The Estimation of the Great Lakes Net Basin Supply: Implications for Water Level Fluctuations

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ABSTRACT

We computed Net Basin Supplies to the Great Lakes by estimated over-lake evaporation using the bulk aerodynamic method and derived over-lake precipitation from MERRA associated with the runoff data provided by GLERL. The long-term trend of NBS components that are over-lake evaporation rate, over-lake precipitation and runoff were also addressed. We also evaluated the relationship between NBS and change in water level for each of the Great Lakes. The simple correlation analysis was performed in order to determine the relationship between the climate teleconnection indices with NBS, over-lake precipitation, and over-lake evaporation. A brief review on the effect of climate teleconnection on the Great Lakes NBS, over-lake evaporation, and over-lake precipitation were given in the last section. The distribution of over-lake precipitation is spread throughout the year with two peaks in April and October. The monthly average of runoff entering to the Great Lakes was highest in April while the lowest monthly mean runoff was in September. The evaporation rate was highest in January for all Lakes but Lake Ontario, which was highest in early December. The evaporation rate then sharply drops in March the evaporation processes continue again in August. The calculations of NBS were limited by the availability of runoff data. The highest NBS was in April while the lowest monthly average NBS was varied in December, January, and February. The correlation analysis was based on various teleconnection indices and NBS, over-lake evaporation, and over-lake precipitation. NAO was positively correlated with NBS in all Lakes but Lake Superior while over-lake evaporation showed a negative correlation with PDO and Niño 3.4.

Keywords: The North American Laurentian Great Lakes; Net Basin Supply; Water Level; Satellite Remote Sensing; MERRA Reanalysis

1. INTRODUCTION

The Great Lakes store a vast amount of water. A relatively small change in lake water level can represent a vast amount of water held by or released from the lakes which is more likely considered as changes in storage or any other component in the Great Lakes water balance. The annual lake level cycle mostly reflects seasonal changes in over-lake precipitation, runoff, and over-lake evaporation [1]. In general, lake levels decline through autumn and winter seasons [2] due to amplified evaporative loss reflecting the vapor pressure difference between the lake surface and the overlying air. Water supply peaks in spring and runoff is a significant contributor with the melting of winter snowpack retained in the watershed. Lake water levels typically reach a maximum during the summer. To understand the changing of water levels, the concept of Net Basin Supplies (NBS) is used. NBS is defined as the water supply to the Great Lakes, which is the different between inflow (runoff and over-lake precipitation) and outflow (over-lake evaporation). Studies showed that teleconnection patterns are associated with anomalous water surface temperature and ice cover on the Great Lakes [3,4]. The North America climate interannual variability is typically affected by two important teleconnection patterns; the Pacific North America (PNA) and the North Atlantic Oscillation (NAO). The Great Lakes are impacted by PNA and NAO, as they are geographically located under the influence of these two patterns. To evaluate the interaction between teleconnection patterns and the Great Lakes NBS components, we used monthly average over-lake evaporation and over-lake precipitation estimated from July 2001 to December 2014. As an insignificant amount of water is gained or lost through the diversion, therefore, we hypothesize that the fluctuation of the Great Lakes water levels is mainly dominated by over-lake evaporation and over-lake precipitation. The main objectives of this study are, therefore, to investigate the intraannual variability of the Great Lakes water level and Net Basin Supply (NSB). Also, to review the seasonal variability of Great Lakes NSB components and its relationship with the teleconnection. In this paper, we first address the trends of over-lake evaporation rates and over-lake precipitation section, follow by the comparison between NBS and lake-wide water levels. We also determine connections between the climate teleconnection indices and NBS components using the simple correlation analysis. A brief review on the effect of climate teleconnection on the Great Lakes NBS is given in the last section.

2. METHODS AND DATA

2.1 Study Area

The Great Lakes--Superior, Michigan, Huron, Erie, and Ontario, as they appear today, were formed from ice sheets about 12,000 years ago. As the ice sheets melted, waters accumulated to form the predecessors of the lakes. The present entire drainage basin covers 528,000 km^2. The Great Lakes cover about one-third of the total area of the Great Lakes Basin and contain about 23,000 km^3 of fresh water, roughly 18% of the world supply. The amount of water that falls directly on the surface of the Great Lakes is greater than all of the water that enters the lakes through runoff [5]. Over-lake precipitation is received in form of rain and snow. Annual total precipitations increase from west to east (downstream) across the Great Lakes basin [1]. Connecting channels restrict the outflow from the Great Lakes and allow the lakes to store large amounts of water. Flow through each connecting channel also increases as the water level rises in the upstream lakes, but the size and position of each connecting channel restrict flow out of a lake as its water level rises. Water flows out of Lake Superior and into Lake Huron through the St. Mary's River. Lake Superior's actual outflow is a combination of flows through three hydropower plants regulated in the twin cities of Sault Ste. Marie, Ontario and Michigan. Lakes Michigan and Huron are connected hydraulically by the broad and deep Straits of Mackinac. Average flow from Lake Michigan to Lake Huron is approximately 1390 m^3/s based on water-balance data reported by [5]. Typically, flow through the St. Clair River is considered to be the outflow of both Lake Michigan and Lake Huron. Water flows out of Lakes Michigan and Huron through the St. Clair-Detroit River waterway. In winter, the presence of ice affects St. Clair, and Detroit River flows directly by slowing the flow of water. Ice jams are especially common to the St. Clair River delta and can reduce flows by as much as 65 percent [6]. The wind regime on Lake Erie causes water levels approximately one meter higher than normal and considerably affects the timing of Detroit River flows. Water flows north out of Lake Erie and into Lake Ontario through the Niagara River and the Welland Canal. In the summertime aquatic plant growth in the Niagara River channel can be affected Lake Erie outflow. Lake Ontario flows though The St. Lawrence River, which is regulated by the St. Lawrence-Franklin D. Roosevelt Power Project. Map of the Great Lakes drainage basin is shown in Figure 1.

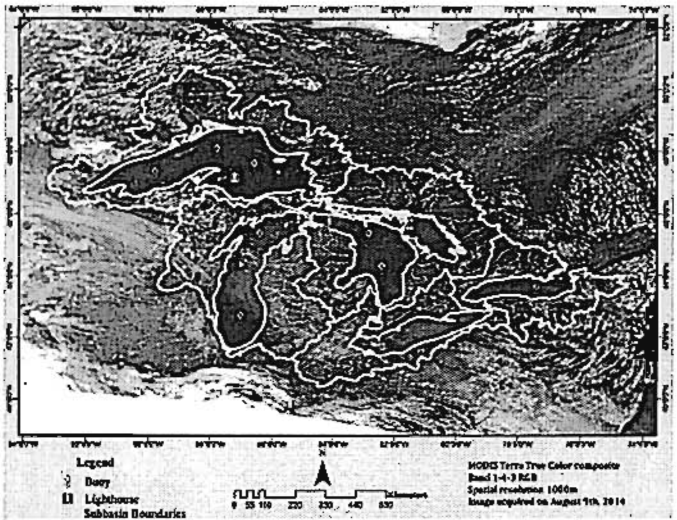

Figure 1 Map of the Great Lakes drainage basin and sub-basin boundaries overlay on Terra MODIS true color composite is acquired on August 9th, 2014

2.2 Net Basin Supplies

The Great Lakes Environmental Research Laboratory (GLERL) has long been estimating the Great Lakes NBS based on available hydrometeorological data. The over-lake precipitation and over-lake evaporation are estimated by interpolated hydrometeorological data from near-shore and land-based measurements that lead to inconsistent NSB estimation [7]. The water supplies to a lake, referred to as the NBS, are defined in terms of their components as:

$$NBS = P_{(lake)} + R - E_{(lake)} \tag{1}$$

where

$P_{(lake)}$ is over-lake precipitation in mm, *R* is basin runoff to the lake, and

$E_{(lake)}$ is over-lake evaporation2.3. Over-lake Precipitation

Over-lake precipitation data were derived from *PRECTOT* total surface precipitation available in MERRA reanalysis IAU 2d land surface diagnostics (tavg1_2d_lnd_Nx) data product. MERRA Data Assimilation System 2-Dimensional land surface diagnostic is the time averaged single-level at the native resolution product (detailed in chapter one). We performed daily mean in time-averaged period. Then daily average *PRECTOT* were downloaded directly from the NASA website (http://disc.sci.gsfc.nasa.gov/) from July 2001 to December 2014 in the HDF-EOS (Grid) format, based on HDF4. We then converted HDF into IMG file using GDAL Translate package on OSGeo4W open source software. Then we resampled *PRECTOT* to 1 km resolution and extracted the over-lake precipitation by using the Great Lakes shoreline as a mask from each of the IMG files on ArcGIS software (Redland, CA). Daily *PRECTOT* were spatially aggregated into monthly average to evaluate the spatial pattern of each variable.

2.4. Runoff Data

Monthly average runoff data using in this study provided by GLERL. Daily lake basin runoff estimates were computed by aggregating the watershed estimates, using stream flow records from major rivers, available from the U.S. Geological Survey for U.S. streams and the Inland Waters Directorate of Environment Canada for Canadian streams. Then, the daily lake basin runoff was divided by the ratio of the area of those basin areas. Monthly runoff was simply computed by totaling the daily runoff estimates for all days in each month. Unfortunately, during the study period, runoff data from GLERL were available through August 2012 for Lake Superior, Lake Erie, and Lake Ontario and through December 2010 for Lake Michigan and Huron.

2.5. Over-lake Evaporation

Due to the vast surface area and lack of year-round direct measurement, over-lake evaporation is estimated using remote sensing technique. [8] showed that in the Great Lakes, the bulk aerodynamic method gave the best results when compared to the eddy covariance method, and therefore the stability-corrected aerodynamic method was used here to estimate the over-lake evaporation. To summarize, the latent heat flux estimated from bulk aerodynamic method is given by:

$$Q_E = -\lambda_v k^2 \frac{\Delta\overline{u}\cdot\Delta\overline{\rho_v}}{[\ln(^{z_2}/_{z_1})]^2} (\Phi_M \Phi_V)^{-1} \tag{2}$$

where

λv is the latent heat of vaporization,

k is the von Kármán constant (0.41)

$\Delta\overline{u}$ is wind speed gradient from MERRA reanalysis

$\ln(^{z_2}/_{z_1})$ is natural logarithm of two different heights

$(\Phi_M \Phi_H)^{-1}$ and $(\Phi_M \Phi_V)^{-1}$ are the dimensionless stability correction terms

In case the atmospheric is stable, Ri positive, the equation is given by;

$$(\Phi_M \Phi_x)^{-1} = (1\text{-}5\ \mathrm{Ri})^2 \tag{3}$$

In the case the atmospheric is unstable, Ri negative, and the equation given by;

$$(\Phi_M \Phi_x)^{-1} = (1\text{-}16\ \mathrm{Ri})^{3/4} \tag{4}$$

Ri is the Richardson number given by;

$$\mathrm{Ri} = \frac{g}{\overline{T}} \frac{(\Delta\overline{T}/\Delta z)}{(\Delta\overline{u}/\Delta z)^2} \tag{5}$$

where

g is acceleration due to gravity (m s^{-2})

$\bar{T}$ is mean temperature in layer Δz (K)

2.6. Lake-wide Water Level

The physical processes over a lake basin that contribute to the water level change of that lake include the over-lake precipitation, lake evaporation and runoff into the lake from its drainage basin [7]. We gathered lake water level data for each lake from the Great Lakes water level dashboard available at http://www.glerl.noaa.gov/data/dashboard/GLWLD.html. The Great Lakes water levels are observed by the Center for Operational Oceanographic Products and Services (NOAA) in the U.S. and by the Canadian Hydrographic Service in Canada. Water levels are recorded at 53 monitoring stations in the U.S. and 33 stations in Canada [9].

2.7. Climate Teleconnection Indies

Various monthly teleconnection indies were downloaded from National Oceanic and Atmospheric Administration, National Centers for Environmental Information (http://www.ncdc.noaa.gov/teleconnections/) website for Arctic Oscillation (AO), North Atlantic Oscillation (NAO), Pacific-North American Pattern (PNA), Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) sea surface temperature (SST) anomalies in the Niño 3.4 region (Niño 3.4). We performed the basic correlation analysis using Pearson correlation to evaluate the influent of climate teleconnection patterns on the Great Lakes NBS.

3. RESULTS AND DISCUSSION

3.1 Over-lake Precipitation

We first compared over-lake precipitation derived from MERRA with the over-lake precipitation provided by the GLERL. The over-lake precipitations from GLERL generated by interpolating near-shore and land based meteorological data using the Thiessen polygon technique. The monthly averaged over-lake precipitations were computed by simply summing the daily average over-lake precipitation [10]. The data from July 2001 to December 2008 (Lake Superior), and from July 2001 to December 2011 (Lake Michigan, Lake Huron, Lake Erie, Lake Ontario) were used to examine validity of the technique. Over-lake precipitation derived from MERRA was comparable with the data provided from GLERL (R^2 rank from 0.2 to 0.5). Nonetheless, the estimated over-lake precipitations from both methods were not compared with in situ data due to the lack of over-lake precipitation measurements. Although precipitation was measured year-round at all of the lighthouse eddy covariance measurement location, the tipping bucket rain gauges used underestimated precipitation due to: solid precipitation (gauges were not heated), wind undercatch (no wind shields were used), and blockage of the orifice due to spiders and other insect debris. Monthly average over-lake precipitation was aggregated from daily average precipitation from July 2001 to December 2014. The distribution of over-lake precipitation was moderately uniform spread throughout the year. However, there were two peaks of over-lake precipitation rate, one in April and the another in October. The highest monthly average precipitation rate was over Lake Huron during April (2.9 mm per day) and during October (3.0 mm per day). The over-lake monthly average over-lake precipitation rate is summarized in Table 1. In the winter, most of the precipitations fell over the lower Great Lakes (e.g. Cleveland, Erie, and Buffalo) in the form of lake effect snow. Cold air masses frequently sweep across the Great Lakes from the north and west. As these air masses move over an open water, the relatively warm lake heats the air, allowing more evaporation from the lake surface. When the air mass moves inland, the cooler land surface cools the air mass and causes the additional moisture to precipitate as lake-effect snow.

Table 1 Summary of monthly mean MERRA-derived over-lake total precipitation (millimeter) from July 2001 to December 2014 for each of the Great Lakes

Lake		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Superior	**Max**	62	59	98	136	148	108	91	90	136	126	107	79
	Min	17	20	10	28	24	29	21	24	25	31	39	26
	Mean	42	34	54	78	72	51	51	54	68	84	68	52
	SD	15	12	23	34	30	24	22	24	30	29	22	14
Michigan	**Max**	86	67	106	135	127	101	105	101	127	134	126	114
	Min	18	23	21	34	29	32	45	36	18	26	27	29
	Mean	51	47	64	81	68	55	69	71	66	78	66	61
	SD	24	14	22	29	29	18	18	20	31	34	30	23
Huron	**Max**	117	86	102	143	158	95	96	103	137	150	145	144
	Min	20	23	12	53	23	31	31	48	13	27	33	31
	Mean	64	54	65	88	73	62	67	71	75	91	79	74
	SD	31	23	24	31	34	19	19	18	32	37	30	28
Erie	**Max**	121	119	136	142	140	138	167	140	139	130	111	134
	Min	31	35	45	32	31	45	62	55	36	49	28	47
	Mean	77	71	78	84	77	86	109	91	81	85	78	92
	SD	25	23	29	36	33	25	32	25	27	30	26	28
Ontario	**Max**	101	115	136	142	144	126	143	116	139	146	136	135
	Min	34	37	27	26	25	52	44	32	35	56	21	51
	Mean	71	62	75	84	77	77	89	70	73	86	80	91
	SD	22	22	32	35	32	23	28	22	29	26	29	27

For the purpose of comparison, we cumulated the over-lake precipitation for the water year, which is defined as the 12-month period from October 1st through September 30th of the following year. Therefore, data from July to September 2001 and from October to December 2014 were not included. Over-lake monthly average cumulative precipitation is summarized in Table 2. The highest over-lake monthly average cumulative precipitation was 1152.0 mm in Lake Erie during 2002 water year while the lowest was 561.7 mm in Lake Superior during 2007 water year.

Table 2 Over-lake monthly average cumulative precipitation (mm) based on the water year (1-October through 30-September)

Water year	Superior	Michigan	Huron	Erie	Ontario
2002	898.3	930.2	977.6	1152.0	1021.9
2003	722.2	752.5	803.3	1008.3	909.2
2004	843.2	820.4	908.9	959.9	1026.2
2005	620.9	718.2	874.7	1024.1	1007.8
2006	602.3	770.3	877.9	1110.6	1030.6
2007	561.7	677.8	784.1	911.9	814.4
2008	744.2	771.5	922.1	1096.3	997.8
2009	622.6	733.3	906.6	1030.0	934.8
2010	767.7	828.1	762.8	902.5	803.5
2011	624.1	732.5	765.6	1108.2	1012.4
2012	635.3	664.3	750.2	894.6	870.4
2013	707.8	797.1	930.9	1029.3	950.4
2014	776.0	785.6	908.6	964.0	886.3

3.2 Runoff

We applied runoff data provided by GLERL, which were calculated based on streamflow records from major rivers in the Grete Lakes basin. Monthly average of runoff entering to the Great Lakes (excluded the channels flow) is summarized in Table 3. The highest monthly mean runoff was in Lake Ontario (302.7 mm) during April while the lowest monthly mean runoff was in Lake Michigan and Huron system in September (29.0 mm). Most of the precipitation drains into streams that discharge into the lakes. Thousands of streams drain approximately 320,000 km^2 of land area and feed directly into the Great Lakes. Direct overland flow to the Great Lakes is also a component of runoff. The amount of water that enters the Great Lakes as runoff is slightly less than the quantity of water that enters the lakes through over-lake precipitation. Therefore, it peaks in spring (April) due to the melting of winter snowpack preserved in the watershed and usually negative in fall and early winter. Likewise, ice formation and ice jams typically slow stream flow in the river of the lakes during winter. Runoff is also a significant part of the Great Lakes water supply especially during the thawing season of March to early June. Because of the large size of the Great Lakes, lake precipitation and evaporation are of the same order of magnitude as runoff.

Table 3 Summary of monthly average runoff flow to the Lakes (millimeters) from July 2001 to July 2012 for all Lakes but Lake Michigan and Huron system (July 2001 to December 2010).

Lake		Jan	Feb	Mar	Apr	May	Jun	Jun	Aug	Sep	Oct	Nov	Dec
Superior	Max	26	33	26	34	21	15	21	34	33	21	12	13
	Min	60	118	88	115	104	110	99	117	88	54	128	101
	Mean	39	53	43	56	47	38	44	59	48	33	39	46
	SD	13	26	22	24	22	29	21	30	18	9	34	33
Michigan & Huron	Max	35	30	62	53	50	37	25	22	20	26	37	40
	Min	102	84	116	173	138	89	52	40	47	95	96	107
	Mean	70	57	91	113	87	59	37	31	29	46	58	71
	SD	20	20	19	34	30	19	11	6	9	20	20	20
Erie	Max	43	27	94	30	41	13	8	11	11	11	27	48
	Min	293	214	287	209	256	113	84	87	58	121	148	258
	Mean	118	101	170	112	105	54	34	29	30	48	62	123
	SD	86	62	64	50	64	31	25	22	17	41	35	63
Ontario	Max	122	94	195	129	102	55	35	31	30	61	92	126
	Min	304	263	470	469	464	180	160	121	212	269	309	315
	Mean	213	169	301	303	193	108	76	66	77	138	167	236
	SD	71	62	77	115	108	38	35	32	51	70	70	63

3.3 Over-lake Evaporation

To estimated over-lake evaporation, we converted latent heat fluxes (Wm^{-2}) to evaporation rate (mm per day) and excluded negative fluxed during April to June (April to July in Lake Superior) from the long-term trend. The Great Lakes receive energy from incoming solar radiation from April through July. Therefore, during this time the latent heat flux usually flow downward directly into the water surface (negative flux representing condensation events) so that evaporation during these months is negligible. The Great Lakes evaporation occur during late fall through early winter, when the water temperature is much higher than the overlying atmosphere. The cold, dry air flow down from the Canadian continental climate meets the relatively warm lake and produces strong vapor pressure gradients in addition to high winds, causing the very high lake evaporation rates. The intense convection and the strong local atmospheric are response through lake-effect precipitation [7]. During the winter, lake-effect snow is common, which influences the local terrestrial water balance. An excellent example of the typical synoptic atmospheric conditions during cold-air outbreaks is lake-effect clouds. The highest evaporation rate was found in Lake Superior during January with a monthly average of 8.1 mm. per day, follow by Lake Michigan (6.2 mm. per day), Lake Huron (6 mm per day), and Lake Erie (4.3 mm. per day) respectively. In Lake Ontario, the highest evaporation rate was in December (3.1 mm. per day). The evaporation rate then decreased sharply in March, and the evaporation processes continued again in August. It should be noted that unlike all the other Lakes, evaporation from Lake Ontario begin in early July with the rate of 0.9 mm. per day and also ended in early February. We only observed that Lake Ontario evaporation lasting longer in March 2002 and March 2013. During the study period, the mean maximum evaporation has been found highest in 2003-2004 (~12 mm per day) and lowest in 2011-2012 (~5.5 mm per day). Monthly mean lake-wide evaporation rate (mm per day) are summarized in Table 4.

Table 4 Summary of monthly mean lake-wide evaporation rate (mm per day)

Lake		Jan	Feb	Mar	Apr	May	Jun	Jun	Aug	Sep	Oct	Nov	Dec
Superior	**Max**	12.0	10.5	6.0	0.8	0.6	0.4	0.7	1.0	2.8	3.0	5.5	9.8
	Min	4.5	2.6	0.7	0.5	0.0	n/a	n/a	0.6	0.7	0.9	1.1	2.7
	Mean	8.1	6.4	2.1	0.7	0.4	n/a	0.3	0.7	1.2	1.8	3.3	6.0
	SD	2.5	2.3	1.4	0.1	0.2	1.0	0.3	0.1	0.7	0.7	1.3	1.8
Michigan	**Max**	9.3	7.9	3.3	0.7	0.6	0.7	0.9	1.1	3.6	3.5	5.3	8.1
	Min	2.8	2.1	0.7	0.4	n/a	n/a	0.5	0.7	1.0	1.7	1.3	2.8
	Mean	6.0	4.9	1.6	0.6	0.3	0.3	0.7	1.0	1.8	2.5	3.2	5.0
	SD	2.0	1.8	0.8	0.1	0.3	0.3	0.1	0.1	0.8	0.6	1.2	1.5
Huron	**Max**	9.0	7.5	3.0	0.7	0.6	0.7	0.9	1.4	3.1	4.2	7.4	8.9
	Min	3.3	2.5	0.7	0.5	n/a	n/a	0.7	0.9	1.0	1.8	1.5	3.0
	Mean	6.2	5.0	1.5	0.6	0.4	0.3	0.7	1.1	1.8	2.7	3.5	5.1
	SD	1.7	1.4	0.8	0.1	0.3	0.7	0.1	0.2	0.7	0.8	1.4	1.6
Erie	**Max**	4.7	1.6	0.8	0.6	0.7	0.8	1.2	1.1	2.5	3.9	5.3	5.3
	Min	0.9	0.7	0.4	0.1	0.3	0.6	0.8	0.8	0.9	1.6	1.2	1.5
	Mean	2.3	1.1	0.7	0.5	0.6	0.7	0.9	1.0	1.5	2.6	2.8	3.0
	SD	1.1	0.3	0.1	0.2	0.1	0.0	0.1	0.1	0.6	0.7	1.2	1.1
Ontario	**Max**	7.3	5.8	1.5	0.7	0.6	0.7	1.3	1.3	2.8	4.5	6.7	7.9
	Min	2.0	1.5	0.6	0.4	n/a	n/a	0.7	0.8	0.8	1.5	1.1	2.1
	Mean	4.3	3.2	0.9	0.5	0.1	0.5	0.8	0.9	1.2	2.3	2.6	3.7
	SD	1.5	1.5	0.3	0.1	0.6	0.4	0.1	0.1	0.5	0.8	1.5	1.5

n/a is evaporation rate during the period of negative downward fluxes that can be ignored

The over-lake cumulative evaporation was calculated based on monthly mean over-lake evaporation from July 2001 to December 2014. However, the calculations of the cumulative evaporation were based on water year period begin in October and end in September the following year (Table 5). Therefore, data from July to September 2001 and from October to December 2014 were not included. The highest annual cumulative evaporation was in 2014 in Lake Huron (1158.6 mm) and Lake Michigan (1213.0 mm). During the winter of 2013~2014, the Great Lakes experienced consistent lowest temperatures and highest ice cover in recent history [11]. Also, during this time Lake Superior had approximately 88% ice cover. With extent ice cover, therefore, the monthly cumulative evaporation of Lake Superior was found slightly lower than Lake Michigan-Huron system.

Evaporation of the Great Lakes is not spatially uniform, as evaporation rates vary with the movement of synoptic-scale air masses over the lake [12]. The evaporation begins in Lake Erie, Lake Ontario, and south of Lake Michigan as early as July. The highest evaporation rates tend to occur in the lateral regions of in Lake Superior in January particularly in Thunder Bay area then switches to offshore regions by January and February, when ice cover begins to limit evaporation in near shore regions. Evaporation rate drops close to zero in April, May, and June. Then, Lakes Erie, Ontario and South Michigan begin to evaporate again in July. It has also shown that not until August that Lake Superior starts to evaporate. Recent extreme ice extent in Lake Superior during winter 2013 -2014 slightly hold the overall evaporation trend down. While other Lakes though also experienced extreme ice extent, they were only partial covered which in turn intensify evaporation. Evaporation rate in Lake Erie trends to increase nearly 0.9 mm per day while Michigan –Huron system tendency was roughly increase 0.4 mm per day. Lake Ontario has a lowest positive trend (~0.25 mm. per day).

Table 5 Over-lake monthly average cumulative evaporation (mm) based on the water year

Water year	Superior	Michigan	Huron	Erie	Ontario
2002	1135.2	749.1	807.7	426.5	504.0
2003	1076.8	1044.1	971.0	565.0	655.4
2004	1027.1	847.3	838.8	588.9	582.6
2005	877.1	743.0	895.6	507.4	594.7
2006	717.7	756.2	772.2	563.2	583.7
2007	714.3	661.8	704.7	425.2	542.6
2008	830.1	771.4	808.6	480.9	602.0
2009	1070.0	810.3	838.8	507.0	560.2
2010	756.1	805.2	763.1	554.9	518.8
2011	900.2	876.5	937.5	574.6	682.4
2012	700.3	647.0	682.2	484.8	483.9
2013	1097.2	956.3	1046.5	624.4	921.3
2014	1007.6	1156.7	1158.6	604.6	1018.0

3.4 Net Basin Supply

The calculations of NBS were limited by the availability of runoff data that were available from July 2001 to August 2012 for Lake Superior, Erie and Ontario and from July 2001 to December 2010 for Lake Michigan and Huron system. The NBS components were illustrated in Figure 2.

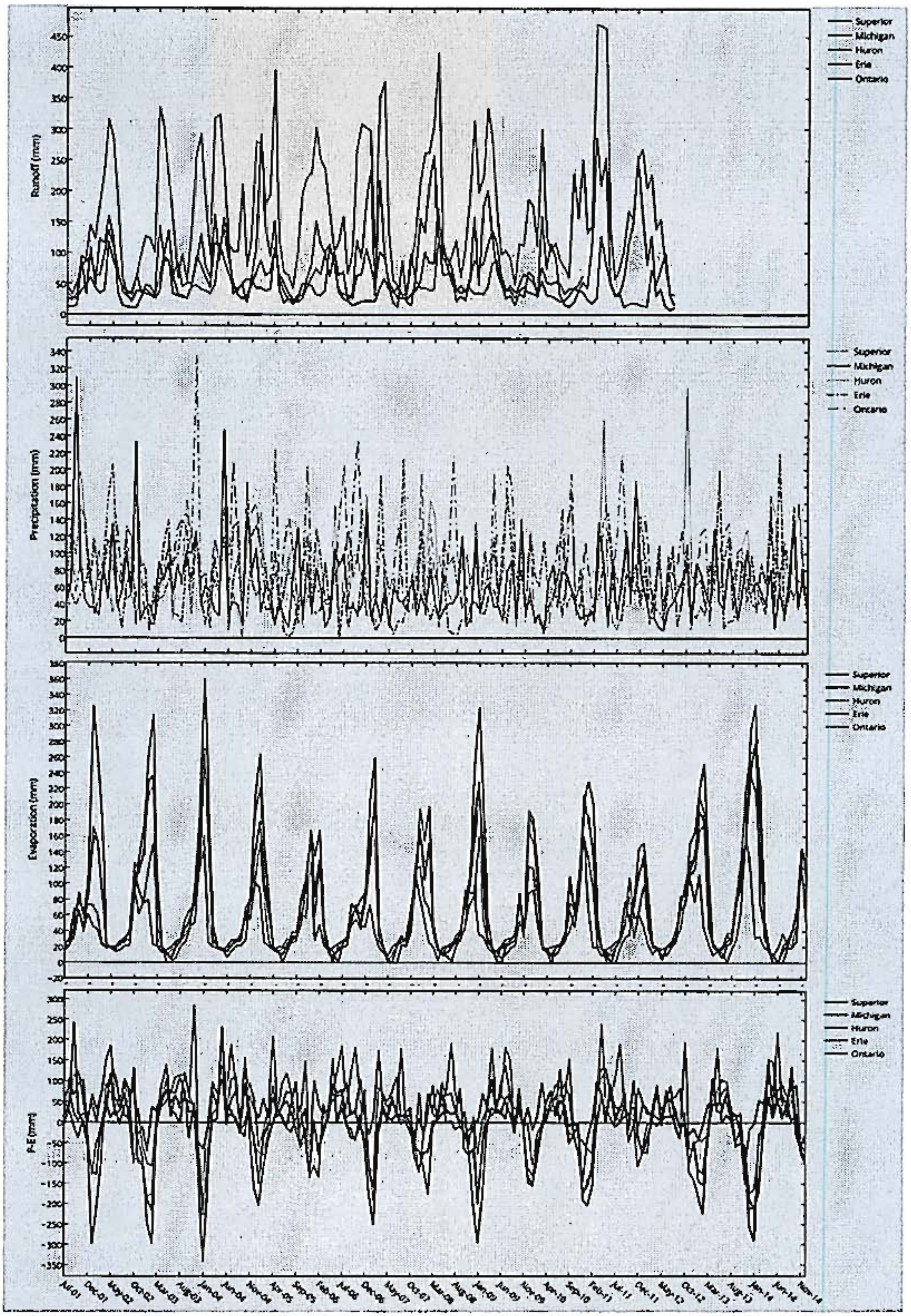

Figure 2 Monthly NBS component (from top runoff, over-lake precipitation, over-lake evaporation and precipitation – evaporation, respectively) observed from July 2001 through August 2012 for Lake Superior, Erie and Ontario, and July 2001 through December 2010 for Lake Michigan and Huron.

The monthly average NBS generally peaked in April due to the high volume of runoff flow into the Great Lakes. The highest NBS was in Lake Ontario (~400 mm), while the lowest monthly average NBS is in Lake Superior (~-150 mm) because of the high evaporation. Also, the monthly average NBS was negative in Lakes Superior, Michigan, and

Huron during December, January, and February. The monthly average NBS to each of the Great Lakes is summarized in Table 6.

Table 6 Summary of monthly mean NBS to each of the Great Lakes (mm)

Lake		Jan	Feb	Mar	Apr	May	Jun	Jun	Aug	Sep	Oct	Nov	Dec
Superior	**Max**	-56	-62	103	210	227	151	120	118	97	214	76	34
	Min	-304	-272	-61	54	55	70	21	1	0	-27	-25	-171
	Mean	-168	-138	33	134	133	100	63	47	44	72	24	-82
	SD	84	67	44	47	61	22	29	40	30	71	29	60
Michigan	**Max**	72	35	149	179	369	111	111	107	277	170	141	173
	Min	-156	-186	53	104	80	51	15	31	-11	-36	-60	-106
	Mean	-64	-41	88	136	167	94	73	66	70	62	26	-11
	SD	77	73	31	26	88	20	31	25	88	70	64	83
Huron	**Max**	79	110	206	218	267	130	116	129	146	218	145	186
	Min	-169	-151	41	62	76	50	23	32	-2	-57	-49	-116
	Mean	-46	-30	114	160	160	92	83	63	55	58	43	1
	SD	87	80	55	44	64	28	27	29	58	78	65	90
Erie	**Max**	303	284	394	339	386	144	165	266	131	180	195	342
	Min	-27	41	106	42	46	58	38	18	-12	-90	-4	-93
	Mean	116	133	228	172	168	112	102	103	61	32	86	115
	SD	112	84	96	94	111	31	50	68	46	78	64	113
Ontario	**Max**	316	329	536	606	594	297	345	264	228	450	544	334
	Min	22	-13	223	128	144	129	93	47	38	15	58	67
	Mean	158	139	343	389	265	190	197	152	127	166	212	225
	SD	102	107	95	157	137	51	85	66	71	111	151	83

To evaluate the relationship between the NBS and water levels, we calculated the change in water levels by simply subtracting monthly water level from the previous month then evaluated the correlation using linear regressions. Lag-correlations between the monthly mean NBS and change in monthly water level for each of the Great Lakes are shown in Figure 3. The correlation between NBS and change in water level for each of the Great Lakes, the bias and root mean square error (RMSE) are summarized in Table 7. The relationship between NBS to the Great Lakes with change in water level were relatively low (R^2 ~0.2–0.4) may be due to the uncertainty of the estimation NBS components especially in over-lake precipitation. The temporal lag between NBS to the lakes and change water levels has the highest correlation coefficient at a lag of one month. Thus, there was approximately a month delay between the time of maximum NBS input into the lakes and the time of maximum change in water levels.

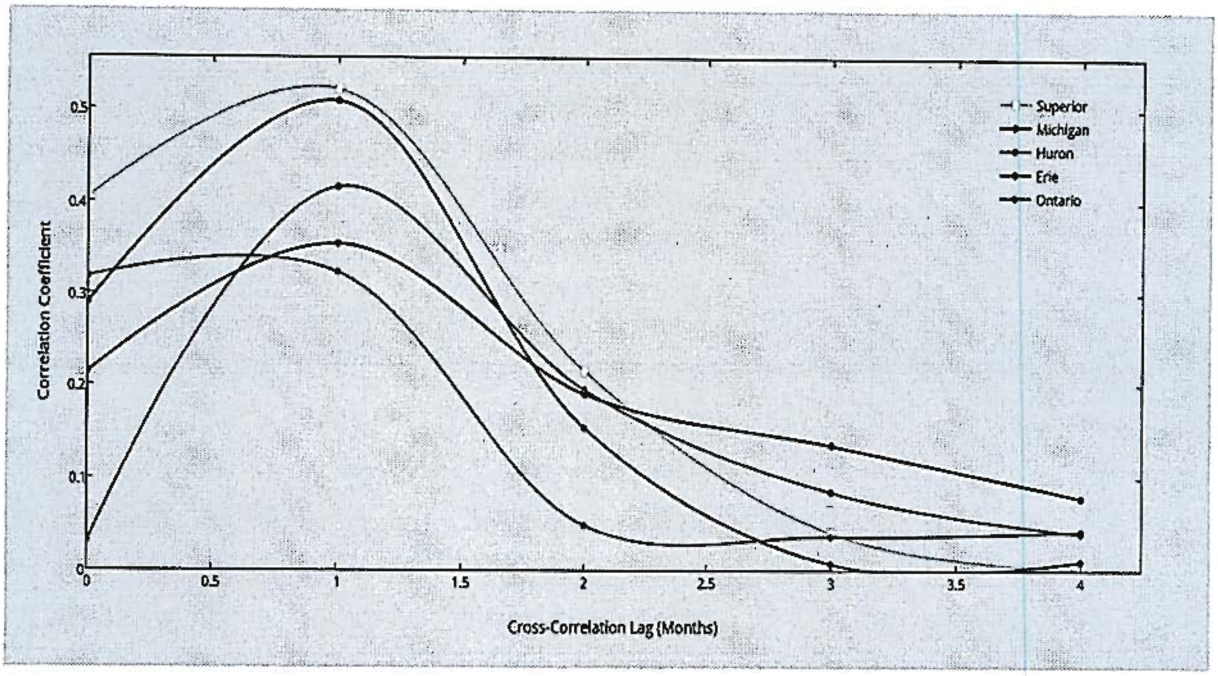

Figure 3 Lag-correlations between the monthly mean NBS and change in monthly water level for each of the Great Lakes. Maximum correlation coefficients were obtained with a lag of one month between NBS to the Great Lakes and the change in water level.

Table 7 The bias, RMSE and R^2 between monthly average NBS and change in monthly water level for one-month temporal lag

Lakes	R^2	RMSE	Coefficients	
		(mm.)	Intercept (mm.)	Slope (mm./mm.)
Superior	0.5188	8.544	21.2	1.21
Michigan	0.3853	8.307	54.6	0.795
Huron	0.4224	8.124	62.7	0.821
Erie	0.5087	8.124	119.3	0.689
Ontario	0.2919	10.488	213.0	0.500

3.5. Correlation between climate teleconnections and the Great Lakes Net Basin Supplies

In this section, five different teleconnection indices were correlated with NBS to the Great Lakes using simple Person correlation to evaluate the influence of teleconnection patterns on the Great Lakes evaporation. The relationship among monthly mean climate teleconnection indices and lake-wide monthly mean evaporation were given in correlation matrix in Table 8

Table 8 The relationship among monthly average climate teleconnection Indies and monthly average NBS, over-lake evaporation, and over-lake precipitation during winter months (DJF). The highest correlation both positive and negative is shown in *bold* front.

		AO	NAO	PDO	Niño 3.4	PNA
NBS	**Superior**	-0.07	-0.14	-0.13	-0.06	0.17
	Michigan	0.31	0.14	-0.28	-0.15	-0.02
	Huron	0.39	0.25	-0.35	-0.24	0.03
	Erie	***0.59***	***0.52***	-0.28	-0.15	-0.12
	Ontario	0.41	0.24	***-0.47***	***-0.35***	***-0.21***
Over-lake evaporation	**Superior**	0.14	-0.25	-0.07	-0.07	-0.17
	Michigan	0.31	0.14	-0.28	-0.15	-0.02
	Huron	0.39	0.25	-0.35	-0.24	0.03
	Erie	***0.55***	***0.46***	-0.20	-0.21	-0.14
	Ontario	0.41	0.21	***-0.52***	***-0.34***	***-0.19***
Over-lake precipitation	**Superior**	0.32	0.26	-0.17	0.01	-0.07
	Michigan	0.24	0.19	-0.30	***-0.24***	-0.30
	Huron	0.38	0.30	-0.25	-0.22	-0.20
	Erie	***0.53***	***0.48***	***-0.34***	-0.19	***-0.32***
	Ontario	0.30	0.25	-0.25	-0.12	-0.31

In our analysis, AO and NAO showed a positive correlation with NBS in all the Lakes but Lake Superior. In Lake Erie, the link between AO and NBS was highest (r= 0.59) as well as the over-lake (r = 0.55) while the over-lake evaporation and PDO showed a negative correlation (r =-0.52). We also assessed multivariate correlation on the teleconnection and NBS, over-lake evaporation, over-lake precipitation. However, the statistical agreement was lower than simple correlation. Also, our analysis agree with [13] which investigated the respond of low ice cover in the Great Lakes during the winter 2011-2012 on a strong positive Arctic Oscillation (AO)-North Atlantic Oscillation (NAO) and the La Niña event. They found that during the event, the sensible heat flux dominated most to the net surface heat flux and surface air temperature was the main factor controls the inter-annual variability of Great Lakes ice cover. In general, warm winters and below average ice covers were associated with west–east atmospheric circulation (zonal) while cold winters and above average ice covers were associated with a north–south circulation (meridional). On the contrary, [11] investigated the impact of extreme winter on Lake Michigan thermal condition during the winter of 2013–2014. The results showed that as the lakes experienced recorded lowest temperatures caused in highest ice extents, then the over-lake evaporation rates might decrease and that water levels might rise. During that time, PDO turned from negative to a positive phase. The warm phase of PDO is correlated with anomalously warm and dry winter-spring conditions in the northern half of North America and anomalously wet conditions over the southern US and Northern Mexico (El Niño-like). The cool phase of PDO is correlated with the opposite (La Niña-like) climate patterns over North America [14,15]. The PDO index is broadly used to characterize North Pacific decadal variability and anomalies of Northern Hemisphere climate and the North Pacific ecosystem [16]. The study of [17] found that interannual and decadal variability of PDO is well formed as the sum of direct forcing by El Niño–Southern Oscillation (ENSO) [18]. [14] described PDO as an El Niño-like pattern that centered over the Pacific Ocean and North America. The PDO impact on climate sensitive including the water supplies and snow pack in North America, and major coastal zone of California through north the Gulf of Alaska and the Bering Sea. There are three main characteristics distinguish PDO from ENSO. First, PDO events endured for 20–30 years, while typical ENSO events short-lived for 6 to 18 months. Second, the PDO are most present in the North Pacific-North American sector, while ENSO exist in the tropics and third, the mechanisms that cause PDO are currently unknown, while causes for ENSO are relatively well-understood. The wide area of above average water temperatures off the coast of North America from Alaska to the equator is indicated the warm phase of PDO. While the expansive area of below average water temperatures off the coast of North America from Alaska to the equator signals the cold phase of the PDO.

In the PDO warm phase, the warm waters wrap in a horseshoe shape around a core of below average water temperature in the central Pacific Ocean. Normally, the expected impacts on the Great Lakes include below average winter temperatures and above average winter precipitation. On the contrary, during the PDO cold phase, the area of above average sea surface temperatures in the central Pacific are surrounded by below average temperatures near the North American continent. Expected impacts from a cold PDO phase on the Great Lakes including above average winter temperatures and below average winter precipitation especially in the lower Great Lakes. Also, the PNA index was positively relative with over-lake evaporation in all Lakes. [19] addressed the nonlinear teleconnections with winter severity and annual maximum ice cover in the Great Lakes [20]. There are two types of atmospheric circulation over North America associated with a high positive Pacific North American (PNA) index [21]. The first type is the true PNA pattern that amplified ridge-trough system. The second type is associated with strong warm ENSO events. The latter is described by a flattening of the Polar jet stream and southward shift of the Subtropical jet [22,23].

4. SUMMARY AND CONCLUSIONS

We computed Net Basin Supplies to the Great Lakes by estimated over-lake evaporation using the bulk aerodynamic method and derived over-lake precipitation from MERRA associated with the runoff data provided by GLERL. The long-term trend of NBS components that are over-lake evaporation rate, over-lake precipitation and runoff were also addressed. We also evaluated the relationship between NBS and change in water level for each of the Great Lakes. The simple correlation analysis were performed in order to determine the relationship between the climate teleconnection indices with NBS, over-lake precipitation, and over-lake evaporation. A brief review on the effect of climate teleconnection on the Great Lakes NBS, over-lake evaporation, and over-lake precipitation were given in the last section. The distribution of over-lake precipitation is spread throughout the year with two peaks in April and October. The monthly average of runoff entering to the Great Lakes was highest in April while the lowest monthly mean runoff was in September. The evaporation rate was highest in January for all Lakes but Lake Ontario, which was highest in early December. The evaporation rate then sharply drops in March the evaporation processes continue again in August. The calculations of NBS were limited by the availability of runoff data. The highest NBS was in April while the lowest monthly average NBS was varied in December, January, and February. The correlation analysis was based on various teleconnection indices and NBS, over-lake evaporation, and over-lake precipitation. NAO was positively correlated with NBS in all Lakes but Lake Superior while over-lake evaporation showed a negative correlation with PDO and Niño 3.4.

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