A tug-of-war within the hydrologic cycle of a continental freshwater basin

A. D. Gronewold[1,2], H. X. Do[1,3], Y. Mei[1], and C. A. Stow[4]

[1]School for Environment and Sustainability, University of Michigan, Ann Arbor, Michigan, USA 48109
[2]Department of Earth and Environmental Sciences, University of Michigan, Ann Arbor, Michigan USA 48109
[3]Faculty of Environment and Natural Resources, Nong Lam University, Ho Chi Minh City, Vietnam 700000
[4]Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, Ann Arbor, Michigan, USA 48108

Key Points:

- An intensifying tug-of-war between precipitation and evaporation is dominating water level variability on Earth's largest lake system
- Competing forces are increasing or becoming more variable, setting the stage for oscillations between record high and record low levels
- Conditions evolved through abundant precipitation, and an abrupt decline in evaporation coinciding with a change in the Arctic polar vortex

---

Corresponding author: Andrew D. Gronewold, `drewgron@umich.edu`

Abstract

The past decade was the wettest on record for much of central and eastern North America. Near the beginning of this period of regional water abundance, however, drought conditions reinforced concerns that high temperatures and evapotranspiration foreshadowed a persistent imbalance in the hydrologic cycle characterized by water loss. These fluctuating hydrologic conditions were manifest by water level variability on the Laurentian Great Lakes, the largest system of lakes on Earth. We show that, during this period, the two dominant hydrologic forces acting directly on the vast surfaces of the Lakes, over-lake precipitation and over-lake evaporation, have evolved differently. More specifically, we find that over-lake precipitation has risen to extraordinary levels, while over-lake evaporation diminished rapidly in 2014 (coinciding with a strong Arctic polar vortex deformation). Our findings offer a new perspective on the impacts of competing hydrologic forces on large freshwater systems in an era of climate change.

1 Introduction

Over the past decade, persistent, abundant precipitation has led to extremely high soil moisture and widespread flooding across central and eastern North America [*Feng et al.*, 2016; *Carter and Steinschneider*, 2018]. Previous studies characterizing historical fluctuations in the hydrologic cycle of this region document increasing trends in precipitation and in the likelihood of flood events [*Groisman and Easterling*, 1994; *Hirabayashi et al.*, 2013; *Roque-Malo and Kumar*, 2017]. These conditions are associated with changes in atmospheric moisture fluxes and increasing air temperatures; yet, in other parts of North America (and the globe) climate change is more commonly associated with aridification and drought [*Lofgren et al.*, 2013; *Milly and Dunne*, 2017]. Near the beginning of this period of regional water abundance, however, drought conditions reinforced concerns that high temperatures and evapotranspiration might foreshadow a persistent imbalance in the hydrologic cycle characterized by net water loss [*Mallya et al.*, 2013; *Gronewold and Stow*, 2014; *Wang et al.*, 2014]. The recent fluctuation between these hydrologic conditions has been manifest by water level variability on the Laurentian Great Lakes [*Gronewold et al.*, 2016; *Gronewold and Rood*, 2019], the largest system of lakes on Earth.

In the absence of anthropogenic control, the water balance of most fresh surface water systems involves a trade-off between atmospheric transfer of moisture onto and across land surfaces, storage in surface and subsurface lakes and aquifers, and water loss through evapotranspiration [*Jasechko et al.*, 2013; *Munoz and Dee*, 2017]. The water balance of basins containing Earth's large lakes, however, is governed by additional hydrological processes, including those related to heat exchange and evaporation [*Blanken et al.*, 2003; *Gronewold and Stow*, 2014; *Xiao et al.*, 2018], over-lake precipitation [*Swenson and Wahr*, 2009; *Holman et al.*, 2012; *Fujisaki-Manome et al.*, 2020], and enhanced intra-basin precipitation recycling [*Notaro et al.*, 2013; *Fu and Steinschneider*, 2019]. These processes play a critical role in global water balance accounting and water management, given that Earth's ten largest lakes contain roughly 80% of all fresh, unfrozen surface water [*Messager et al.*, 2016; *Cael et al.*, 2017]. On the Great Lakes, for example, an understanding of historical and potential future changes in the major components of the water balance guides decisions related to flood risk (particularly along the shoreline of Lake Ontario), hydropower management, and commercial navigation [*Millerd*, 2011; *Gronewold and Rood*, 2019; *Labuhn et al.*, 2020].

Understanding the water balance of large lakes is important not only because it facilitates water resources management by accounting for the majority of Earth's fresh surface water storage, but also because it provides insight into pathways through which climate change and other continental-scale phenomena are propagating into processes that are not addressed in conventional land surface hydrology [*Lofgren and Gronewold*, 2013; *Milly and Dunne*, 2017]. These processes include, for example, the subsidence of the Earth's surface beneath the lakes in response to the weight of the increased load of the recent water level rise [*Argus et al.*, 2020].

Here, we fill a gap in knowledge about the distinction between land and lake surface hydrological processes on the continental water balance through an analysis of the Upper St. Lawrence River Basin. The St. Lawrence River has the second highest annual average discharge from the North American continent (table 1; estimates of discharge are derived from *Nilsson et al.* [2005]), though the variability of that discharge is relatively low compared to other continental rivers because the water balance of the upper portion of the basin is dominated by the storage capacity of the Laurentian Great Lakes. It is informative to note that there are multiple potential delineations of the boundary of the St. Lawrence River basin, depending on the definition of the River's outlet. We extracted a basin boundary delineation from the HydroBASINS dataset [*Lehner and Grill*, 2013] where the Great Lakes and St. Lawrence River system outlet is defined as the point where it meets the

Table 1. Annual average discharge (in cubic meters per second, cms) of North America's eight largest rivers (rounded to the nearest hundred).

River	Annual average discharge (cms)
Mississippi	18,400
St. Lawrence	10,800
Mackenzie	9,900
Columbia	7,500
Yukon	6,400
Fraser	3,600
Nelson	2,800
Koksoak	2,400

Saguenay River; our delineations are also consistent with definitions in the Global Lakes and Wetlands Database [*Lehner and Döll*, 2004].

We note that most historical studies of the water balance in North America are constrained to land surface processes either strictly within the United States or strictly within Canada because of the challenges associated with harmonizing hydrometeorological data across the international border [*Gronewold et al.*, 2018; *Mason et al.*, 2019]. Historical studies linking climate change to hydrology also commonly omit basins with large lakes because, we believe, of the challenge of representing them accurately in land surface and atmospheric models [*Nijssen et al.*, 2001; *Maurer et al.*, 2002; *Gu et al.*, 2013; *Notaro et al.*, 2013]. To address this limitation, we have synthesized the most reliable estimates for each component of the water balance of the Laurentian Great Lakes. Importantly, these estimates address components of the water balance not only over the land surface, but also over the lake surfaces of this massive freshwater system.

2 Datasets

2.1 Historical Great Lakes water levels.

We obtained monthly average Great Lakes water level data from the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (hereafter simply "Coordinating Committee”). This *ad hoc* group of federal scientists from the United States and Canada synthesizes, and distributes to the public, a comprehensive suite of climate and hydrological data for the Great Lakes and St. Lawrence River system [*Gronewold et al.*, 2018]. The Coordinating Committee calculates, and reports, monthly average water level values for each of the Great Lakes based on a network of shoreline-based water level monitoring stations maintained by the National Oceanic and Atmospheric Administration (NOAA) and the Canadian Hydrographic Service. The data is distributed through multiple portals, including web sites hosted by the Coordinating Committee, the United States Army Corps of Engineers, and NOAA [*Smith et al.*, 2016].

2.2 Components of the Great Lakes water balance.

We developed multiple estimates of each component of the Great Lakes water balance (see Supporting Information) and selected those that we believe to be the most accurate (see Supporting Information figure S2). It is informative to note that, given the seasonality of each component of the Great Lakes hydrologic cycle, we aggregated monthly water balance component estimates into a modified version of the conventional hydrological “water year”; our water year (for each lake) begins July 1, and ends on the last day of the following June.

Annual precipitation totals on the land surface surrounding the Great Lakes and St. Lawrence River (red and green areas in figure 1) are derived from areally-averaged gage measurements documented in the NOAA Great Lakes Environmental Research Laboratory (GLERL) Great Lakes Monthly Hydrometeorological Database, or GLM-HMD [*Hunter et al.*, 2015]. Land evapotranspiration estimates starting in 1950 and ending in 2013 are from what is commonly referred to as the “Livneh Gridded Precipitation and Other Meteorological Variables product” [*Livneh et al.*, 2015]. Land evapotranspiration estimates from 2014 onward are from ERA5 [*Copernicus Climate Change Service (C3S)*, 2017].

Estimates of runoff, lake precipitation, lake evaporation, and net lake moisture flux are derived from the Large Lake Statistical Water Balance Model (L2SWBM). The L2SWBM includes a series of conventional lake water balance algorithms encoded within a Bayesian statistical framework [*Gronewold et al.*, 2020] that infers (with an expression of uncertainty) each component of the water balance for either a single lake, or for a connected system of lakes. We then aggregated these estimates, using the surface area of each lake,

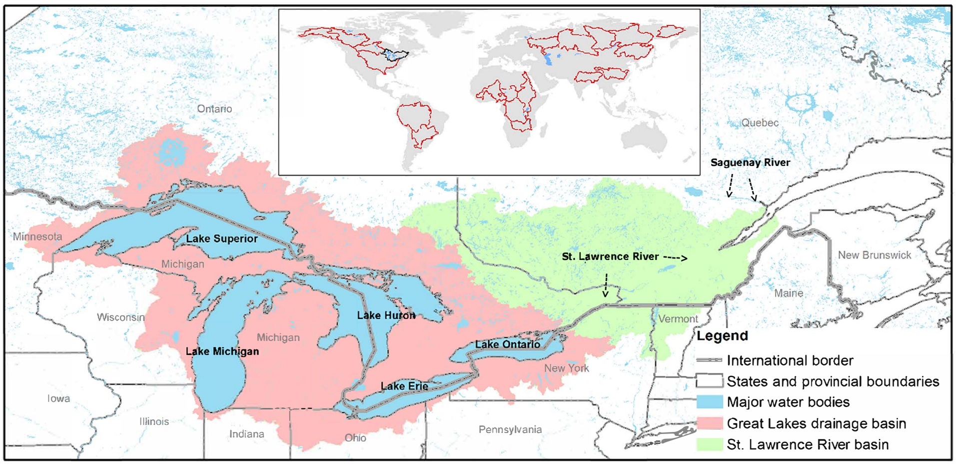

Figure 1. Map of the St. Lawrence River basin, including a delineation of the sub-basin of the Laurentian Great Lakes (i.e. the upper portion of the St. Lawrence River basin). Inset figure delineates the 20 largest river basins on Earth (St. Lawrence River basin is outlined in black in inset).

into a single value of total over-lake precipitation, total over-lake evaporation, and total lake inflow through tributary runoff. Details of our parameterization of the L2SWBM for this study, as well as the L2SWBM simulations and corresponding code, are available via the University of Michigan's DeepBlue archive [*Do et al.*, 2020].

3 Results and Discussion

Water levels across the Great Lakes system have risen sharply over the past five years (figure 2) surpassing both monthly and all-time record highs. Lake Superior and Lake Michigan-Huron, for example, set new monthly high water level records in 2019 and 2020. Lake Ontario set a new all-time high level in 2017, and both Lake Erie and Lake Ontario set new all-time high level records 2019. These conditions are all-the-more profound given that water level measurements on the Great Lakes date to 1860 (see Supporting Information, figure S1), and that water levels on Lakes Superior and Michigan-Huron were at or near record low conditions for much of the period from 1999 through 2013 (figure 2). Lake Superior reached record monthly lows in both August and September of 2007, while Lake Michigan-Huron reached a record low for the month of December in 2012 and an all-time record low in January 2013 [*Gronewold and Stow*, 2014].

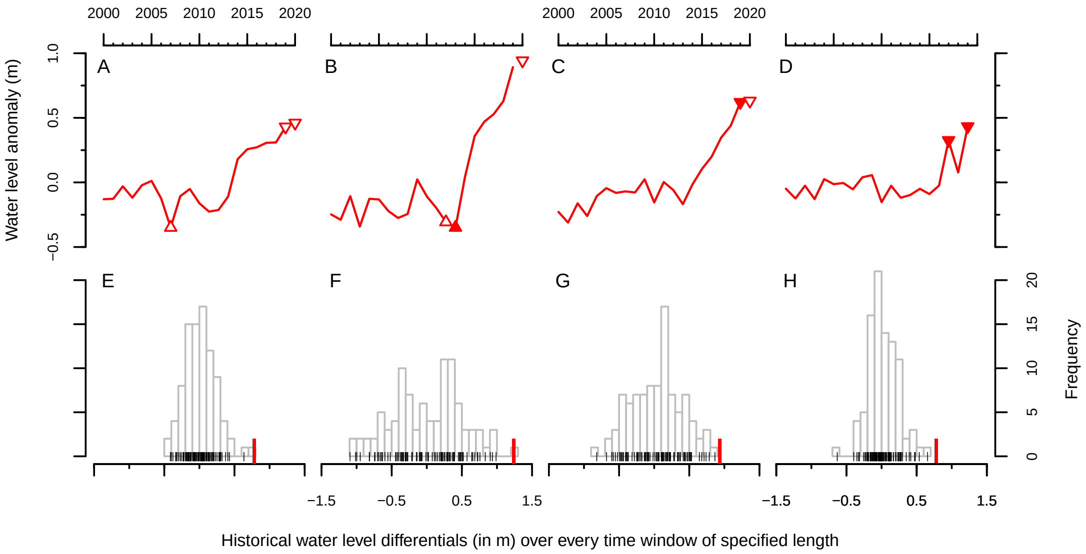

Figure 2. Annual water level anomalies from 2000 to 2019 for Lake Superior (A), Michigan-Huron (B), Erie (C), and Ontario (D). Upward-pointing hollow and solid triangles represent years with either a monthly or (respectively) all-time record low water level. Downward-pointing hollow and solid triangles represent years with either a monthly or (respectively) all-time record high water level. Histograms of historical water level differentials across every incremental window of 12 years for Lake Superior (E), 6 years for Michigan-Huron (F), 7 years for Erie (G), and 10 years for Ontario (G). Black tick marks represent the differential from each historical time window; red tick mark represents the most recent water level differential shown in panels (A), (B), (C), or (D), respectively.

Water level fluctuations across this massive lake system are driven by seasonal and interannual partitioning of precipitation and evapotranspiration across the lake and surrounding land surfaces. Water balance assessments of the Great Lakes, and other large lakes, commonly aggregate these processes into three discrete components: lake lateral tributary runoff (defined here as the summation of lake inflow from all lateral tributaries and streams, with the exception of inflow from a lake's upstream connecting channel), over-lake precipitation, and over-lake evaporation [*Lenters*, 2001; *Pietroniro et al.*, 2007; *Fry et al.*, 2013; *Gaborit et al.*, 2017]. Our analysis of changes in these water balance components across the upper portion of the St. Lawrence River basin dating to 1950 (figure 3) indicates that the recent (2013-2018) extreme water level fluctuations on the Great Lakes are a response to an increase in both the magnitude and variability of precipitation, land surface evapotranspiration, and lake evaporation. It is informative to note that while Great Lakes water level *in situ* measurements date to 1860, few data sets extend evaporation records prior to 1950 because of the limited extent of hydrometeorological monitoring networks prior to that year. As such, our historical context for the recent water level surge is based on a record dating to 1900, however our historical context for changes in the water balance dates only to 1950.

We find that precipitation over the land surfaces of the basin (figure 3A) has risen steadily over the past two decades and is now at extraordinary levels. The three highest years of precipitation between 1950 and 2020 were 2018 (highest), 2013 (second highest), and 2016 (third highest). It very unlikely that this pattern is the result of natural variability alone. In fact, this sequence aligns with climate change projections for the Great Lakes region, which generally indicate an expected increase in long-term regional precipitation [*Chao*, 1999; *Michalak et al.*, 2013; *Lofgren and Gronewold*, 2014; *Milly and Dunne*, 2017]. One study, for example [*Notaro et al.*, 2015], showed that 33 general circulation models (GCMs) selected from the fifth Coupled Model Intercomparison Project (CMIP5) projected virtually no change (3 GCMs) or a definitive increase (30 GCMs) in annual precipitation across the Great Lakes by the mid-21st century (with an expected continued increase through the end of the 21st century). A related study [*Basile et al.*, 2017] also found that most regional climate models (RCMs) driven by GCMs from CMIP5 indicate a 10 to 20% increase in precipitation (specifically for Lake Erie) by mid-21st century.

Interestingly, between 1998 and 2013, when water levels on Lakes Superior, Michigan, and Huron were very low (figure 2), land evapotranspiration and lake evaporation dominated the water balance (figure 3B and E). Only when lake evaporation shifted abruptly from above- to below-average conditions in the winter of 2013-2014 (figure 3E) did abundant precipitation across the region propagate into a record-setting rate of water level rise [*Gronewold et al.*, 2016] and the recent series of record-high monthly and annual average levels (figure 2).

It is informative to note that the rapid decline in over-lake evaporation in early 2014 coincided with an extreme Arctic polar vortex deformation [*Clites et al.*, 2014; *Zhang et al.*, 2016] which resulted in an outburst of very cold air over central North America, and a decrease in Great Lakes surface water temperatures [*Gronewold et al.*, 2015]. While there appears to be a strong association between the cold air outburst and the decrease in evaporation, the nature of connections between global climate change and the frequency, intensity, and orientation of Arctic polar vortex deformations is less clear [*Zhang et al.*,

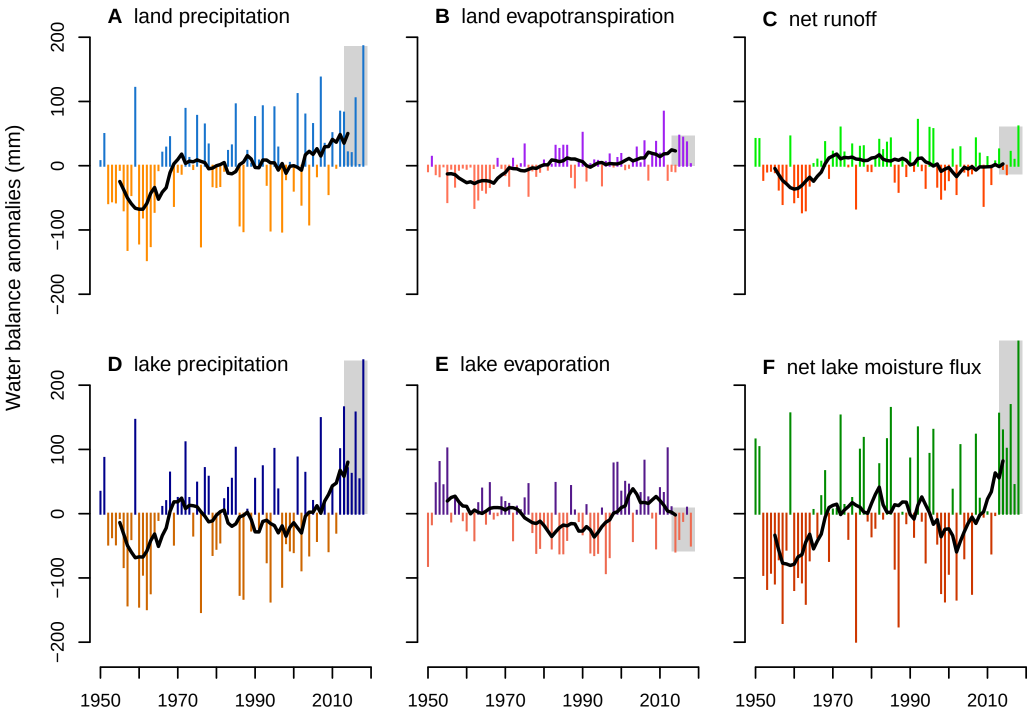

Figure 3. Anomalies in the components of the Great Lakes water balance including over-land precipitation (A), evapotranspiration (B), lateral tributary (or the "net" difference between land precipitation and land evapotranspiration) runoff (C), over-lake precipitation (D), over-lake evaporation (E), and the difference (i.e. "net" moisture flux) between over-lake precipitation and over-lake evaporation (D) from 1950 to present. Values are expressed as annual water totals distributed over the collective surface area of the lakes (A-C) and the land portion (D-F) of the basin. Colors differentiate positive and negative anomalies. Black lines represent the (centered) ten-year rolling mean. Grey regions bound anomalies between 2013 and 2018.

2016; *Lee and Butler*, 2020]. It is also worth noting that evapotranspiration on the land surface of the Great Lakes basin, which had been increasing over the period of record (figure 3B), also abruptly declined in 2014 but, unlike lake evaporation, has since returned to high levels. Improving understanding of the mechanisms that initiated and continue to maintain low levels of evaporation after 2014, and whether those mechanisms might continue to be linked to Arctic polar vortex deformations in the future, is an area for future research.

We have found evidence of an increase in the variability of competing forces on the water balance across a large portion of central and eastern North America, suggesting a continental-scale hydrological tug-of-war. We also note that runoff into the lakes, despite the rise in regional precipitation, has been relatively stable over much of the past 30 years, reflecting the offsetting effect of water loss through high evapotranspiration from the land surface. While water levels on the Great Lakes surged when lake evaporation slowed in 2014, our research suggests that any comparable change in one of the region's water balance components could lead to an extreme water level fluctuation. A decrease in regional precipitation, for example, given its current magnitude, could lead to sudden water level declines.

4 Conclusion

In freshwater basins with large lakes, water balance accounting on land surfaces alone does not address the full suite of changes in the hydrologic cycle that can lead to flooding, coastal erosion, and threats to human health and safety. We have shown that changes in precipitation and lake evaporation across the surfaces of one of Earth's largest lake systems have profoundly influenced inland coastal water level variability and continental discharge. These findings have provided insight into important hydroclimate relationships that are not reflected in commonly-used global data sets and models [*Notaro et al.*, 2013; *Wright et al.*, 2013; *Bryan et al.*, 2015; *Minallah and Steiner*, 2020]. This type of inconsistency in the representation of hydrologic conditions between models and data sets developed at different spatial scales further exacerbates challenges facing regional climate science and water management. Reconciling and forecasting the water balance for managing human and environmental health and safety warrants adoption of data development and modeling protocols that explicitly propagate global climate dynamics into hydrologic response at regional scales. In future research, we suggest implementing similar analyses for lake-dominated hydrologic systems to ensure an appropriate accounting of historical, and potential future variability in Earth's fresh surface water storage.

Acknowledgments

The authors thank Alexander Vandeweghe for a preliminary analysis of lake evaporation. Vincent Fortin and Lauren Fry provided insight on continental discharge estimates and water level records during the formulation of this manuscript. Jenna Sherwin confirmed our calculation of water level record highs and lows, and updated the historical water level plot in the Supplementary Information. This is NOAA-GLERL publication No. XXXX.

Data Availability Statement

Data sets and model simulations for this project derived from the GLM-HMD [*Hunter et al.*, 2015], L2SWBM [*Gronewold et al.*, 2020; *Do et al.*, 2020], WCPS [*Deacu et al.*, 2012; *Durnford et al.*, 2018], AHPS [*Gronewold et al.*, 2011; *Apps et al.*, 2020], WATFLOOD [*Kouwen*, 1988], CaPA [*Mahfouf et al.*, 2007; *Lespinas et al.*, 2015], MPE [*Seo*, 1998; *Seo and Breidenbach*, 2002], and the 'Merged' overlake precipitation data set [*Gronewold et al.*, 2018] have been compiled and sotred on the University of Michigan DeepBlue archive at `https://deepblue.lib.umich.edu/data/concern/data_sets/sb3978457`.

Additionally, estimates of over-land precipitation are available directly from the NOAA-GLERL repository at `www.glerl.noaa.gov/data/dashboard/data/hydroIO/precip/`. ERA5 data [*Copernicus Climate Change Service (C3S)*, 2017] is available at:

`https://cds.climate.copernicus.eu/`, and the data developed by Dr. Ben Livneh [*Livneh et al.*, 2015] is available at:

`www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:Livneh-Model`.

Soil moisture data was obtained from the NOAA CPC at:

`https://psl.noaa.gov/data/gridded/data.cpcsoil.html`.

References

Apps, D., L. M. Fry, and A. D. Gronewold (2020), Operational seasonal water supply and water level forecasting for the Laurentian Great Lakes, *Journal of Water Resources Planning and Management*, *146*(9), 04020,072.

Argus, D. F., B. Ratliff, C. DeMets, A. A. Borsa, D. N. Wiese, G. Blewitt, J. W. Crowley, H. R. Martens, C. Kreemer, and F. W. Landerer (2020), Rise of Great Lakes surface water, sinking of the upper Midwest of the United States, and viscous collapse of the forebulge of the former Laurentide ice sheet, *Journal of Geophysical Research: Solid Earth*, *125*(9), e2020JB019,739.

Basile, S. J., S. A. Rauscher, and A. L. Steiner (2017), Projected precipitation changes within the Great Lakes and western Lake Erie basin: a multi-model analysis of intensity and seasonality, *International Journal of Climatology*, *37*(14), 4864–4879.

Benke, A. C., and C. E. Cushing (2011), *Rivers of North America*, Academic Press.

Blanken, P. D., W. R. Rouse, and W. M. Schertzer (2003), Enhancement of evaporation from a large northern lake by the entrainment of warm, dry air, *Journal of Hydrometeorology*, *4*(4), 680–693.

Bryan, A. M., A. L. Steiner, and D. J. Posselt (2015), Regional modeling of surface-atmosphere interactions and their impact on Great Lakes hydroclimate, *Journal of Geophysical Research: Atmospheres*, *120*(3), 1044–1064.

Cael, B. B., A. J. Heathcote, and D. A. Seekell (2017), The volume and mean depth of Earth's lakes, *Geophysical Research Letters*, *44*(1), 209–218.

Carter, E., and S. Steinschneider (2018), Hydroclimatological drivers of extreme floods on Lake Ontario, *Water Resources Research*, *54*(7), 4461–4478.

Chao, P. (1999), Great Lakes water resources: climate change impact analysis with transient GCM scenarios, *JAWRA Journal of the American Water Resources Association*, *35*(6), 1499–1507.

Clites, A. H., J. Wang, K. B. Campbell, A. D. Gronewold, R. A. Assel, X. Bai, and G. A. Leshkevich (2014), Cold water and high ice cover on Great Lakes in spring 2014, *Eos, Transactions American Geophysical Union*, *95*(34), 305–306.

Copernicus Climate Change Service (C3S) (2017), ERA5: Fifth generation of ECMWF atmospheric reanalysis of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), *Accessed 25 May 2020, https://cds.climate.copernicus.eu/cdsapp#!/home*.

Deacu, D., V. Fortin, E. Klyszejko, C. Spence, and P. D. Blanken (2012), Predicting the net basin supply to the Great Lakes with a hydrometeorological model, *Journal of Hydrometeorology*, *13*(6), 1739–1759.

Do, H. X., J. P. Smith, L. M. Fry, and A. D. Gronewold (2020), Seventy-year long record of monthly water balance estimates for Earth's largest lake system, *Scientific Data*, *7*(276).

Durnford, D., V. Fortin, G. C. Smith, B. Archambault, D. Deacu, F. Dupont, S. Dyck, Y. Martinez, E. Klyszejko, M. MacKay, and L. Liu (2018), Toward an operational water cycle prediction system for the Great Lakes and St. Lawrence River., *Bulletin of the American Meteorological Society*, *99*(3), 521–546.

Feng, Z., R. Leung, S. Hagos, R. A. Houze, C. D. Burleyson, and K. Balaguru (2016), More frequent intense and long-lived storms dominate the springtime trend in central US rainfall, *Nature Communications*, *7*(1), 1–8.

Fry, L. M., T. S. Hunter, M. S. Phanikumar, V. Fortin, and A. D. Gronewold (2013), Identifying streamgage networks for maximizing the effectiveness of regional water balance modeling, *Water Resources Research*, *49*(5), 2689–2700.

Fu, W., and S. Steinschneider (2019), A diagnostic-predictive assessment of winter precipitation over the Laurentian Great Lakes: effects of ENSO and other teleconnections, *Journal of Hydrometeorology*, *20*(1), 117–137.

Fujisaki-Manome, A., E. J. Anderson, J. Kessler, P. Y. Chu, J. Wang, and A. D. Gronewold (2020), Simulating impacts of precipitation on ice cover and surface water temperature across large lakes, *Journal of Geophysical Research - Oceans*, *125*(5).

Gaborit, E., V. Fortin, X. Xu, F. Seglenieks, B. A. Tolson, L. M. Fry, T. S. Hunter, F. Anctil, and A. D. Gronewold (2017), A hydrological prediction system based on the SVS land-surface scheme: efficient calibration of GEM-Hydro for streamflow simulation over the Lake Ontario basin, *Hydrology and Earth System Sciences*, *21*(9), 4825–4839.

Groisman, P. Y., and D. Easterling (1994), Variability and trends in total precipitation and snowfall over the United States and Canada, *Journal of Climate*, *7*(1), 184–205.

Gronewold, A. D., and R. B. Rood (2019), Recent water level changes across Earth's largest lake system and implications for future variability, *Journal of Great Lakes Research*, *45*(1), 1–3.

Gronewold, A. D., and C. A. Stow (2014), Water loss from the Great Lakes, *Science*, *343*(6175), 1084–1085.

Gronewold, A. D., A. H. Clites, T. S. Hunter, and C. A. Stow (2011), An appraisal of the Great Lakes advanced hydrologic prediction system, *Journal of Great Lakes Research*, *37*(3), 577–583.

Gronewold, A. D., E. J. Anderson, B. M. Lofgren, P. D. Blanken, J. Wang, J. P. Smith, T. S. Hunter, G. A. Lang, C. A. Stow, D. Beletsky, and J. F. Bratton (2015), Impact of extreme 2013-2014 winter conditions on Lake Michigan's fall heat content, surface temperature, and evaporation, *Geophysical Research Letters*, *42*(9), 3364–3370.

Gronewold, A. D., J. Bruxer, D. Durnford, J. P. Smith, A. H. Clites, F. Seglenieks, S. S. Qian, T. S. Hunter, and V. Fortin (2016), Hydrological drivers of record-setting water level rise on Earth's largest lake system, *Water Resources Research*, *52*(5), 4026–4042.

Gronewold, A. D., V. Fortin, R. Caldwell, and J. Noel (2018), Resolving hydrometeorological data discontinuities along an international border, *Bulletin of the American Meteorological Society*, *99*(5), 899–910.

Gronewold, A. D., J. P. Smith, L. K. Read, and J. L. Crooks (2020), Reconciling the water balance of large lake systems, *Advances in Water Resources*, *137*, doi: doi.org/10.1016/j.advwatres.2020.103505.

Gu, H., J. Jin, Y. Wu, M. B. Ek, and Z. Subin (2013), Calibration and validation of lake surface temperature simulations with the coupled WRF-lake model, *Climatic Change*, *129*(3), 471–483.

Hirabayashi, Y., R. Mahendran, S. Koirala, L. Konoshima, D. Yamazaki, S. Watanabe, H. Kim, and S. Kanae (2013), Global flood risk under climate change, *Nature Climate Change*, *3*(9), 816–821.

Holman, K. D., A. D. Gronewold, M. Notaro, and A. Zarrin (2012), Improving historical precipitation estimates over the Lake Superior basin, *Geophysical Research Letters*, *39*(3), L03,405.

Hunter, T. S., A. H. Clites, K. B. Campbell, and A. D. Gronewold (2015), Development and application of a monthly hydrometeorological database for the North American Great Lakes - Part I: precipitation, evaporation, runoff, and air temperature, *Journal of Great Lakes Research*, *41*(1), 65–77.

Jasechko, S., Z. D. Sharp, J. J. Gibson, S. S. Birks, Y. Yi, and P. j. Fawcett (2013), Terrestrial water fluxes dominated by transpiration, *Nature*, *496*(7445), 347–350.

Kammerer, J. C. (1990), Largest Rivers in the United States – Report 87-242, *Tech. rep.*, USGS, Reston, VA.

Kouwen, N. (1988), WATFLOOD: a micro-computer based flood forecasting system based on real-time weather radar, *Canadian Water Resources Journal*, *13*(1), 62–77.

Labuhn, K., A. D. Gronewold, T. J. Calappi, A. MacNeil, C. Brown, and E. J. Anderson (2020), Towards an operational flow forecasting system for the Upper Niagara River, *Journal of Hydraulic Engineering*, *146*(9), 05020,006, doi:10.1061/(ASCE)HY.1943-7900.0001781.

Lee, S. H., and A. H. Butler (2020), The 2018-2019 Arctic stratospheric polar vortex, *Weather*, *75*(2), 52–57.

Lehner, B., and P. Döll (2004), Development and validation of a global database of lakes, reservoirs, and wetlands, *Journal of Hydrology*, *296*(104), 1–22.

Lehner, B., and G. Grill (2013), Global river hydrology and network routing: baseline data and new approaches to study the world's large river systems, *Hydrological Processes*, *27*(15), 2171–2186.

Lenters, J. D. (2001), Long-term trends in the seasonal cycle of Great Lakes water levels, *Journal of Great Lakes Research*, *27*(3), 342–353.

Lespinas, F., V. Fortin, G. Roy, P. Rasmussen, and T. Stadnyk (2015), Performance evaluation of the Canadian Precipitation Analysis (CaPA), *Journal of Hydrometeorology*, *16*(5), 2045–2064.

Livneh, B., T. J. Bohn, D. W. Pierce, F. Munoz-Arriola, B. Nijssen, R. S. Vose, D. R. Cayan, and L. Brekke (2015), A spatially comprehensive, hydrometeorological data set for Mexico, the US, and Southern Canada 1950-2013, *Scientific Data*, *2*(1), 1–12.

Lofgren, B. M., and A. D. Gronewold (2013), Reconciling alternative approaches to projecting hydrologic impacts of climate change, *Bulletin of the American Meteorological Society*, *94*(10), ES133–ES135.

Lofgren, B. M., and A. D. Gronewold (2014), Water Resources, in *Climate Change in the Midwest: A Synthesis Report for the National Climate Assessment*, edited by J. A. Winkler, J. A. Andresen, J. L. Hatfield, D. Bidwell, and D. Brown, pp. 224–237, Island Press, Washington, DC.

Lofgren, B. M., A. D. Gronewold, A. Acciaioli, J. Cherry, A. L. Steiner, and D. W. Watkins (2013), Methodological approaches to projecting the hydrologic impacts of climate change, *Earth Interactions*, *17*(22), 1–19.

Mahfouf, J.-F., B. Brasnett, and S. Gagnon (2007), A Canadian precipitation analysis (CaPA) project: Description and preliminary results, *Atmosphere-Ocean*, *45*(1), 1–17.

Mallya, G., L. Zhao, C. Song, D. Niyogi, and R. S. Govindaraju (2013), 2012 midwest drought in the United States, *Journal of Hydrologic Engineering*, *18*(7), 737–745.

Mason, L. A., A. D. Gronewold, M. Laitta, D. J. Gochis, K. Sampson, L. K. Read, E. Klyszejko, J. Kwan, L. M. Fry, K. Jones, P. Steeves, A. Pietroniro, and M. Major (2019), A new transboundary hydrographic dataset for advancing regional hydrological modeling and water resources management, *Journal of Water Resources Planning and Management*, *145*(6), 06019,004.

Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier, and B. Nijssen (2002), A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States, *Journal of Climate*, *15*(22), 3237–3251.

Messager, M. L., B. Lehner, G. Grill, I. Nedeva, and O. Schmitt (2016), Estimating the volume and age of water stored in global lakes using a geostatistical approach, *Nature Communications*, *7*(1), 1–11.

Michalak, A. M., E. J. Anderson, D. Beletsky, S. Boland, N. S. Bosch, T. B. Bridgeman, J. D. Chaffin, K. Cho, R. Confesor, I. Daloglu, J. V. Depinto, M. A. Evans, G. L. Fahnenstiel, L. He, J. C. Ho, L. Jenkins, T. H. Johengen, K. C. Kuo, E. Laporte, X. Liu, M. R. McWilliams, M. R. Moore, D. J. Posselt, R. P. Richards, D. Scavia, A. L. Steiner, E. Verhamme, D. M. Wright, and M. A. Zagorski (2013), Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions., *Proceedings of the National Academy of Sciences of the United States of America*, *110*(16), 6448–6452.

Millerd, F. (2011), The potential impact of climate change on Great Lakes international shipping, *Climatic Change*, *104*, 629–652.

Milly, P. C., and K. A. Dunne (2017), A hydrologic drying bias in water-resource impact analyses of anthropogenic climate change, *JAWRA Journal of the American Water Resources Association*, *53*(4), 822–838.

Minallah, S., and A. L. Steiner (2020), Role of the atmospheric moisture budget in defining the precipitation seasonality of the Great Lakes region, *Journal of Climate*, doi: https://doi.org/10.1175/JCLI-D-19-0952.1.

Munoz, S. E., and S. G. Dee (2017), El Niño increases the risk of lower Mississippi River flooding, *Scientific Reports*, *7*.

Nijssen, B., G. M. O'Donnell, D. P. Lettenmaier, D. Lohmann, and E. F. Wood (2001), Predicting the discharge of global rivers, *Journal of Climate*, *14*(15), 3307–3323.

Nilsson, C., C. A. Reidy, M. Dynesius, and C. Revenga (2005), Fragmentation and flow regulation of the world's large river systems, *Science*, *308*(5720), 405–408.

Notaro, M., K. D. Holman, A. Zarrin, E. Fluck, S. J. Vavrus, and V. Bennington (2013), Influence of the Laurentian Great Lakes on regional climate, *Journal of Climate*, *26*(3), 789–804.

Notaro, M., V. Bennington, and B. M. Lofgren (2015), Dynamical downscaling-based projections of Great Lakes water levels, *Journal of Climate*, *28*(24), 9721–9745.

Pietroniro, A., V. Fortin, N. Kouwen, C. Neal, R. Turcotte, B. Davison, D. Verseghy, E. D. Soulis, R. Caldwell, and N. Evora (2007), Development of the MESH modelling system for hydrological ensemble forecasting of the Laurentian Great Lakes at the regional scale, *Hydrology and Earth System Sciences*, *11*(4), 1279–1294.

Roque-Malo, S., and P. Kumar (2017), Patterns of change in high frequency precipitation variability over North America, *Scientific Reports*, *7*(1), 1–12.

Seo, D.-J. (1998), Real-time estimation of rainfall fields using radar data and rain gage data, *Journal of Hydrology*, *208*(1-2), 37–52.

Seo, D.-J., and J. P. Breidenbach (2002), Real-time correction of spatially nonuniform bias in radar rainfall data usin grain gage measurements, *Journal of Hydrometeorology*, *3*(2), 93–111.

Smith, J. P., T. S. Hunter, A. H. Clites, C. A. Stow, T. Slawecki, G. C. Muhr, and A. D. Gronewold (2016), An expandable web-based platform for visually analyzing basin-scale hydro-climate time series data, *Environmental Modelling & Software*, *78*, 97–105.

Swenson, S., and J. Wahr (2009), Monitoring the water balance of Lake Victoria, East Africa, from space, *Journal of Hydrology*, *370*(1-4), 163–176.

van den Dool, H., J. Huang, and Y. Fan (2003), Performance and analysis of the constructed analogue method applied to US soil moisture over 1981 - 2001, *Journal of Geophysical Research - Atmospheres*, *108*(D16).

Wang, H., S. Schubert, R. Koster, Y.-G. Ham, and M. Suarez (2014), On the role of SST forcing in the 2011 and 2012 extrme US heat and drought: A study in contrasts, *Journal of Hydrometeorology*, *15*(3), 1255–1273.

Wright, D. M., D. J. Posselt, and A. L. Steiner (2013), Sensitivity of lake-effect snowfall to lake ice cover and temperature in the Great Lakes region, *Monthly Weather Review*, *141*(2), 670–689.

Xiao, K., T. J. Griffis, J. M. Baker, P. V. Bolstad, M. D. Erickson, X. Lee, J. D. Wood, C. Hu, and J. L. Nieber (2018), Evaporation from a temperate closed-basin lake and its impact on present, past, and future water level, *Journal of Hydrology*, *561*, 59–75.

Zhang, J., W. Tian, M. P. Chipperfield, F. Xie, and J. Huang (2016), Persistent shift of the Arctic polar vortex towards the Eurasian continent in recent decades, *Nature Climate Change*, *6*(12), 1094.