for less than half of the future time period.

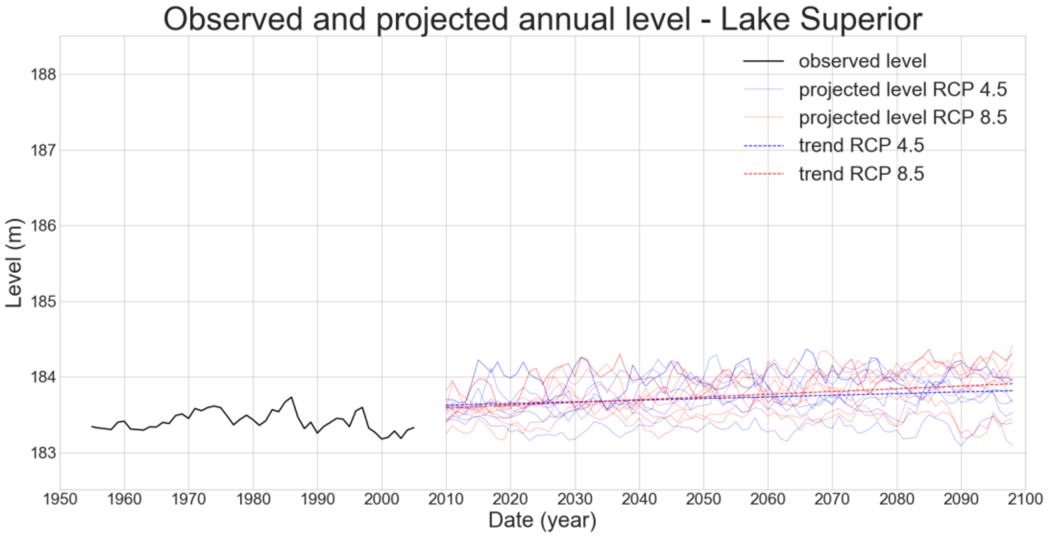


Figure 52: Variability in the annual Lake Superior water levels based on component NBS, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections. Water levels are referenced to IGLD85.

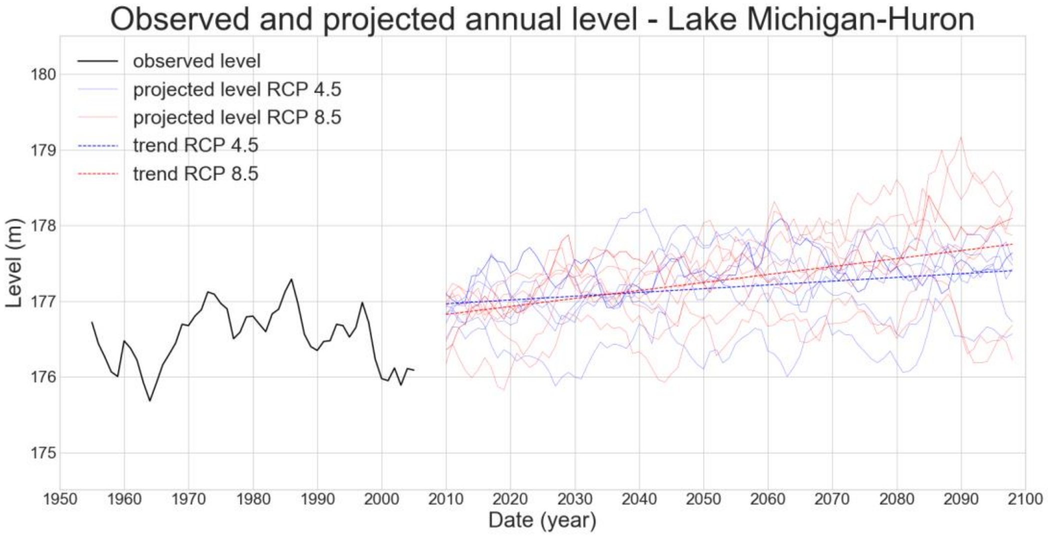


Figure 53: Variability in the annual Lake Michigan-Huron water levels based on component NBS, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections. Water levels are referenced to IGLD85.

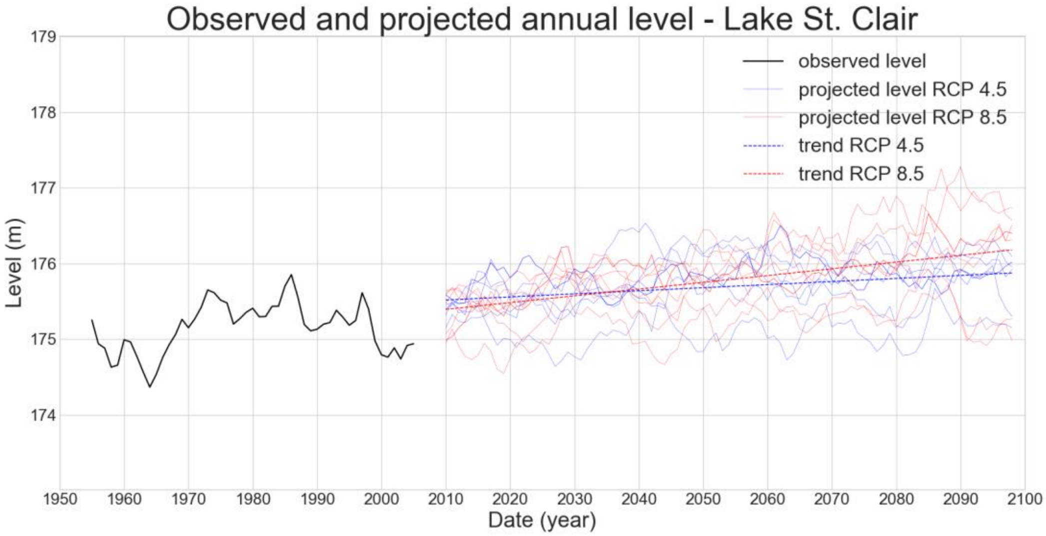


Figure 54: Variability in the annual Lake St. Clair water levels based on component NBS, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections. Water levels are referenced to IGLD85.

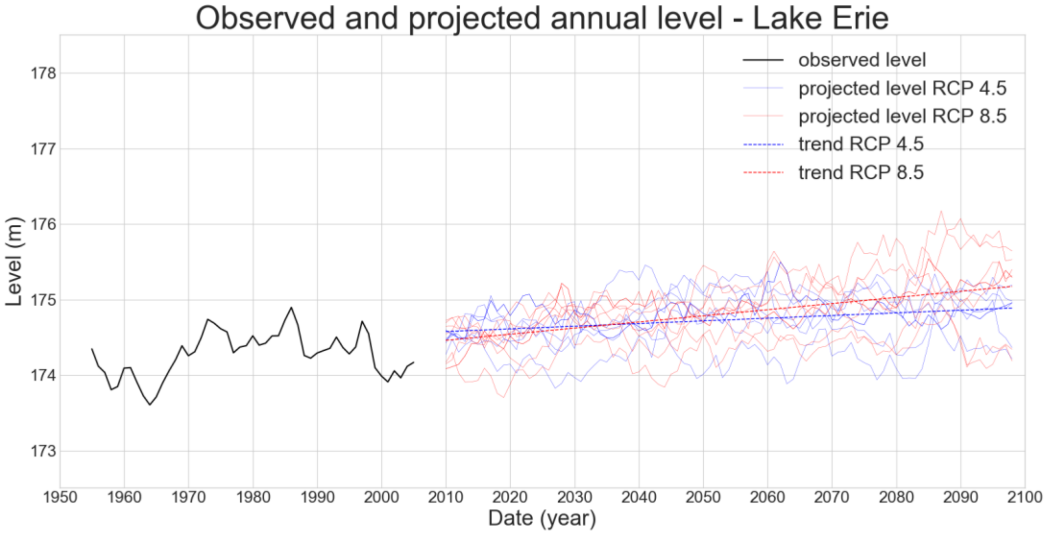


Figure 55: Variability in the annual Lake Erie water levels based on component NBS, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections. Water levels are referenced to IGLD85.

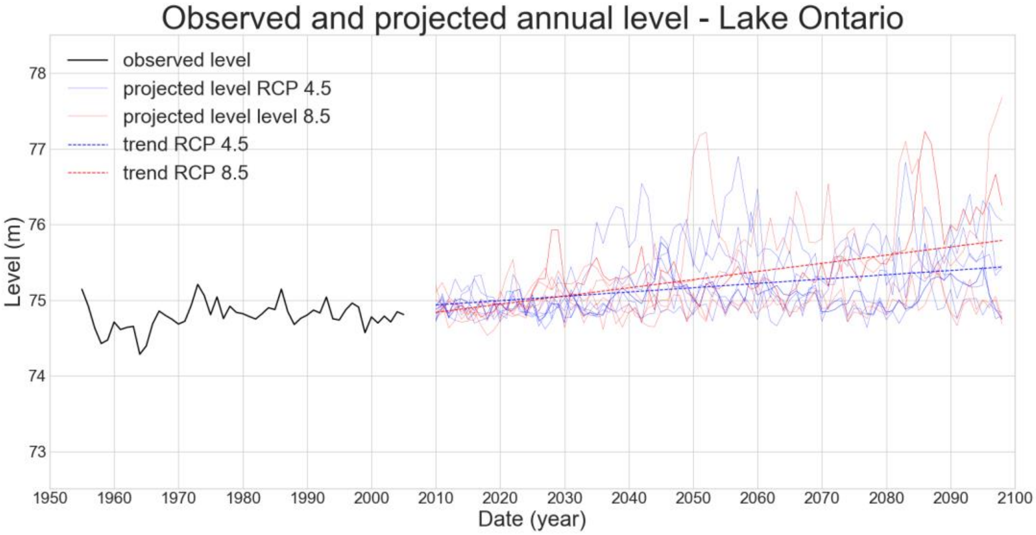


Figure 56: Variability in the annual Lake Ontario water levels based on component NBS, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections. Water levels are referenced to IGLD85.

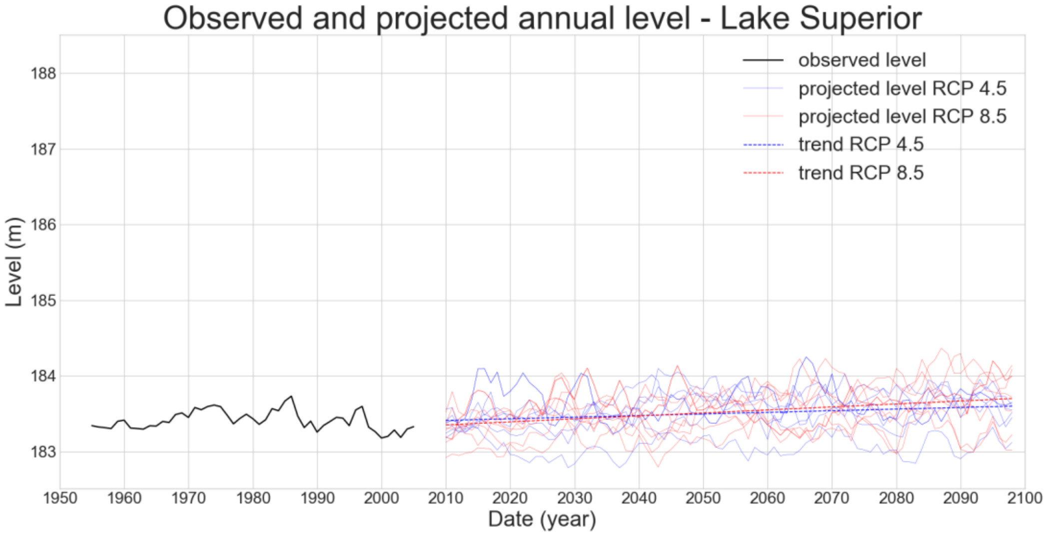


Figure 57: Variability in the annual Lake Superior water levels based on residual NBS, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections. Water levels are referenced to IGLD85.

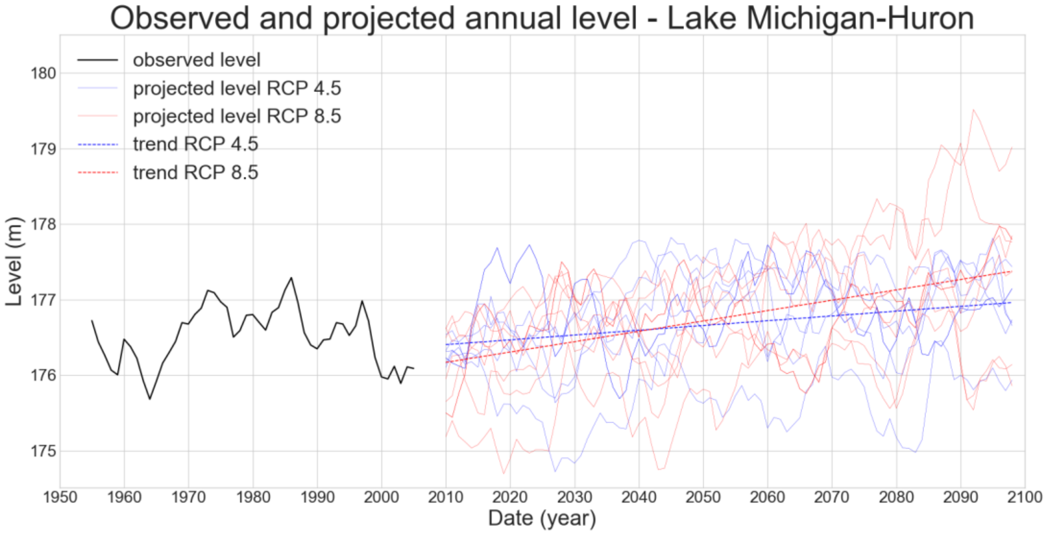


Figure 58: Variability in the annual Lake Michigan-Huron water levels based on residual NBS, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections. Water levels are referenced to IGLD85.

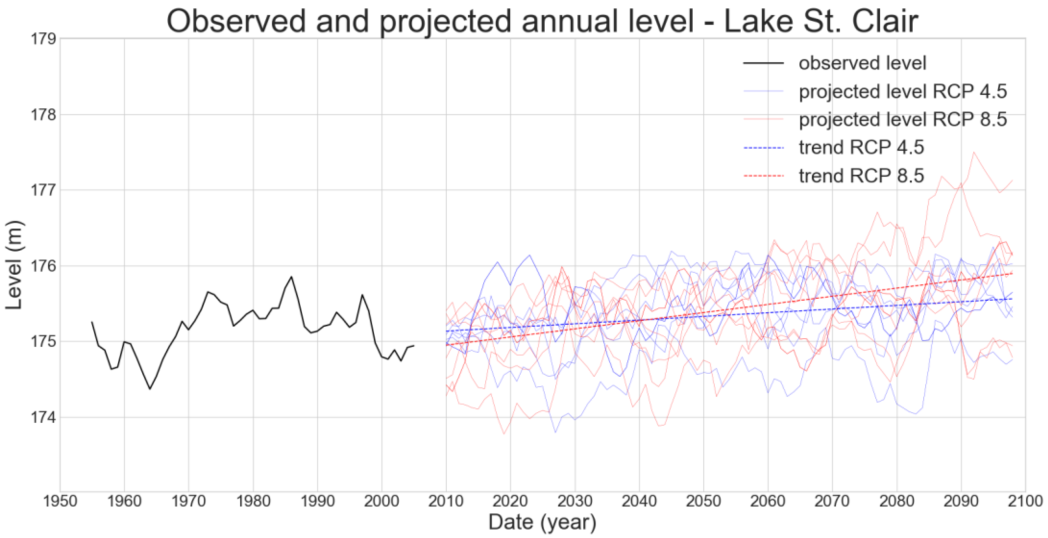


Figure 59: Variability in the annual Lake St. Clair water levels based on residual NBS, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections. Water levels are referenced to IGLD85.

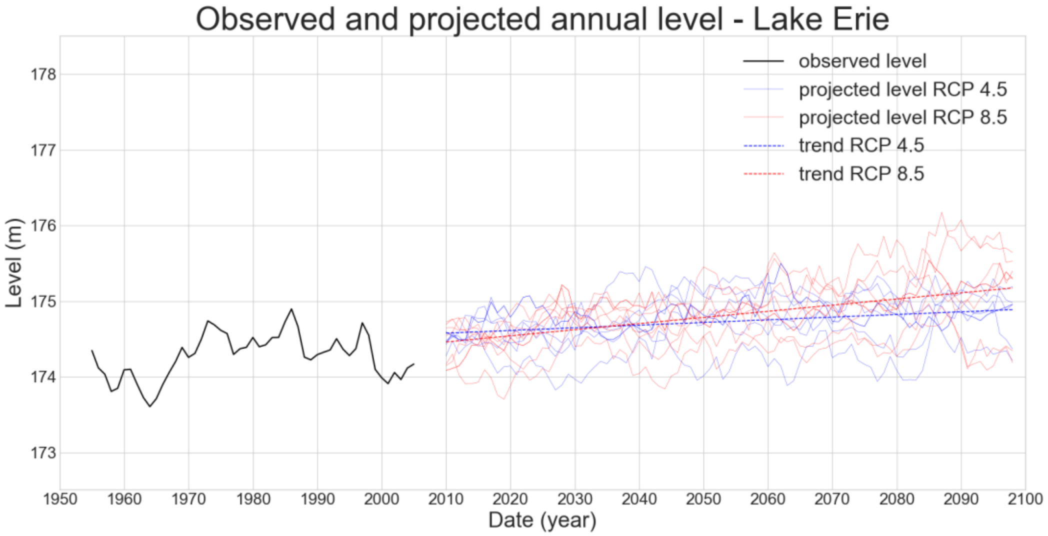


Figure 60: Variability in the annual Lake Erie water levels based on residual NBS, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections. Water levels are referenced to IGLD85.

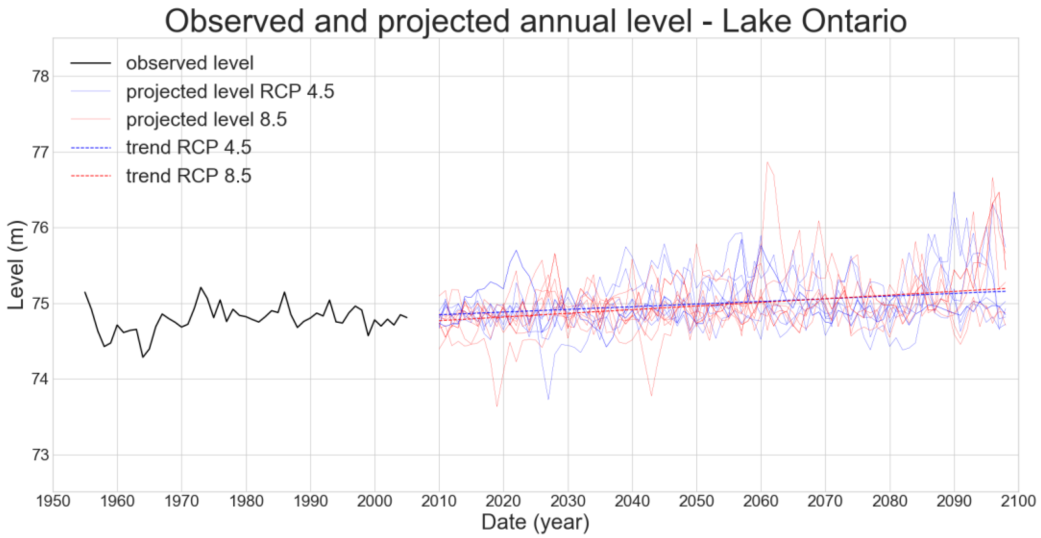


Figure 61: Variability in the annual Lake Ontario water levels based on residual NBS, black line – GLERL Hydromet database, blue solid lines – RCP 4.5 model projections, red solid lines – RCP 8.5 model projections, blue dashed line – trend of RCP 4.5 projections, red dashed line – trend of RCP 8.5 projections. Water levels are referenced to IGLD85.

Using the projected lake levels based on residual NBS, Table 4 presents the lake level differences compared to a reference period of 1961-2000 for the following probabilities of exceedance: 1%, 5%, 50%, 95%, and 99%. The 1% probablility of exceedance can be interpreted as there being a 1% chance in any given year of that level begin exceeded, this is sometimes referenced as the 1 in 100 year flood level. These differences are presented for both the 2050 and 2080 time slides under both the RCP 4.5 and RCP 8.5 emmission scenarios.

Results of the lake level analysis indicate that the water levels of the Great Lakes are projected to increase their variability resulting in both more extreme high and low levels under a changing climate. As well, under the higher emissions scenario of RCP 8.5 there is both a wider range of future projected lake levels as well as higher average values.

The specific values for the future lake levels are based on the particular set of model output that were available for this study. It is highly likely that if output from other models were used it would result in different values for these future lake levels. However, it would be expected that the overall patterns seen in this study would be consistent if other models were available to be used.

Table 4: Projected probability of exceedance of the monthly mean lake level differences in metres compared to the reference period (1961-2000) for the 2050 and 2080 time slices under both RCP 4.5 and RCP 8.5 emission scenarios.

Lake Superior

Percentage Exceedance	Measured (1961-2000)	2050 time slice		2080 time slice	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
1	0.38	0.55	0.57	0.57	0.72
5	0.30	0.44	0.43	0.47	0.57
50	0.00	0.09	0.06	0.12	0.19
95	-0.29	-0.27	-0.31	-0.22	-0.20
99	-0.36	-0.39	-0.45	-0.34	-0.31

Lake Michigan/Huron

Percentage Exceedance	Measured (1961-2000)	2050 time slice		2080 time slice	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
1	0.78	1.03	0.96	1.01	1.51
5	0.59	0.88	0.77	0.84	1.27
50	0.00	0.19	0.07	0.22	0.53
95	-0.71	-0.57	-0.69	-0.40	-0.25
99	-0.98	-0.76	-0.87	-0.55	-0.44

Lake St. Clair

Percentage Exceedance	Measured (1961-2000)	2050 time slice		2080 time slice	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
1	0.63	0.90	0.86	0.92	1.28
5	0.54	0.76	0.69	0.74	1.06
50	0.00	0.21	0.12	0.22	0.48
95	-0.66	-0.41	-0.49	-0.29	-0.16
99	-0.99	-0.58	-0.65	-0.44	-0.33

Lake Erie

Percentage Exceedance	Measured (1961-2000)	2050 time slice		2080 time slice	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
1	0.65	0.92	0.90	0.94	1.23
5	0.51	0.78	0.71	0.75	1.06
50	0.00	0.24	0.16	0.24	0.48
95	-0.58	-0.33	-0.40	-0.26	-0.11
99	-0.86	-0.50	-0.57	-0.42	-0.30

Lake Ontario

Percentage Exceedance	Measured (1961-2000)	2050 time slice		2080 time slice	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
1	0.79	1.31	1.25	1.41	1.45
5	0.49	0.96	0.88	0.99	1.08
50	0.00	0.25	0.17	0.26	0.33
95	-0.43	-0.31	-0.37	-0.32	-0.26
99	-0.79	-0.44	-0.56	-0.46	-0.37

5 Conclusions and future work

In the past few decades, there has been a pattern of general increases in the over-lake precipitation and the over-lake evaporation. The future climate projections found in this study show that these patterns of increases will likely continue, but also the range of high and low values could expand. This would lead to certain future time periods experiencing both higher high values and lower low values for these variables.

The results of this study have the same general message as previous water level studies, which is that although the projected future average water level may be higher or lower, the range and variability of water levels are expected to expand with more extreme highs and lows possible in the future. It is also evident, that more extremes are expected with the higher emission RCP 8.5 scenario than the RCP 4.5 scenario.

There were two different methods used to calculate the NBS in this study, one using component NBS and the other using residual NBS. In terms of both future projected NBS and lake levels, the results using the two different methods were similar and showed the same general patterns.

It must be remembered that the projections of the hydroclimate variables and resulting lake levels are based on the current understanding of the climate system. As well, assumptions have been made about the future behavior of society that will result in the projected amount of greenhouse gases that are put into the atmosphere. The final projected values are subject to various sources of uncertainty that can be divided into three categories: natural variability, model uncertainty, and emission scenario uncertainty (Latif, 2011). A full assessment of these uncertainties is beyond the scope of this study, but with the uncertainties inherent in these projections, they are most useful in showing the general trends of what could happen in the future rather than water levels for a particular time period.

It is also very important not to focus on the extreme water levels that were found for a small number of the simulations of this study. There were a few projections with extremely high and persistent precipitation that resulted in very high water levels, however these were only for the RCP8.5 scenario, and only for the late 21st Century period. Their statistical significance and physical robustness require additional investigation, which is beyond the scope of this study.

Future work should focus on further examination of the reasons for the differences in the future lake level projections between the current and past studies, with an emphasis on the lake models. Another avenue would be a more detailed analysis of the future variability in not only the other variables that are available directly from the CORDEX models (ie. wind speed, lake ice cover, land evaporation, etc.) but also the variables that are derived from the hydrological model (ie. snow water equivalent, soil moisture, streamflow). As well, a new set of data will be available in the next few years from the CMIP6 experiment which will then be able to be downscaled using current RCMs, which were not available at time that this report was written.

The lake level projections from this study were provided to other members of the Wetlands working group of the GPLI to be used as input into a wetlands response model. The results from that model are contained in another study report. The use of these lake level projections can extend beyond wetlands. An appreciation that the extremes that have been observed in the past may be exceeded under a changing climate may help in the planning of future developments and activities within the Great Lakes basin.

6 Acknowledgments

An initial review of a subset of the data was done by Armin Dehghan of Environment and Climate Change Canada, part of this work is a continuation of the work she started. We thank Ouranos for providing their CRCM5 data for this analysis. Versions of this report were reviewed by various people, we thank them for their input and insights. Special thanks to Yin Fan for performing many runs of the Lake Ontario regulation model and Alex Cannon for supplying the bias adjustment code.

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List of abbreviations

Abbreviation	Definition
CGLRRM	Coordinated Great Lakes Regulation and Routing Model
CMIP	Coupled Model Intercomparison Project Phase
COA	Canada – Ontario Agreement
CORDEX-NA	Coordinated Regional Downscaling Experiment – North America
CRCM5	Canadian Regional Climate Model 5
ECCC	Environment and Climate Change Canada
GCM	Global Circulation Model
GLERL	Great Lakes Environmental Research Laboratory
GLPI	Great Lakes Protection Initiative
GLWQA	Great Lakes Water Quality Agreement
IGLD85	International Great Lakes Datum of 1985
NBS_C	Component Net Basin Supply
NBS_R	Residual Net Basin Supply
NHS	National Hydrological Service
NOAA	National Oceanic and Atmospheric Administration
MPI-ESM	Max Planck Institute Earth System Model
RCM	Regional Climate Model
RCP	Representative Concentration Pathways

Appendix A: Seasonal anomalies of NBS components

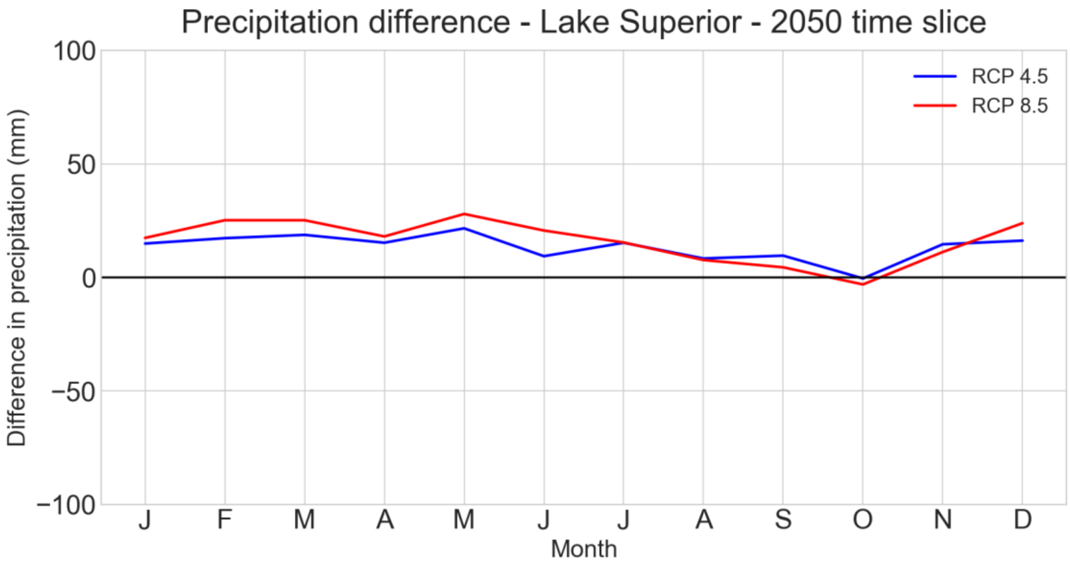

Figure A-1: Monthly anomalies of precipitation between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Superior.

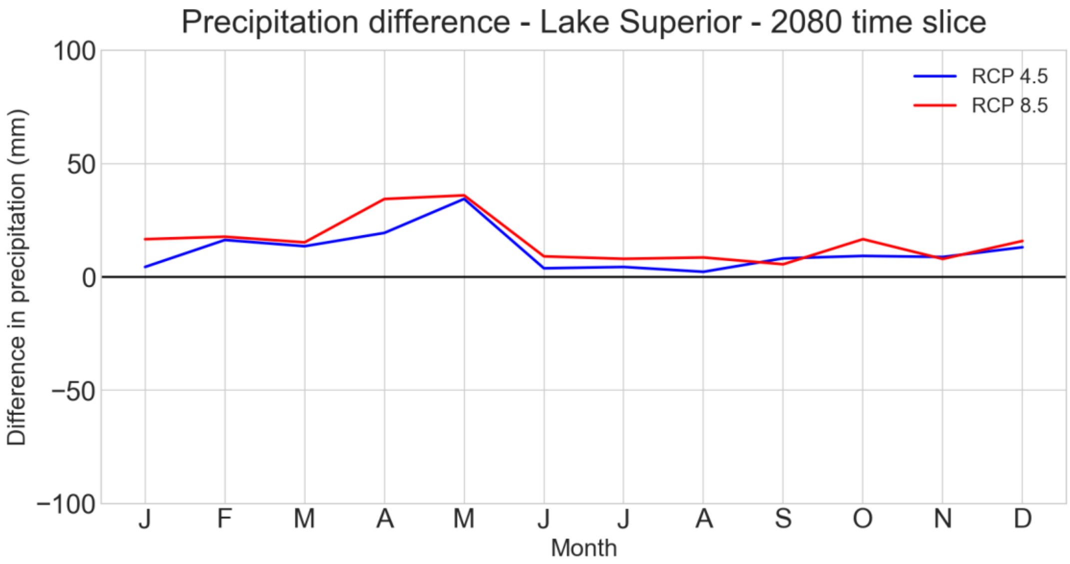

Figure A-2: Monthly anomalies of precipitation between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Superior.

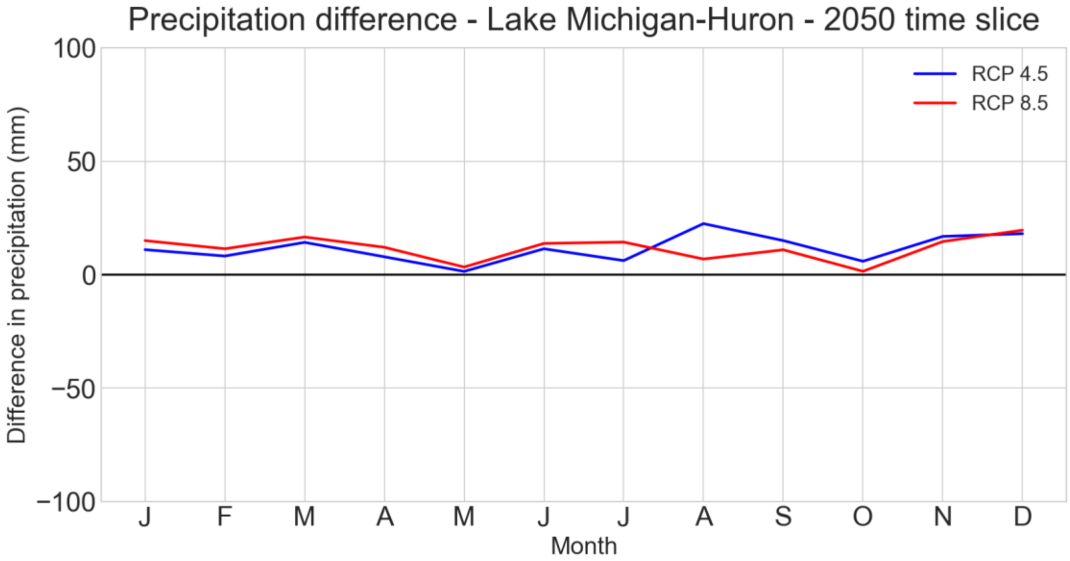

Figure A-3: Monthly anomalies of precipitation between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Michigan-Huron.

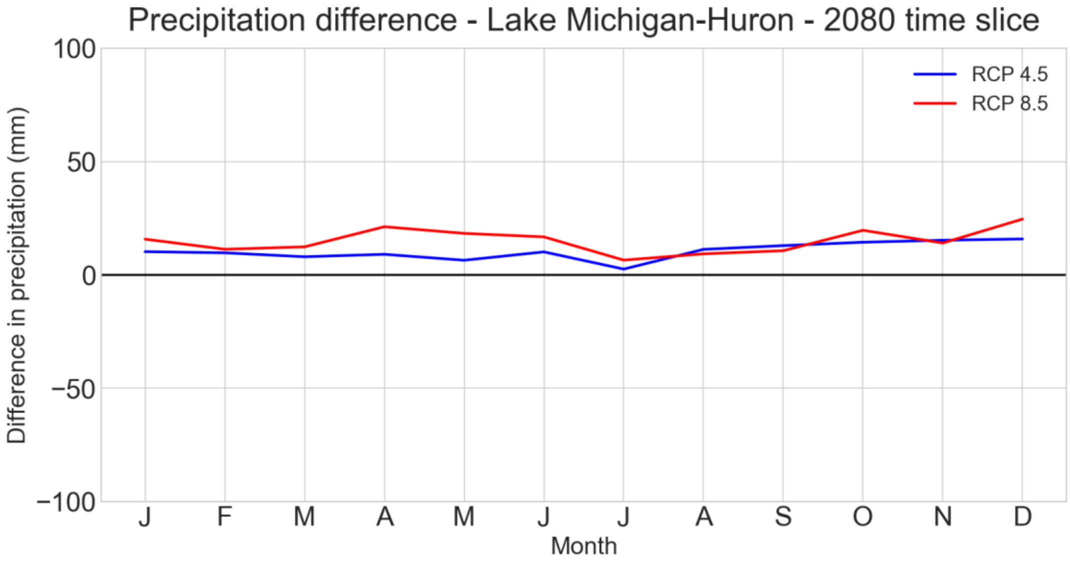

Figure A-4: Monthly anomalies of precipitation between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Michigan-Huron.

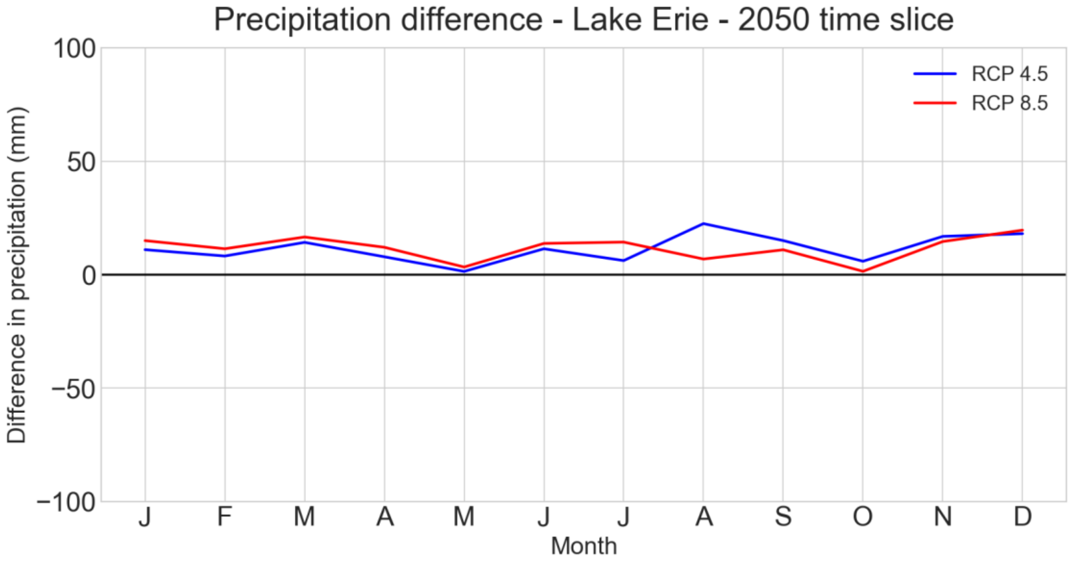

Figure A-5: Monthly anomalies of precipitation between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Erie.

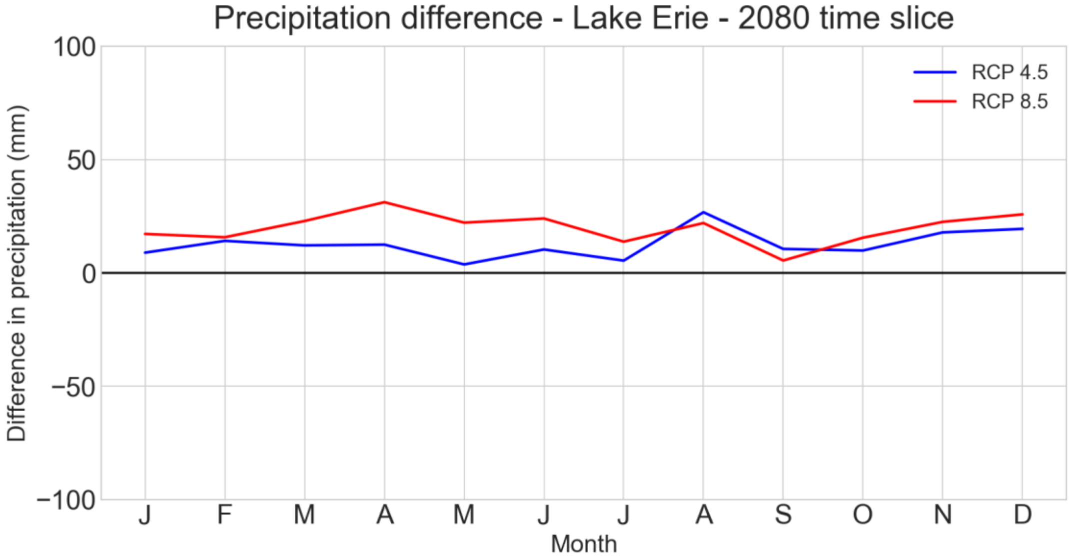

Figure A-6: Monthly anomalies of precipitation between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Erie.

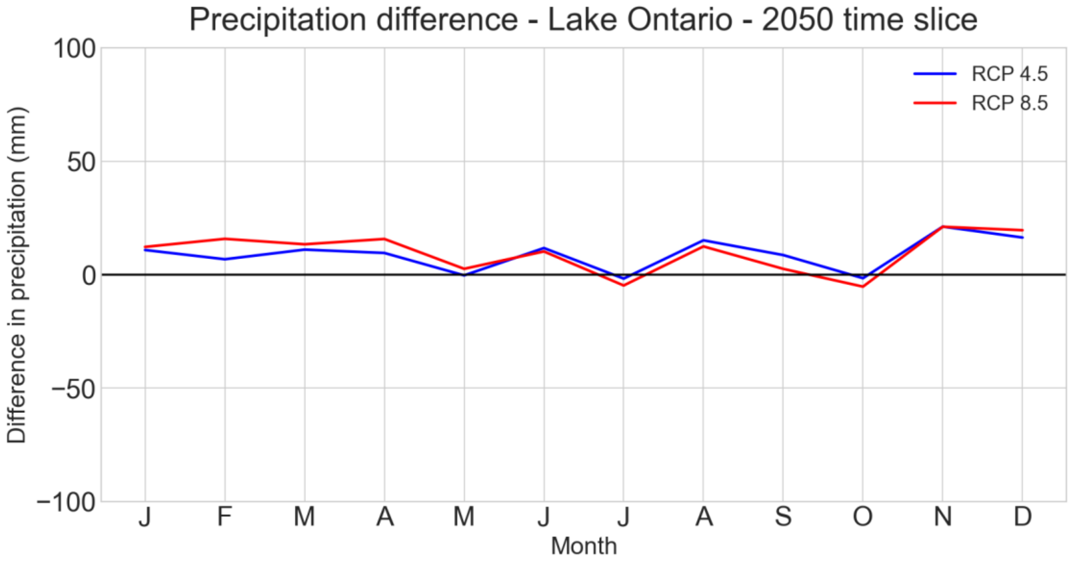

Figure A-7: Monthly anomalies of precipitation between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Ontario.

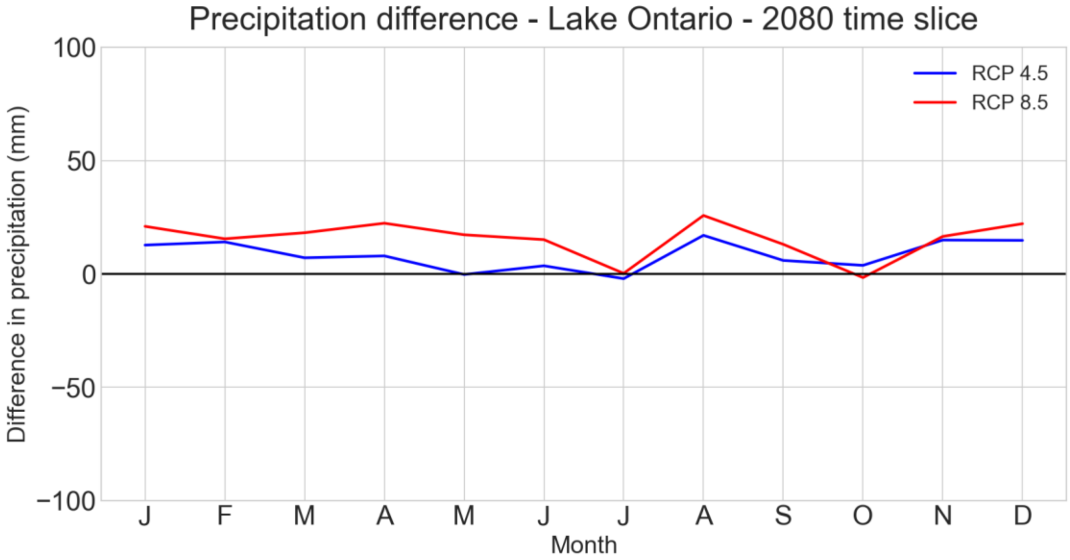

Figure A-8: Monthly anomalies of precipitation between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Ontario.

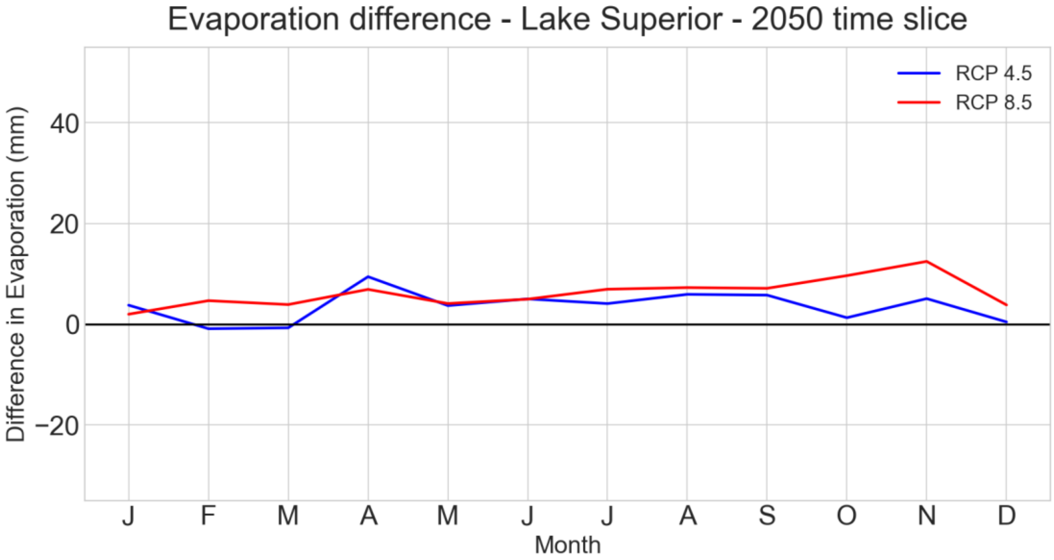

Figure A-9: Monthly anomalies of evaporation between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Superior.

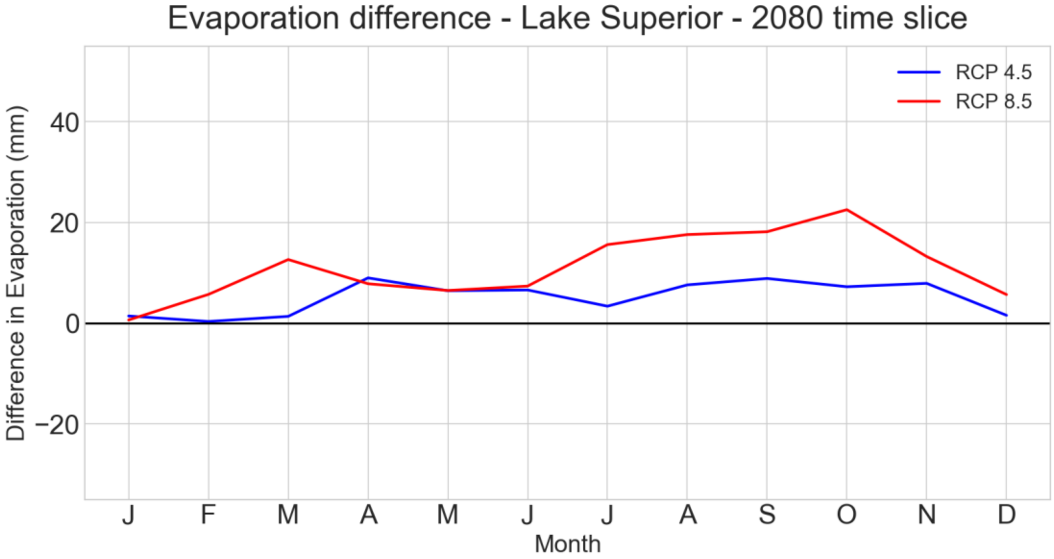

Figure A-10: Monthly anomalies of evaporation between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Superior.

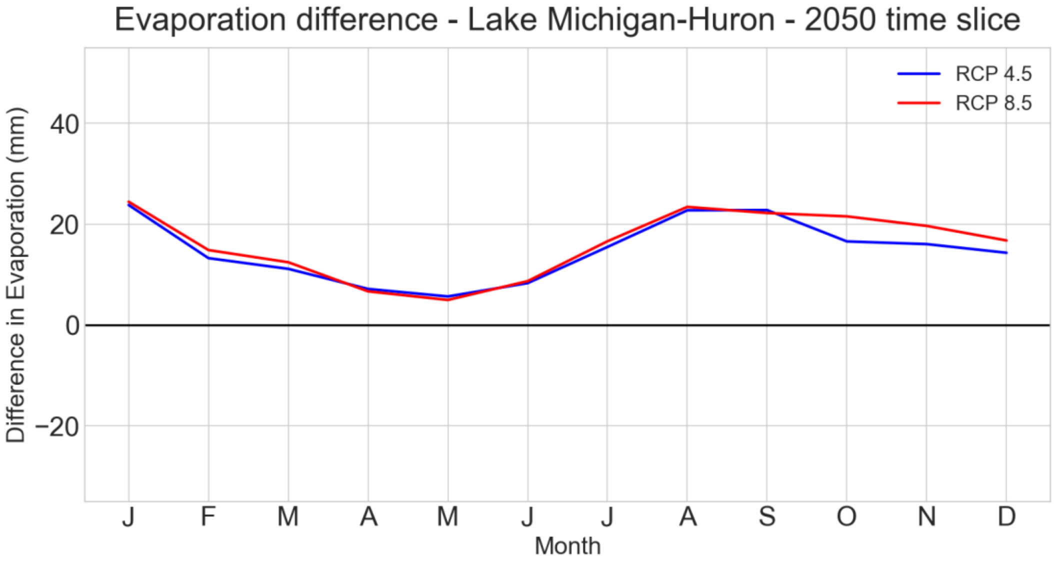

Figure A-11: Monthly anomalies of evaporation between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Michigan-Huron.

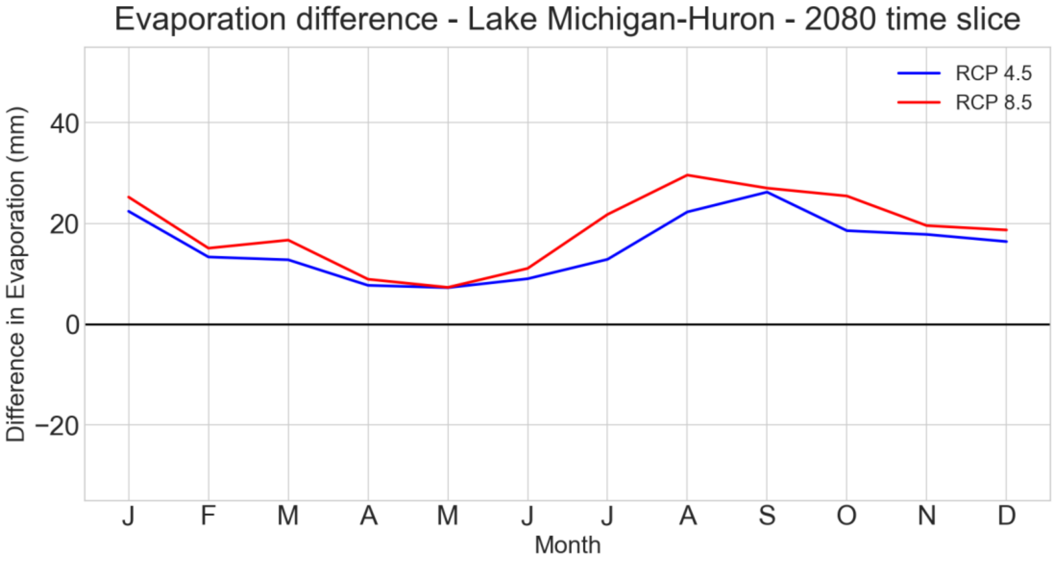

Figure A-12: Monthly anomalies of evaporation between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Michigan-Huron.

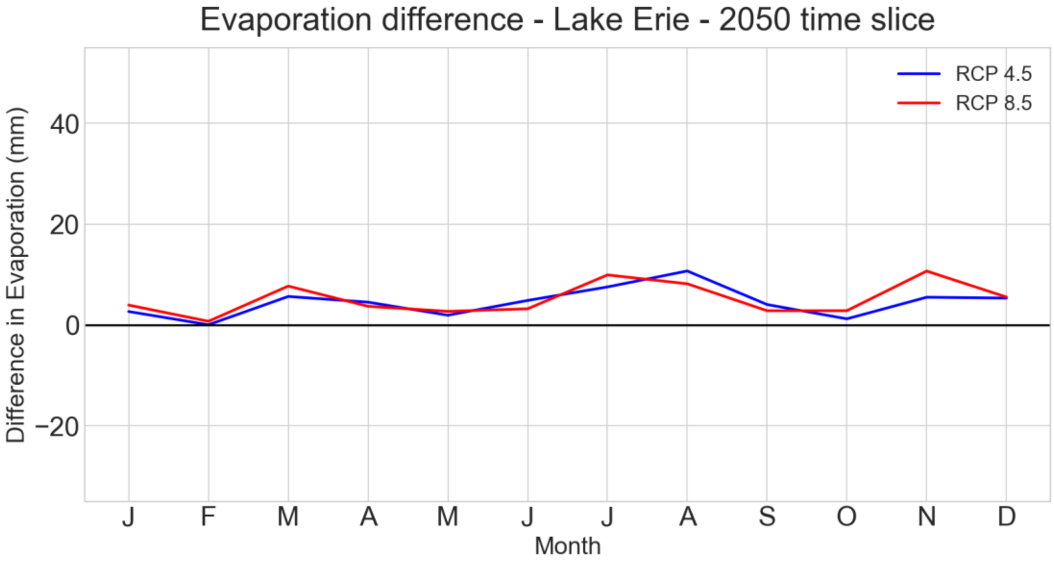

Figure A-13: Monthly anomalies of evaporation between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Erie.

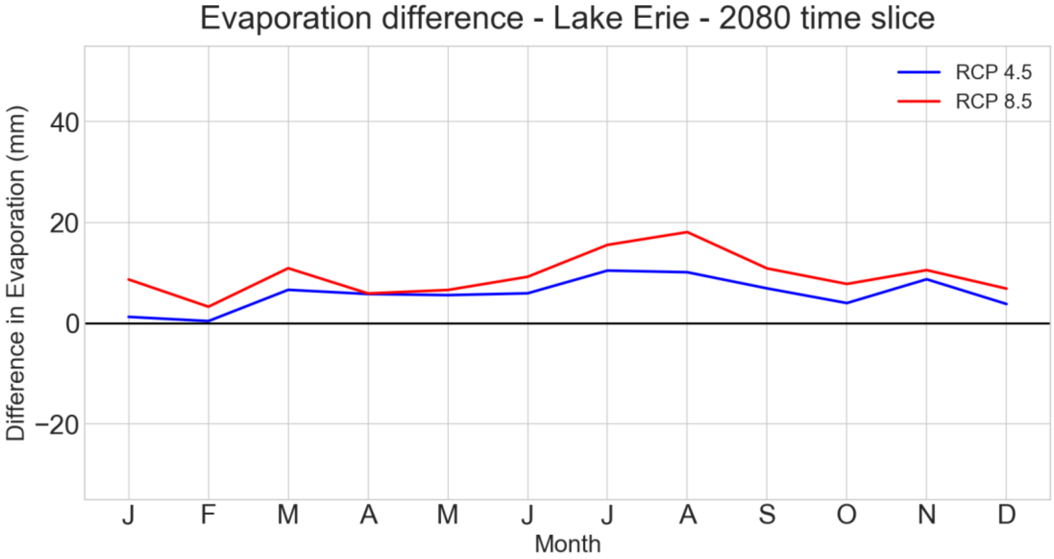

Figure A-14: Monthly anomalies of evaporation between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Erie.

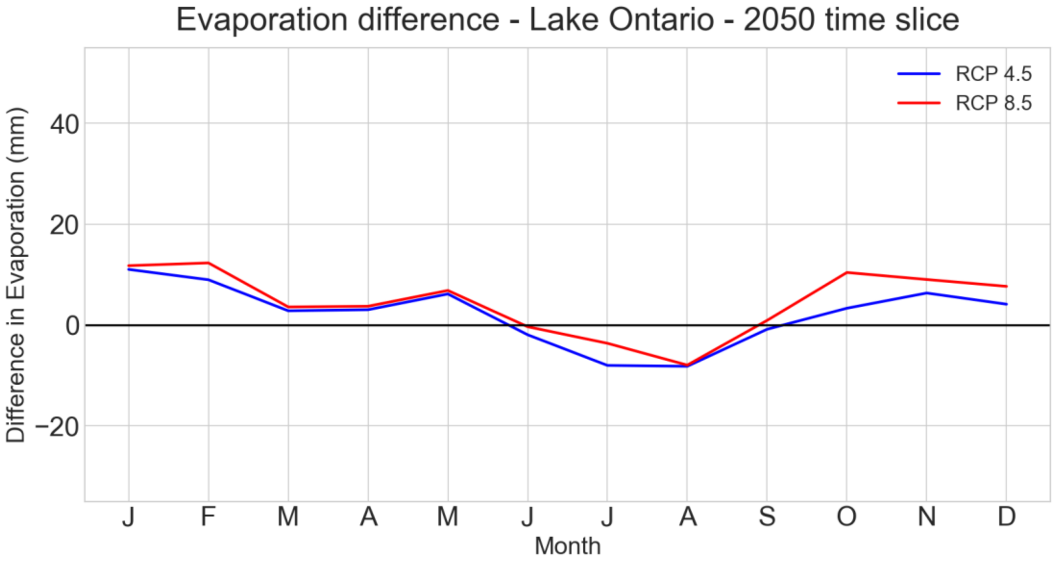

Figure A-15: Monthly anomalies of evaporation between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Ontario.

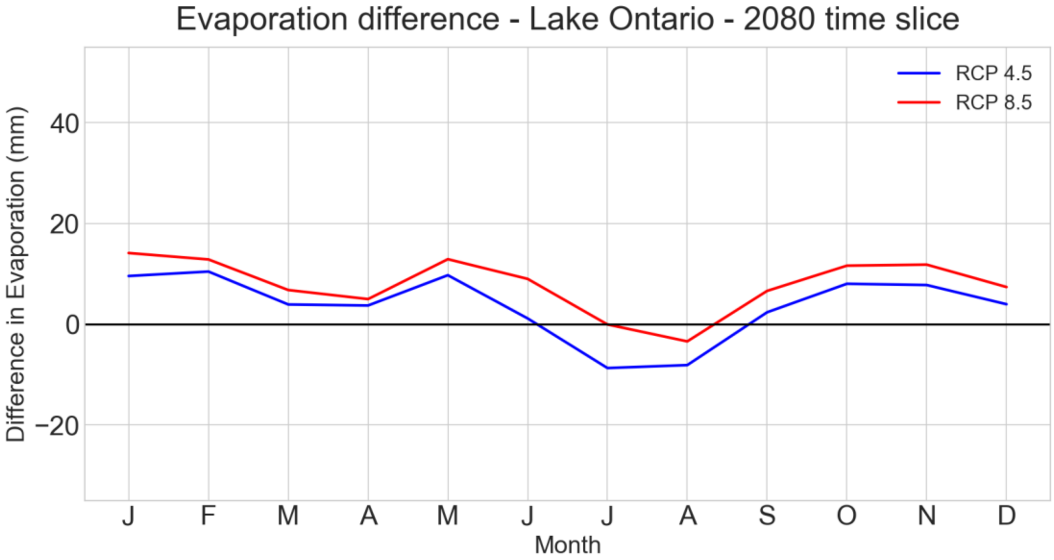

Figure A-16: Monthly anomalies of evaporation between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Ontario.

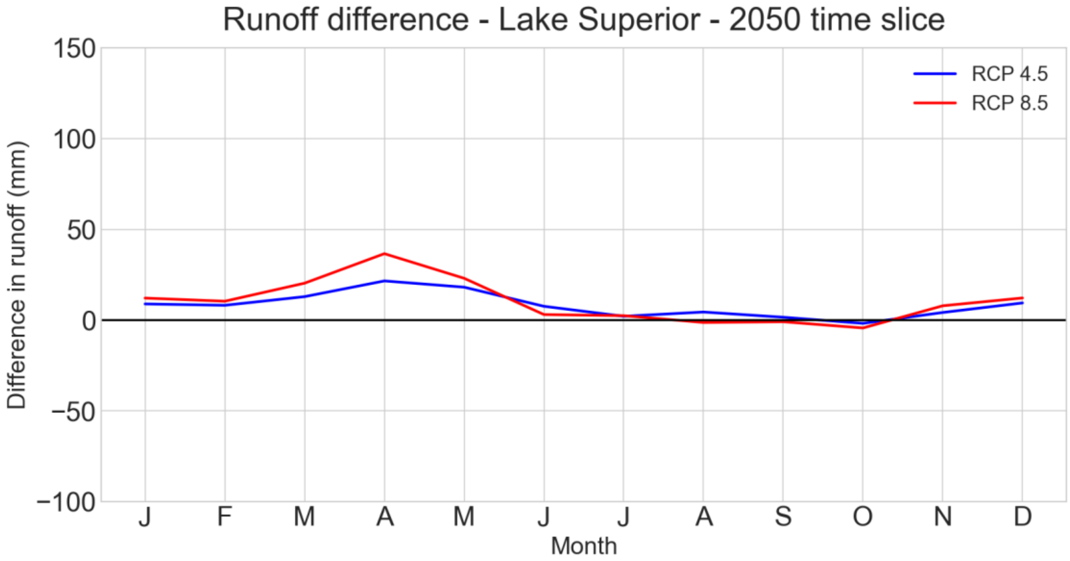

Figure A-17: Monthly anomalies of runoff between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Superior.

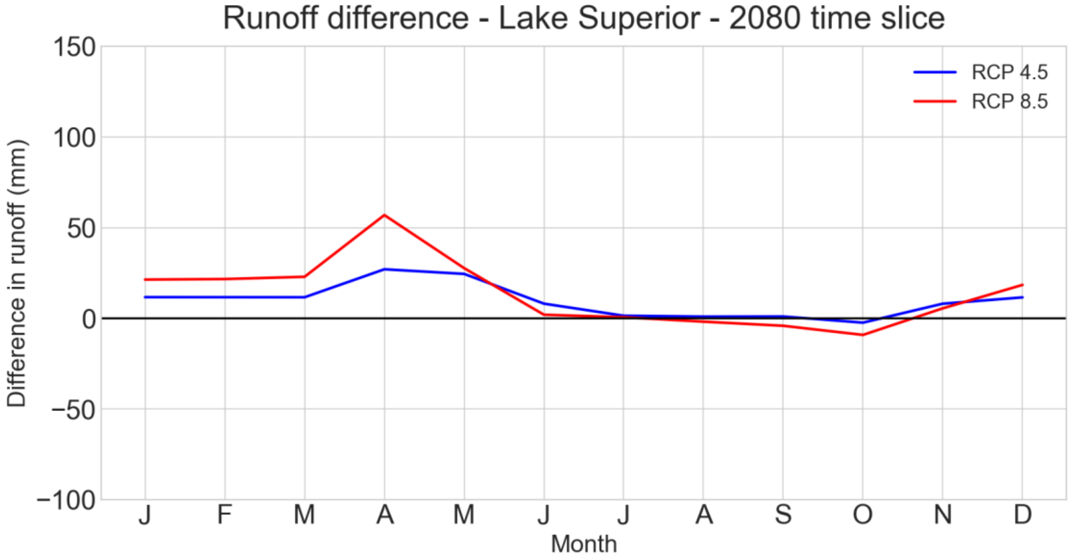

Figure A-18: Monthly anomalies of runoff between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Superior.

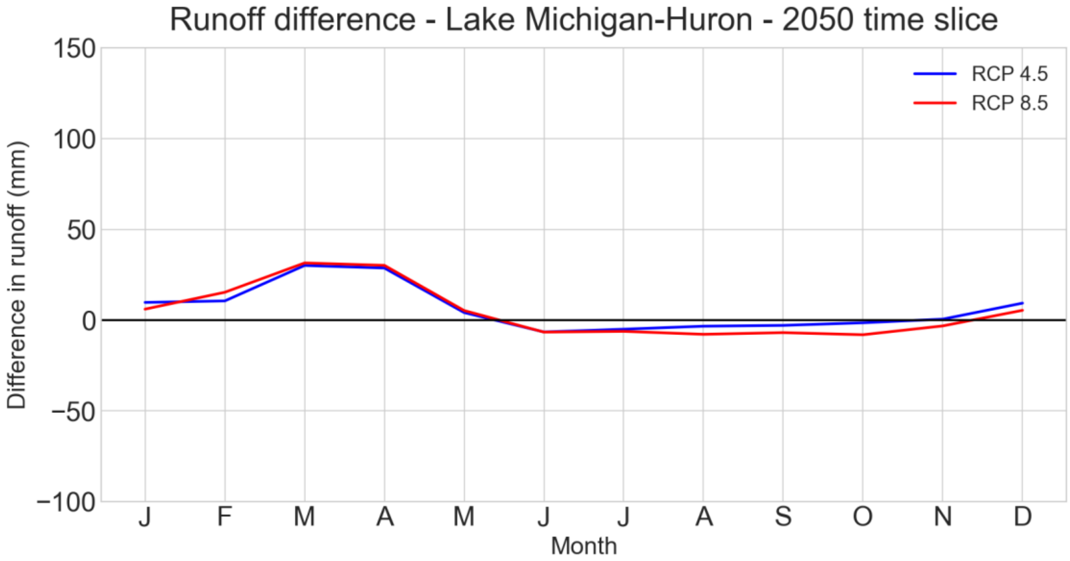

Figure A-19: Monthly anomalies of runoff between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Michigan-Huron.

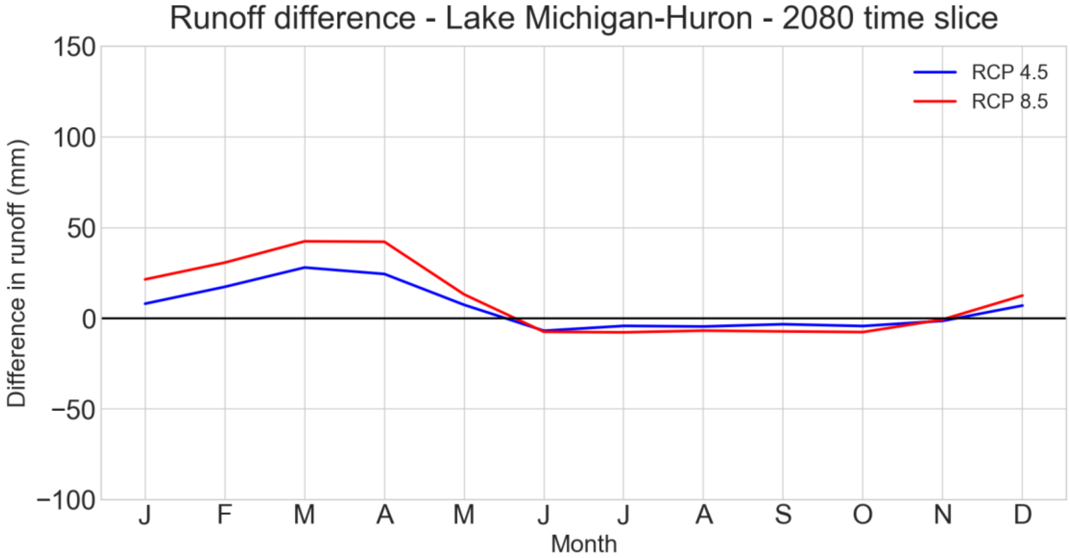

Figure A-20: Monthly anomalies of runoff between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Michigan-Huron.

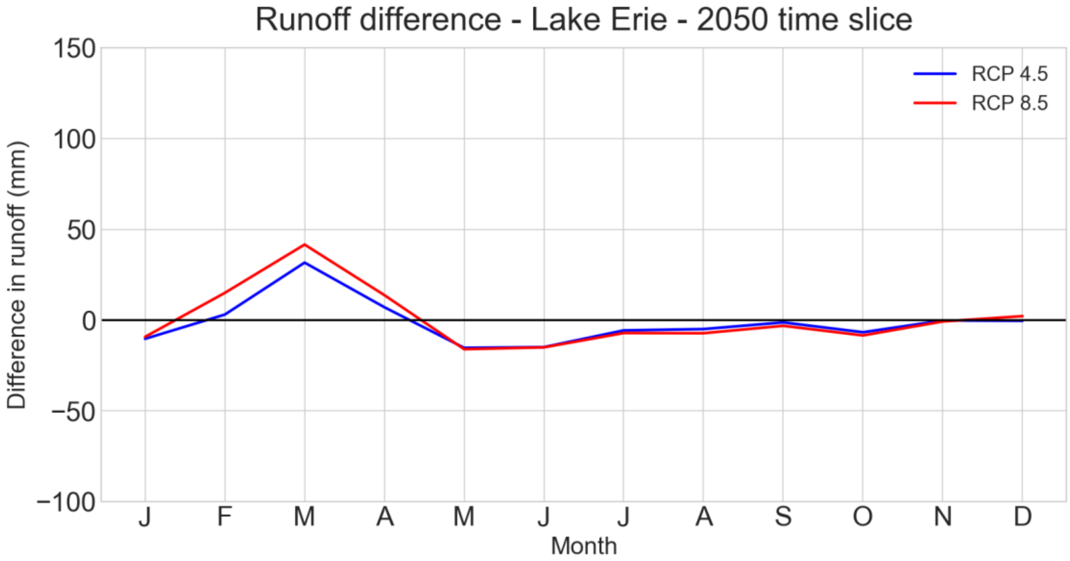

Figure A-21: Monthly anomalies of runoff between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Erie.

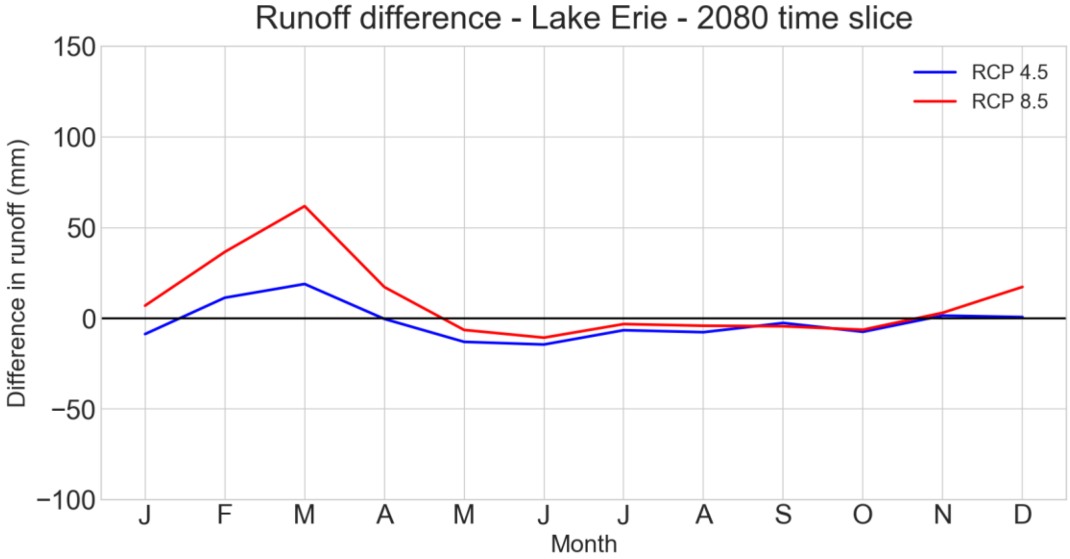

Figure A-22: Monthly anomalies of runoff between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Erie.

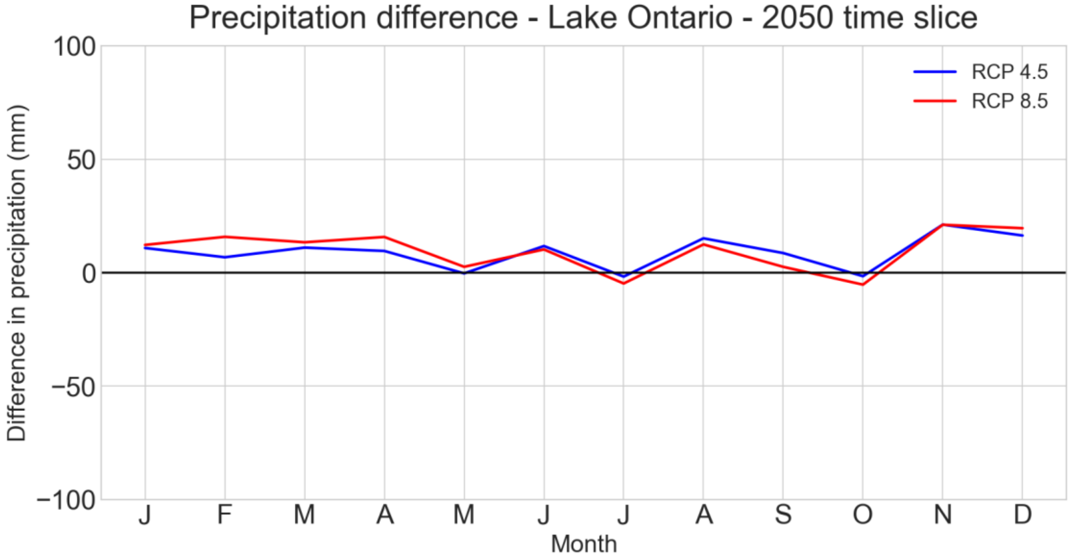

Figure A-23: Monthly anomalies of runoff between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Ontario.

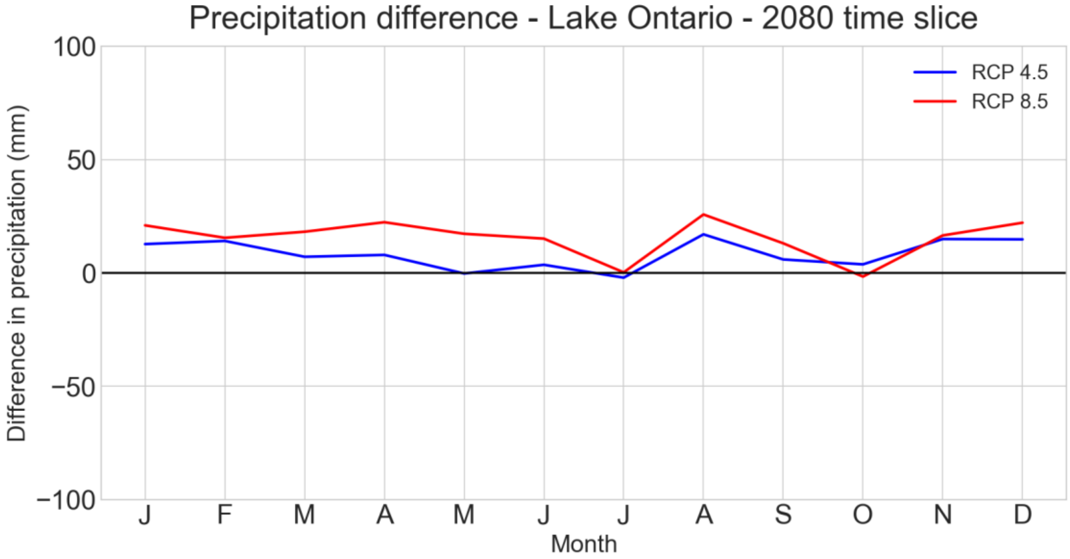

Figure A-24: Monthly anomalies of runoff between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate Lake Ontario.

Appendix B: Seasonal anomalies of component NBS

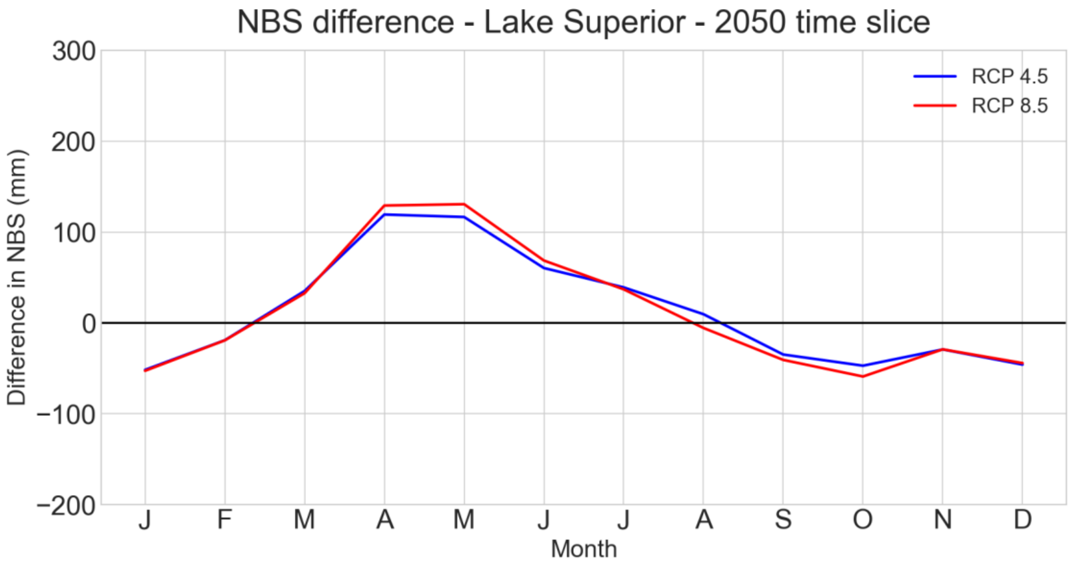

Figure B-1: Variability anomalies of the component NBS between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Superior.

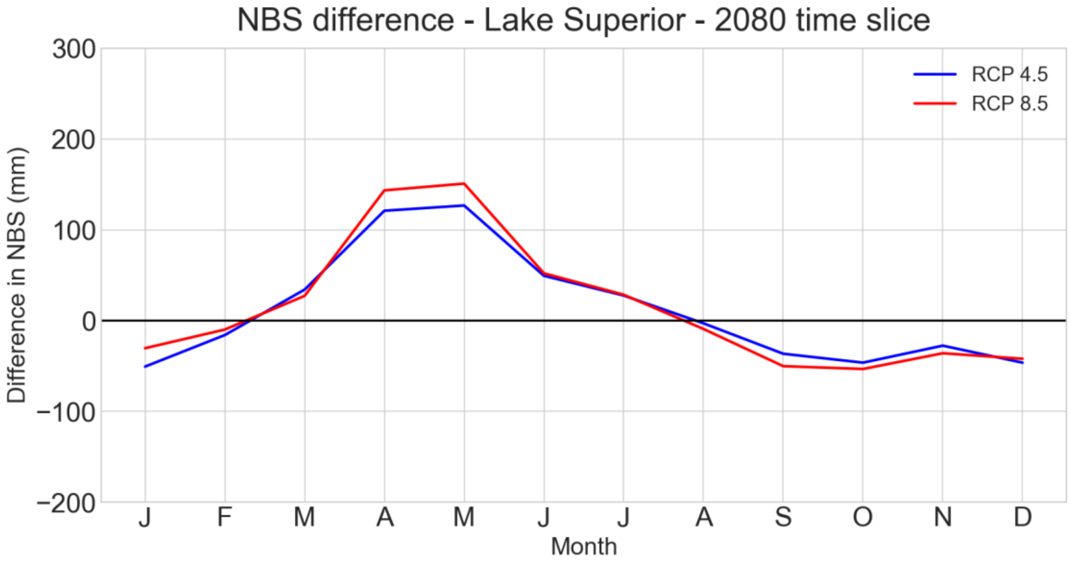

Figure B-2: Variability anomalies of the component NBS between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Superior.

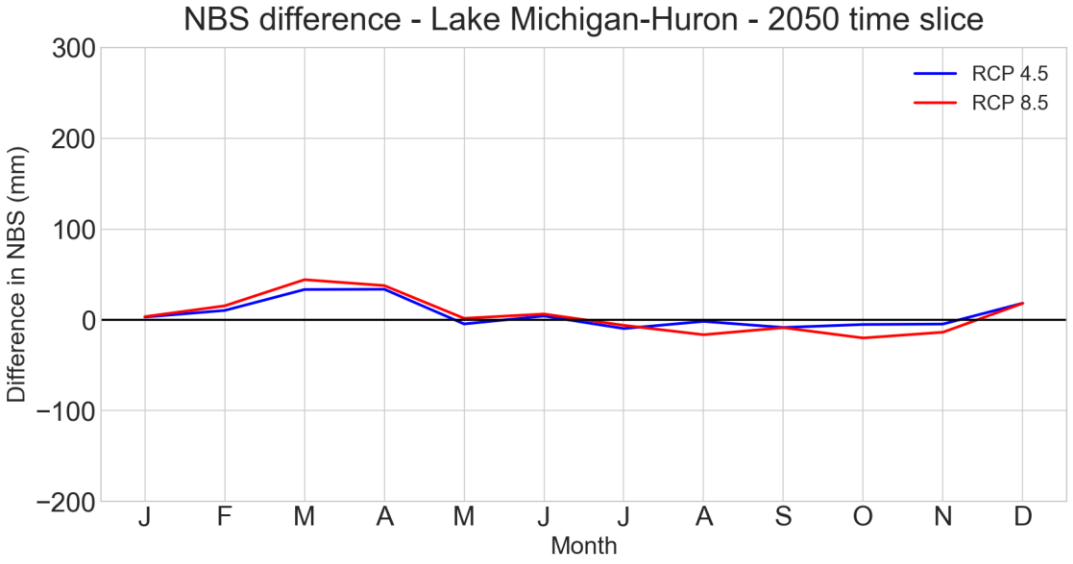

Figure B-3: Variability anomalies of the component NBS between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Michigan-Huron.

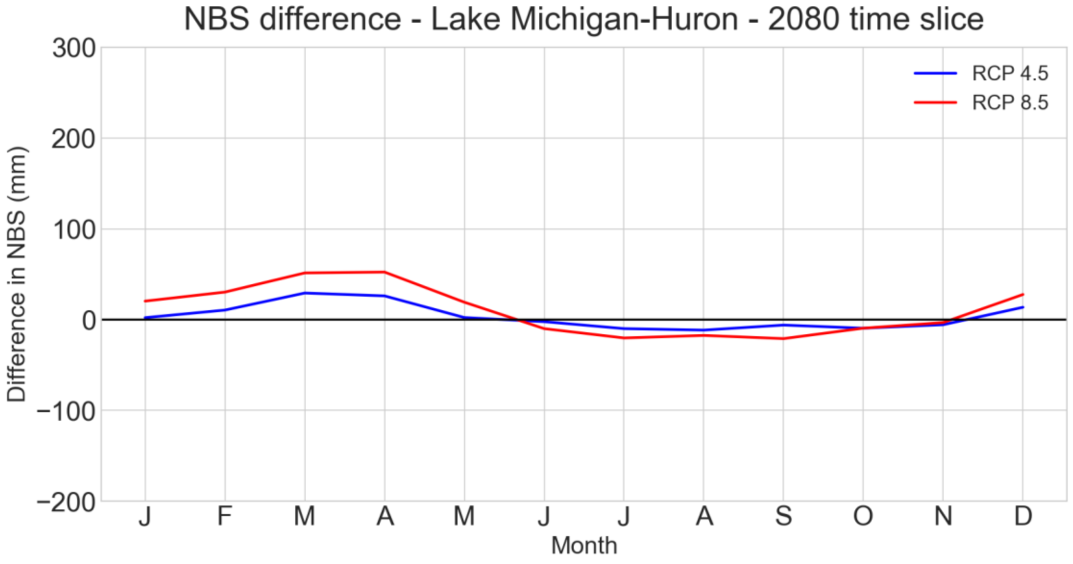

Figure B-4: Variability anomalies of the component NBS between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Michigan-Huron.

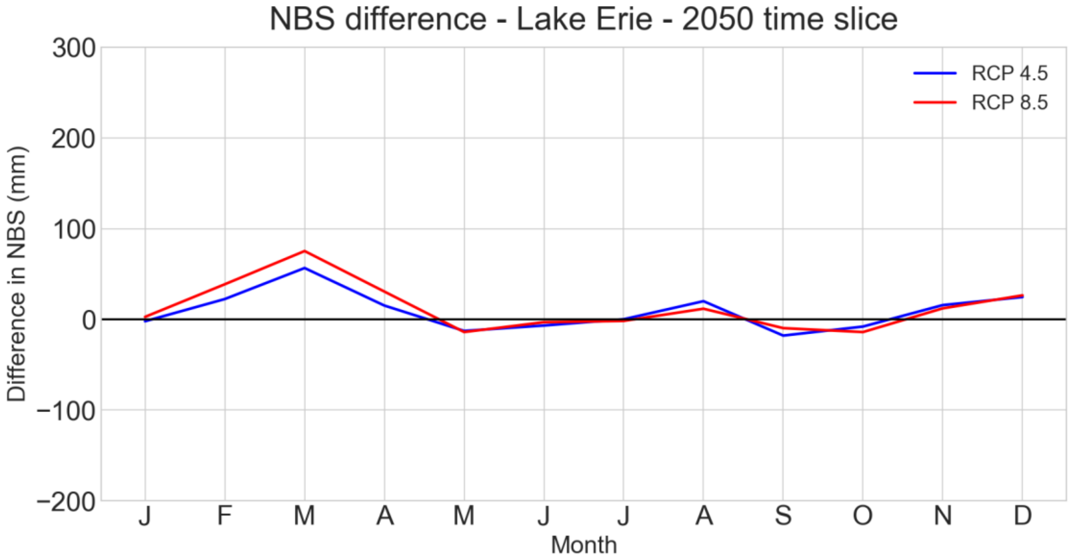

Figure B-5: Variability anomalies of the component NBS between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Erie.

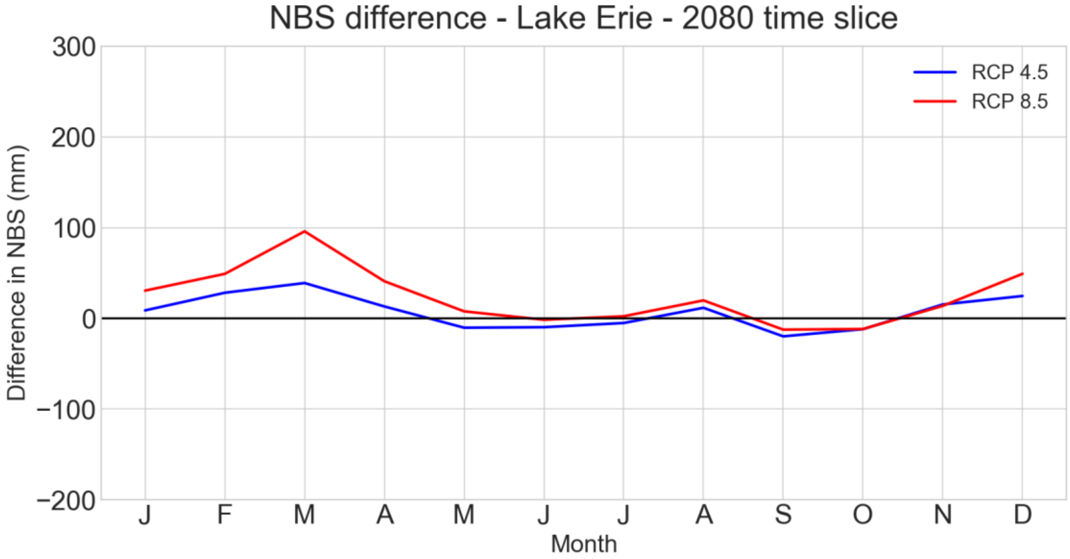

Figure B-6: Variability anomalies of the component NBS between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Erie.

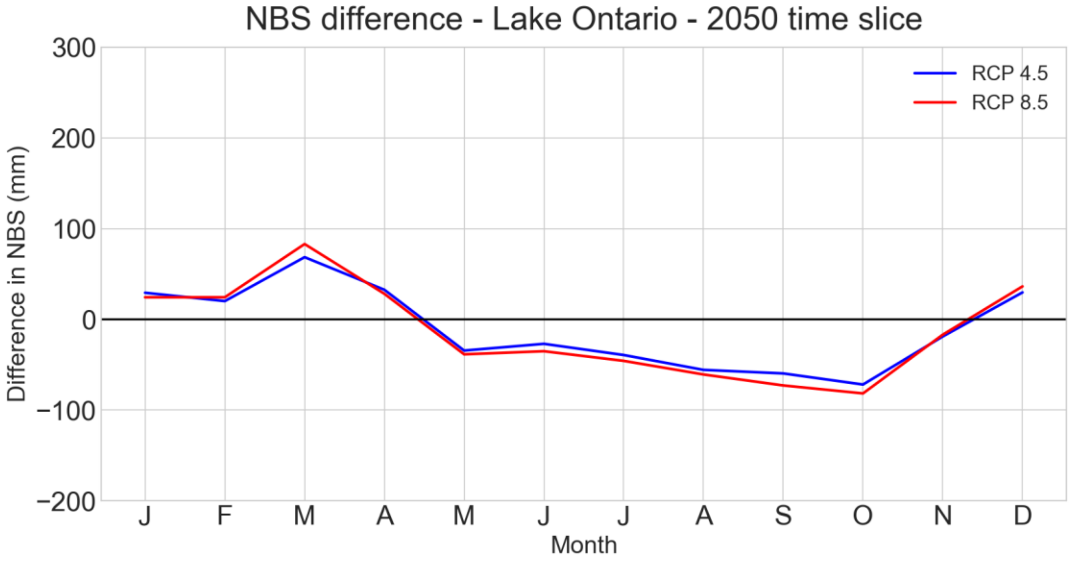

Figure B-7: Variability anomalies of the component NBS between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Ontario.

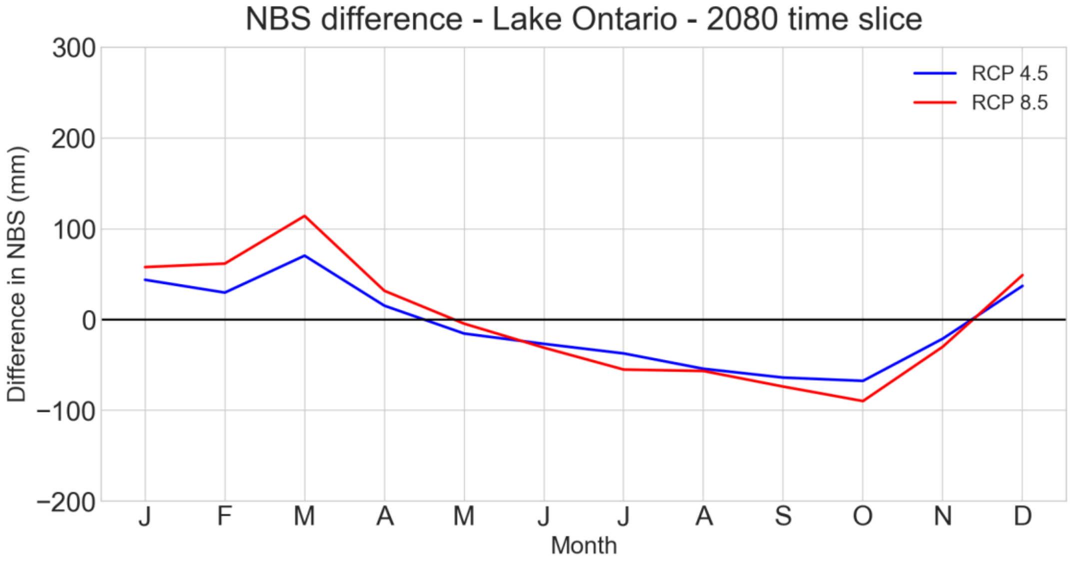

Figure B-8: Variability anomalies of the component NBS between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Ontario.

Appendix C: Seasonal anomalies of residual NBS

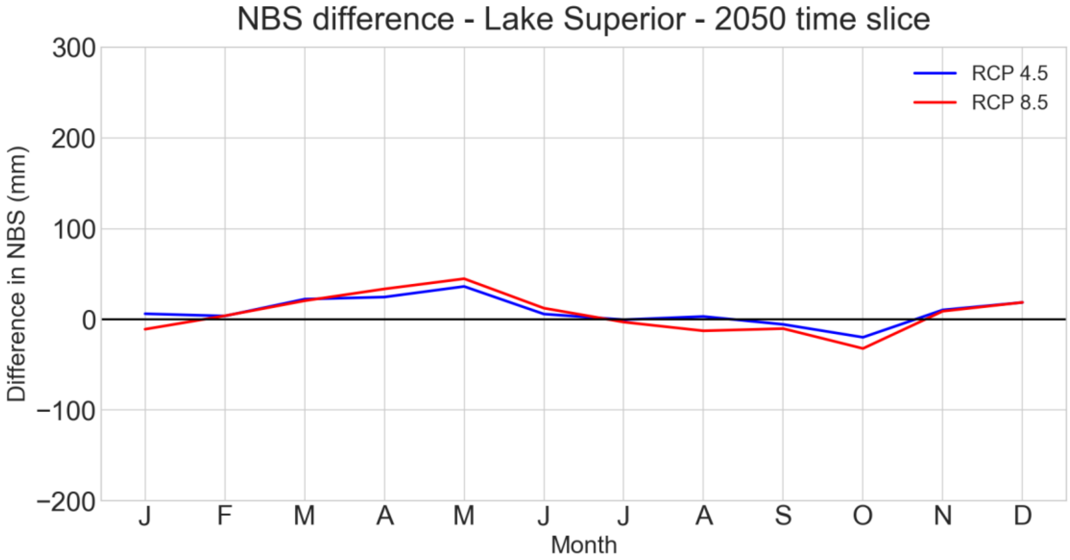

Figure C-1: Variability anomalies of the residual NBS between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Superior.

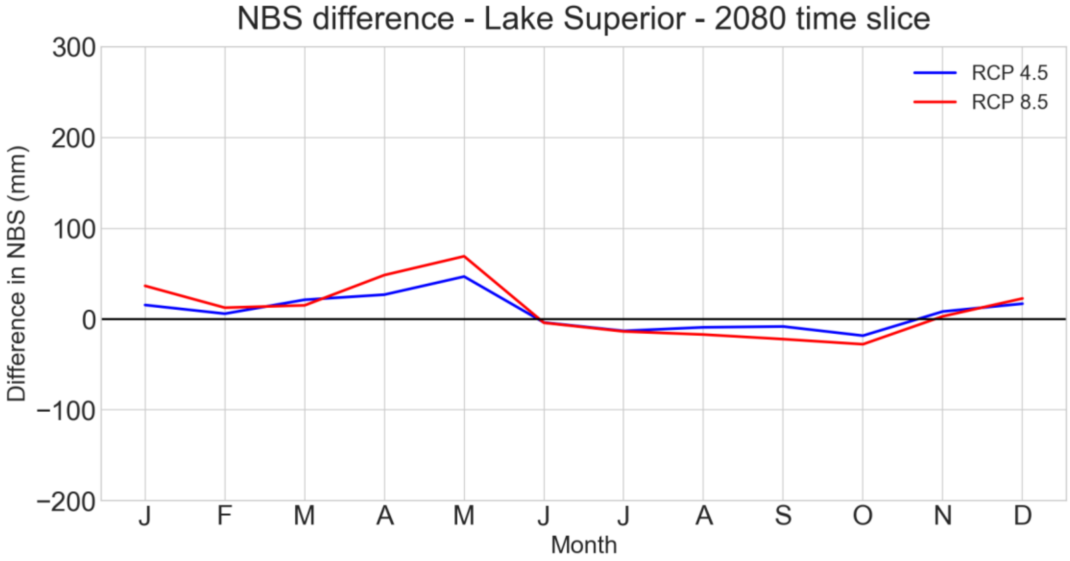

Figure C-2: Variability anomalies of the residual NBS between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Superior.

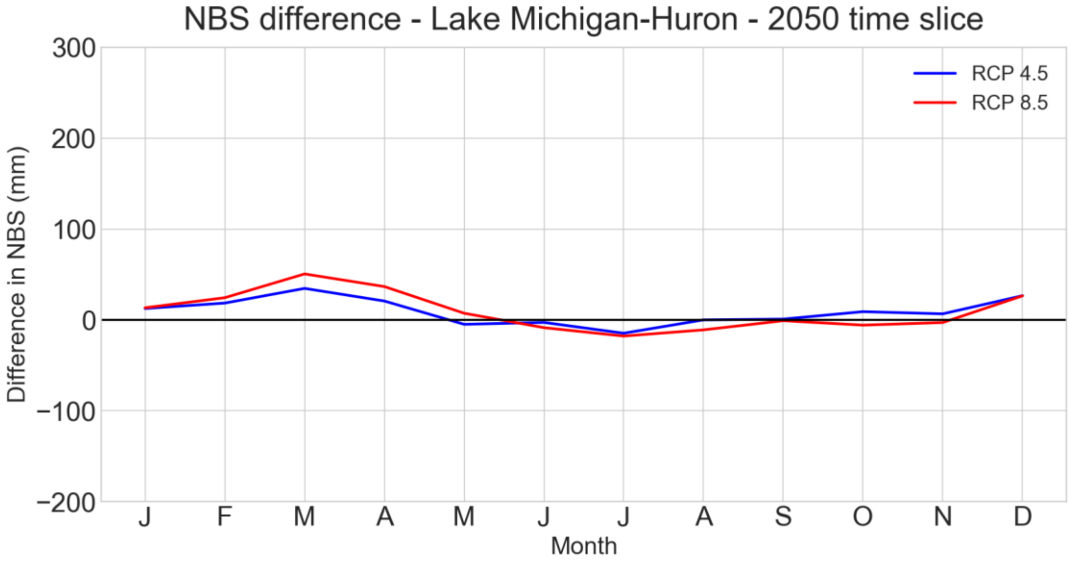

Figure C-3: Variability anomalies of the residual NBS between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Michigan-Huron.

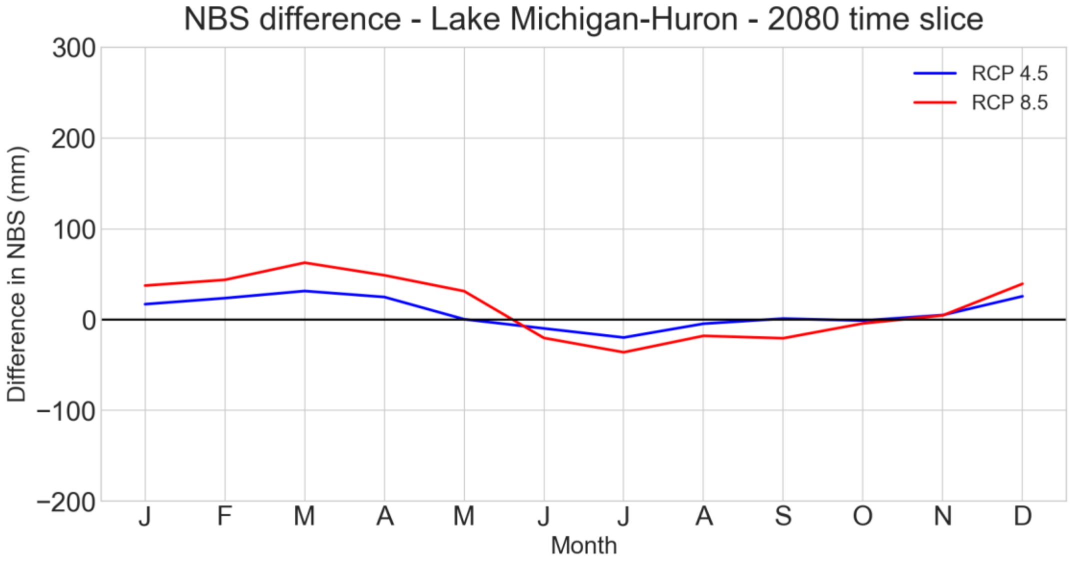

Figure C-4: Variability anomalies of the residual NBS between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Michigan-Huron.

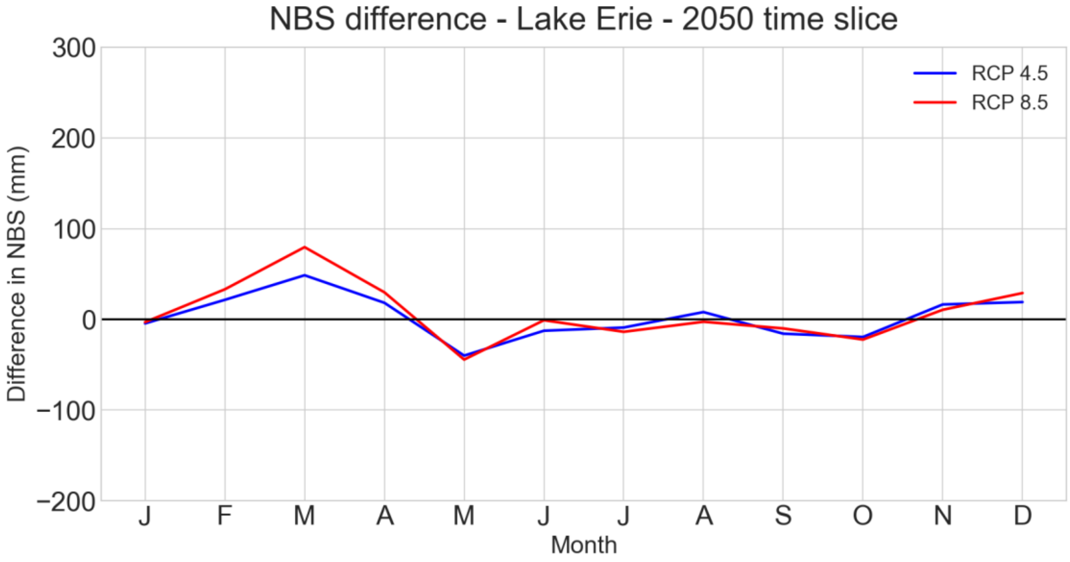

Figure C-5: Variability anomalies of the residual NBS between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Erie.

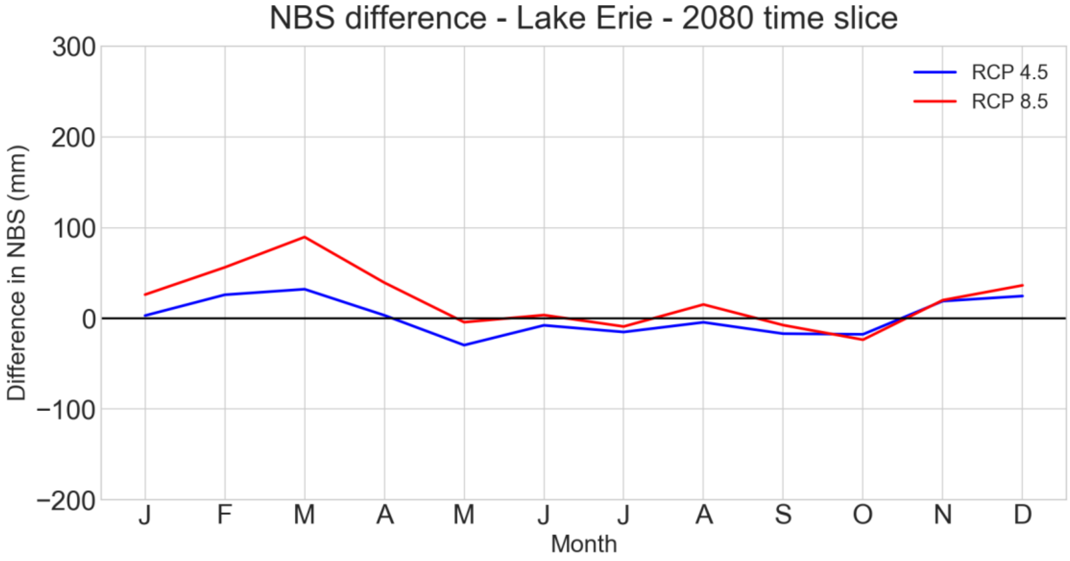

Figure C-6: Variability anomalies of the residual NBS between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Erie.

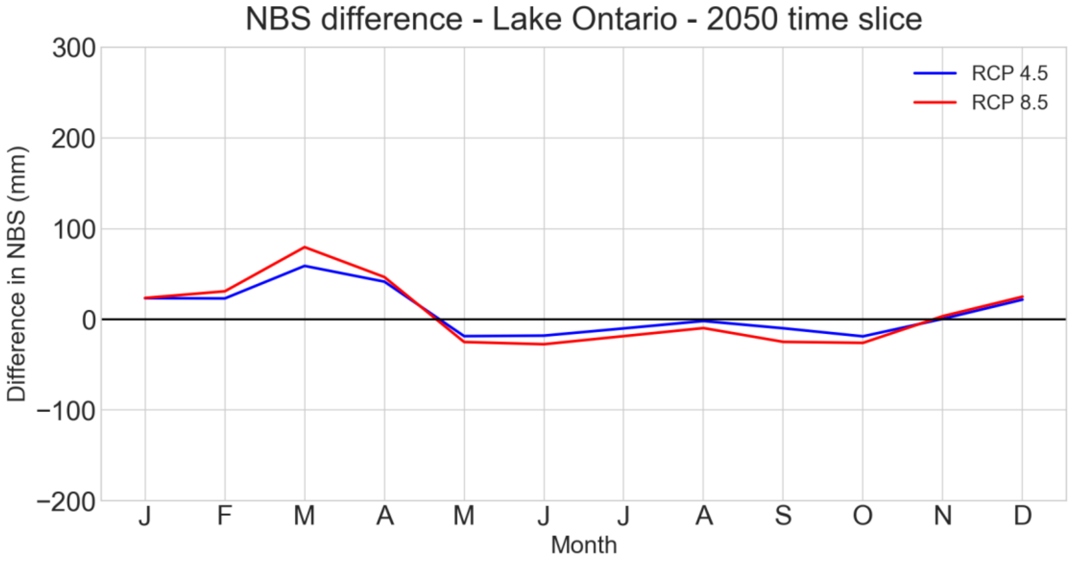

Figure C-7: Variability anomalies of the residual NBS between the 2050 time slice (2036-2065) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Ontario.

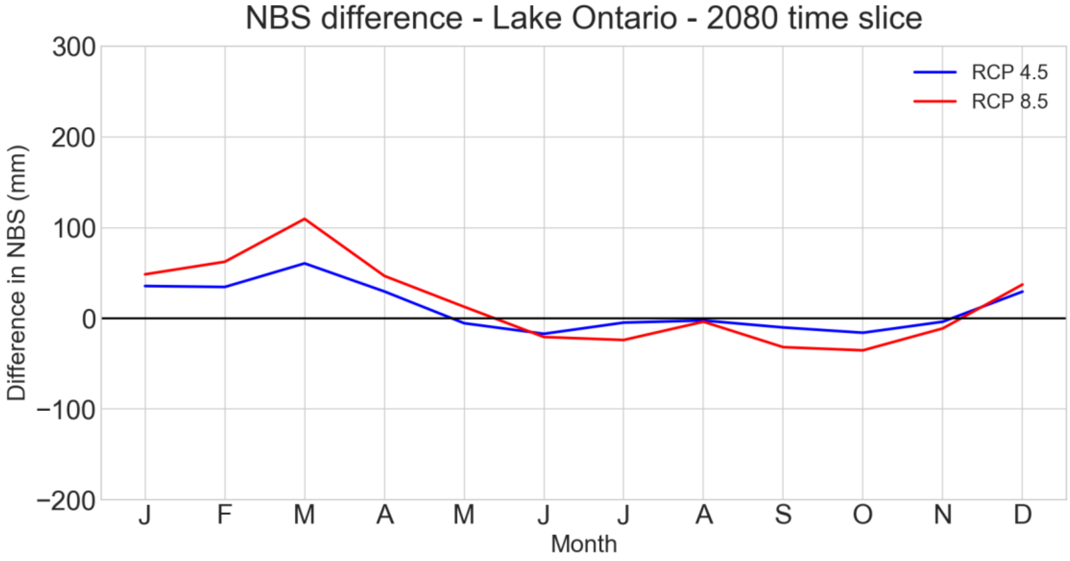

Figure C-8: Variability anomalies of the residual NBS between the 2080 time slice (2066-2095) from all the RCP 4.5 and RCP 8.5 runs and the current climate (1960-2010) for Lake Ontario.