Great Lakes and St. Lawrence Cities Initiative Presents:

Understanding Climate Change
Physical Changes in the Region Over the Next Century

Understanding Lake Level Changes

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Drivers of water level change: hydrologic cycle

water management, given that Earth's ten largest lakes contain roughly 80% of all fresh, unfrozen surface water (Cael et al., 2017; Messager et al., 2016). 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 (Gronewold & Rood, 2019; Labuhn et al., 2020; Millerd, 2011).

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 & Gronewold, 2013; Milly & 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 data set (Lehner & Grill, 2013) where the Great Lakes and St. Lawrence River system outlet is defined as the point where it meets the Saguenay River; our delineations are also consistent with definitions in the Global Lakes and Wetlands Database (Lehner & 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 (Gu et al., 2013; Maurer et al., 2002; Nijssen et al., 2001; 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. Data Sets

#### 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).
abundant, clean water. In contrast, extremely high water levels often lead to extensive shoreline damage, erosion, and loss of both beaches and shoreline property (Rasid et al., 1992). At the same time, high water levels can be a benefit to the shipping industry.

![Figure 2: Annual (black dots) and monthly (light blue dots) historical average lake-wide water levels on each of the Great Lakes. Horizontal red lines represent the mean water level for each of the Great Lakes over the period of record.](image)

Roughly one decade ago, Great Lakes water management authorities were compelled by information in the National Climate Assessment (NCA), among other publicly-available records and reports (Lofgren et al., 2002; Lofgren, 2004; Hayhoe et al., 2010; Angel and Kunkel, 2010), to plan around a future characterized by higher temperatures, increased evapotranspiration and, ultimately, water loss and drought. Indeed, water levels on the upper Great Lakes (i.e. Superior, Michigan, and Huron) had been below or near average
Fig. 5  Historical gauge-based basin-wide precipitation estimates (in mm) for the North American Laurentian Great Lakes and, for comparison, water level observations (for details, see Fig. 3). Green and orange bars represent annual basin-wide precipitation values (in mm) above and below (respectively) the average for the period of record.

(Woodworth 1999; Ekman 1999). This historical record, synthesized in Quinn (1981) and Croley and Hunter (1994), underscores important linkages between changes in Great Lakes regional climate, and how those changes propagate through changes in the Great Lakes water budget and, ultimately, into changes in Great Lakes water levels.

Historical variability in annual basin-wide precipitation, for example, coincides with annual water level fluctuations over much of the period of record (Fig. 5). Over the Lake Superior basin, annual precipitation follows a somewhat cyclical pattern, with an increasing trend from the early 1900s toward the 1950s and 1960s, followed by a slight decreasing trend over the past 30 years. Water levels on Lake Superior have followed a similar pattern. Precipitation over Michigan-Huron, Erie, and Ontario, however, has followed a different pattern, with annual averages since 1970 consistently above the long-term average. While water levels on each of these systems rose significantly during the late 1960s and early 1970s, the water levels on these systems also dropped significantly between 1997 and 2000 despite relatively stable annual precipitation (for further discussion, see Assel et al. 2004; Sellinger et al. 2007; Stowe et al. 2008).

The drops in annual average water levels during the late 1990s do, however, coincide with significant increases in Great Lakes surface water temperatures (not shown) and overlake evaporation rates (Fig. 6). In particular, the steady increase in
overlake evaporation over each of the lake systems for the past 50 years synthesizes long-term changes in multiple regional climate variables including, most notably, the difference between air and surface water temperature (for details, see Austin and Colman 2007) as well as the decreasing areal extent and thickness of lake ice (Wang et al. 2010, 2012). In light of these changes, and of the recently recorded (January 2013) all-time record low water levels on Lake Michigan-Huron, one of the more challenging research questions facing the Great Lakes region at present is, “will water levels rebound, or have we entered a new hydrologic regime?” Responses to this question depend, in part, on forecasts of regional climate variables, and appropriate interpretation of how those forecasts propagate into water level dynamics. Interpretation of these forecasts depends, in turn, on the context in which they are presented. Importantly, this context rarely includes a comparison between historical forecasts and data from the same period of record. This comparison is important, as we discuss further in Section 3, because it provides an indication of model forecasting skill (Gronewold et al. 2011).

2.1 Great Lakes basin precipitation and evaporation monitoring

Basin-wide annual precipitation totals (Fig. 5) are derived from a network of land-based gauges in the US and Canada (using a methodology described in Croley...