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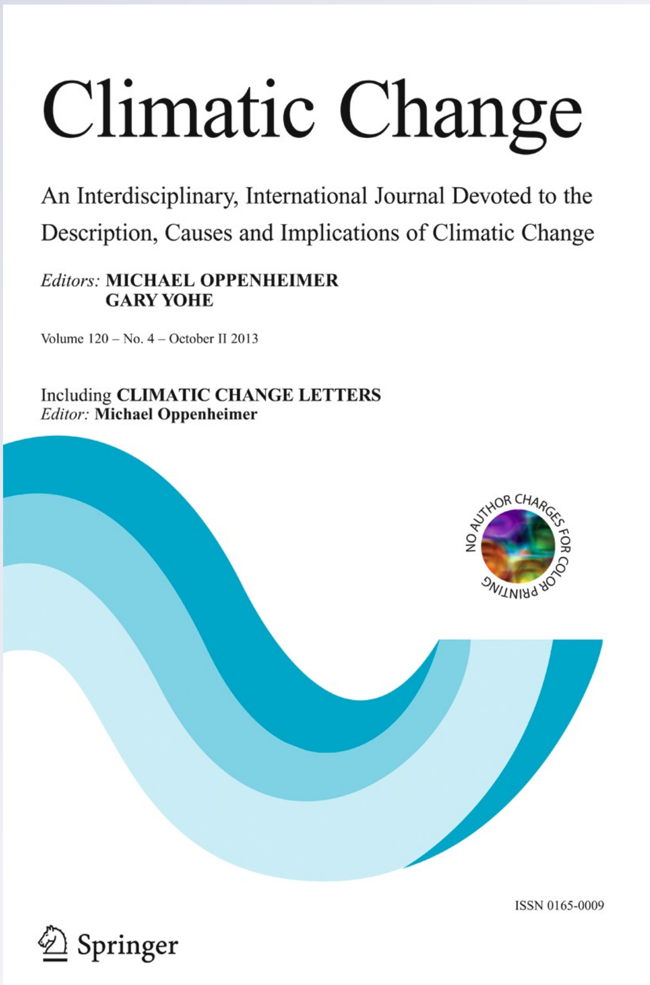

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Coasts, water levels, and climate change: A Great Lakes perspective

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Abstract The North American Laurentian Great Lakes hold nearly 20 % of the earth's unfrozen fresh surface water and have a length of coastline, and a coastal population, comparable to frequently-studied marine coasts. The surface water elevations of the Great Lakes, in particular, are an ideal metric for understanding impacts of climate change on large hydrologic systems, and for assessing adaption measures for absorbing those impacts. In light of the importance of the Great Lakes to the North American and global economies, the Great Lakes and the surrounding region also serve as an important benchmark for hydroclimate research, and offer an example of successful adaptive management under changing climate conditions. Here, we communicate some of the important lessons to be learned from the Great Lakes by examining how the coastline, water level, and water budget dynamics of the Great Lakes relate to other large coastal systems, along with implications for water resource management strategies and climate scenario-derived projections of future conditions. This improved understanding fills a critical gap in freshwater and marine global coastal research.

1 Introduction

Planning for expected changes in coastal water levels is essential for successful climate change adaptation. However, regional decision-making is hindered by uncertainties in down-scaled global projections (Kerr 2011; Willis and Church 2012).

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Coastal areas that have successfully withstood changing water levels, therefore, could provide guidance for ongoing planning in regions where uncertainty impedes effective preparation (Nicholls et al. 1999; Holgate and Woodworth 2004; Willard and Bernhardt 2011). Since the 1930s, communities along the Laurentian Great Lakes coastline have endured both record high and low water levels. Experiences with these pronounced fluctuations may offer useful perspectives for other coastal communities that must plan for uncertain water level changes (Keillor 1990).

The North American Laurentian Great Lakes (Fig. 1), collectively, have the largest surface area (and second largest volume) of any unfrozen fresh surface water body on the planet (Table 1). The Great Lakes coastline along the United States (US) border (Fig. 2), approximately 4,500 miles long, is longer than the US coastline along either the Atlantic Ocean, the Pacific Ocean, or the Gulf of Mexico (National Oceanic and Atmospheric Administration 1975). In addition to serving as a home and source of drinking water to over 30 million people (US Environmental Protection Agency and Government of Canada 1995), the Great Lakes basin is critically linked to the economic health of central North America by supporting a broad range of commercial, industrial, and recreational activities (Field et al. 2007). Buttle et al. (2004) and Millerd (2005), for example, underscore linkages between

Fig. 1 Map of the North American Laurentian Great Lakes including the Great Lakes drainage basin (*shaded in green*), select cities and geographic boundaries, major tributaries, and interconnecting channels (source: U.S. Army Corps of Engineers, Detroit District)

Table 1 Surface area and volume of the earth's largest (by surface area) fresh surface water bodies (for details, see Herdendorf 1990; Lyons et al. 2010). Great Lakes water bodies are in bold font. Lakes Michigan and Huron are joined by the Straits of Mackinac and are therefore, from a large–scale hydrological perspective, typically viewed as a single system

Name	Country	Surface area (km^2)	Volume (km^3)
Michigan–Huron	**U.S. and Canada**	**117,250**	**8,457**
Superior	**U.S. and Canada**	**82,100**	**12,230**
Victoria	Multiple	68,460	2,700
Tanganyika	Multiple	32,900	18,900
Baikal	Russia	31,500	22,995
Great Bear Lake	Canada	31,326	2,381
Malawi/Nyasa	Multiple	29,400	7,720
Great Slave Lake	Canada	28,568	2,088
Erie	**U.S. and Canada**	**25,657**	**483**
Winnipeg	Canada	24,387	371
Ontario	**U.S. and Canada**	**19,000**	**1,637**

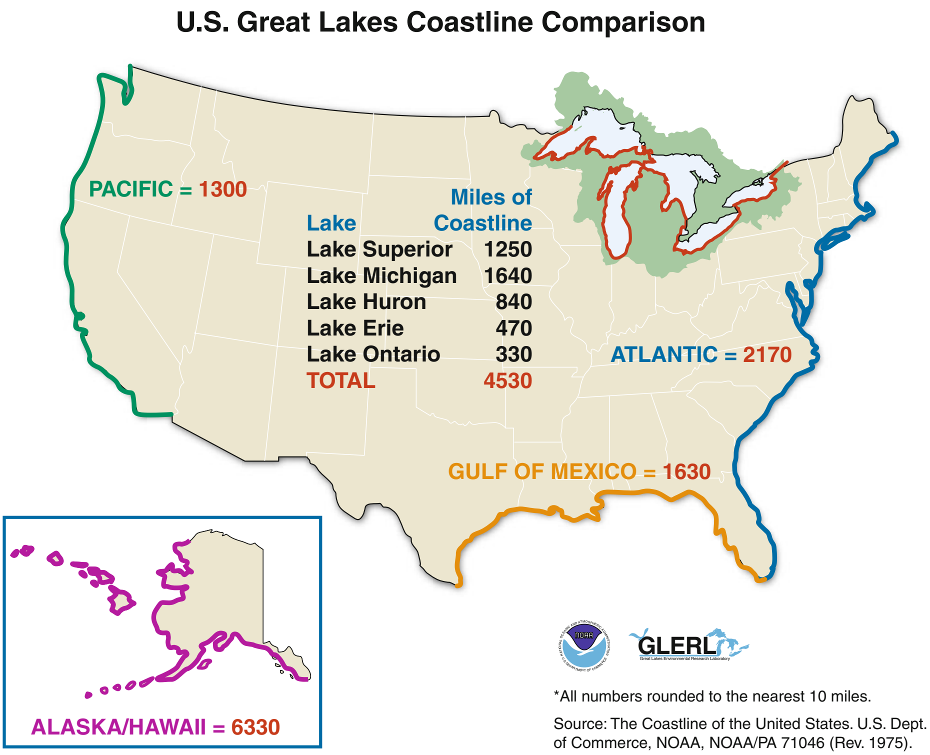

Fig. 2 Comparison between the length of Great Lakes and marine coastlines of the United States (from National Oceanic and Atmospheric Administration 1975). All distances are in miles (*multiply by 1.61 to convert to kilometers*). The green shaded area of the figure represents the Great Lakes drainage basin. The length of marine coastline is based on measurements collected by the National Ocean Survey in 1915 and 1948 ('*general coastline*') using navigational charts and includes embayments, but does not account for tidal variability or offshore islands. Similarly, the Great Lakes coastline was measured in 1970 and includes connecting rivers and islands

the Great Lakes and the regional shipping and hydropower industries, as well as the potential impacts of changes in Great Lakes water levels on those industries. These and similar studies represent a growing body of literature that propagate historical and potential future changes in regional climate, land use, and water resources management practices into not just economic impacts, but into impacts on ecosystem services, as well as human and environmental health (see, for example, Hartmann 1990; Mortsch et al. 2000; Moulton and Cuthbert 2000).

Great Lakes surface water elevation measurements (Fig. 3) are derived from a series of shoreline gauging stations in both the US and Canada. Consequently, water level assessments over different spatial and temporal scales require binational data coordination. The precedent set by this collaborative effort is particularly significant to other large surface water bodies that share international borders (Table 1) but either do not have an extensive monitoring network, or operate networks as independent nations. Specifically, the US gauge network in the Great Lakes was established in the mid-1800s by the US Lake Survey District (also referred to as the "Lake Survey") of the Army Corps of Engineers, while the first use of multiple recording Canadian gauges was initiated by the Department of Public Works in 1906. The Great Lakes water level monitoring network is currently maintained collectively by the National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA) and by the Canadian Hydrographic Service of the Canadian Department of Fisheries and Oceans (Bunch 1970; Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data 1978; Woodford 1991).

It is informative to recognize the magnitude of water level variability along the Great Lakes coastline and how it compares to water level variability along other coastlines. Each of the four Great Lake systems (Lakes Michigan and Huron have the same long-term surface water elevation) fluctuate in response to multiple drivers (we describe these in greater detail in Section 2) across a range of temporal and spatial scales (Ghanbari and Bravo 2008; Hanrahan et al. 2009). Monthly, interannual, and decadal Great Lakes coastal water level variability, for example (Fig. 3), is not only either greater than, or comparable to, water level variability along other marine coasts, but it is also documented in an unusually long and continuous record of measurements. In contrast to Great Lakes water levels, annual average water levels at gauges in New York City (US), San Diego (US), and Dublin (Ireland) have all experienced a gradual, approximately monotonic increase over the past several decades. Annual and monthly measurements at Anchorage (US) and at the mouth of the Rangoon River (Myanmar), while variable, are documented (Holgate et al. 2012) in relatively short and discontinuous records relative to Great Lakes coastal water level measurements.

Storm surges, tides, seiches, and other factors also influence both Great Lakes and marine coastal water levels, but do so in different ways and at different temporal scales (for further discussion, see Donner 2012; Zhang and Church 2012). For example, intermittent storms on the Great Lakes can (particularly on Lake Erie, due in large part to its east-west orientation) lead to water level surges of a magnitude comparable to tidal surges on marine coasts (Fig. 4), yet these storm-induced surges on the Great Lakes are more challenging to predict (Schwab and Bedford 1994; Anderson et al. 2010). Hourly-scale Great Lakes water level dynamics can also be influenced by massive storms along the Atlantic Coast, as evidenced during

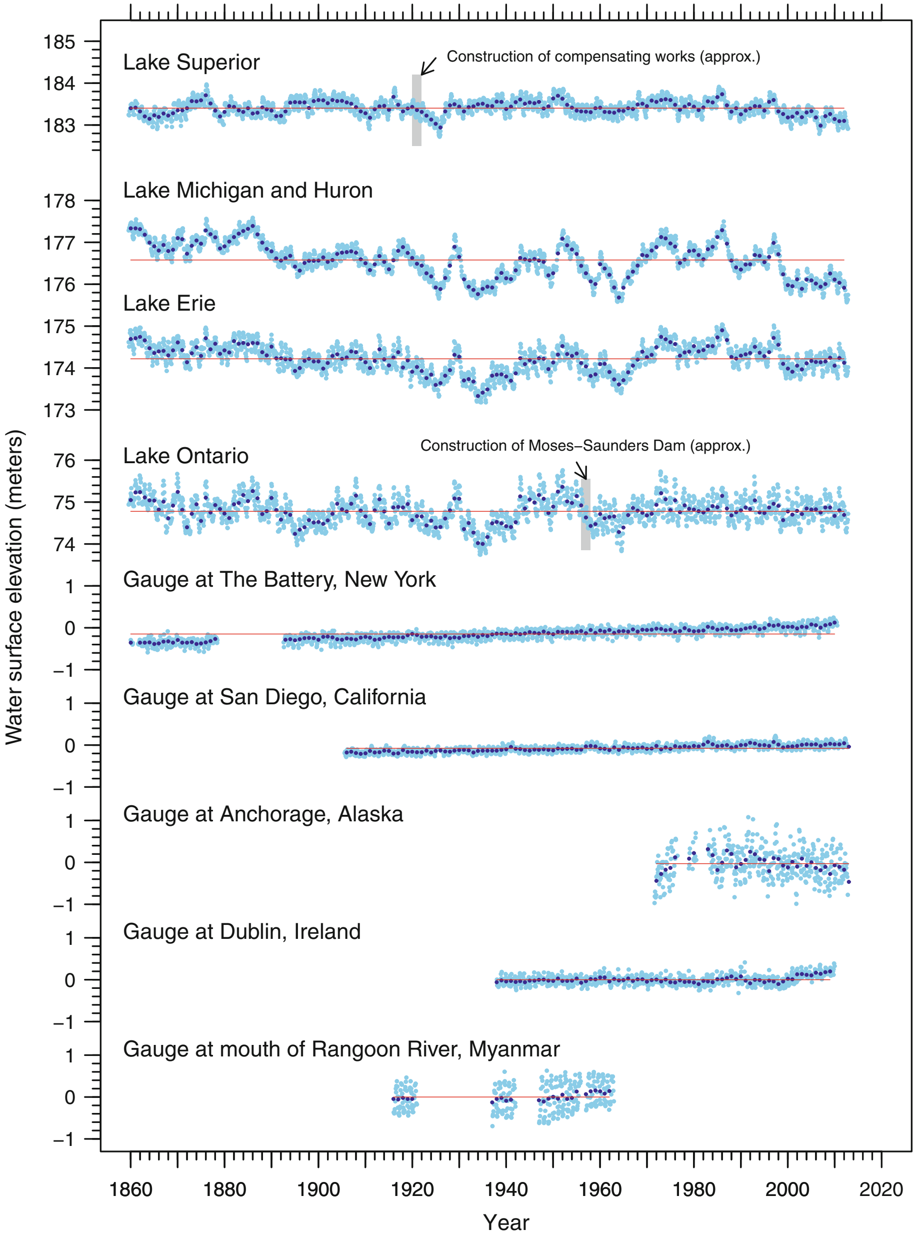

Fig. 3 Historical monthly and annual average surface water elevations in the North American Great Lakes and at other gauges from around the world. Annual average water levels are represented by black dots, and monthly average water levels are represented by light blue dots. Average elevations for each period of record are represented by horizontal red lines. Surface water elevations are referenced to either the 1985 International Great Lakes Datum (for the Great Lakes) or mean sea water level and are plotted at the same vertical scale. Breaks in the y-axis values between Great Lakes data sets reflect elevation changes through the St. Marys River, Niagara Falls, and the St. Lawrence River, respectively

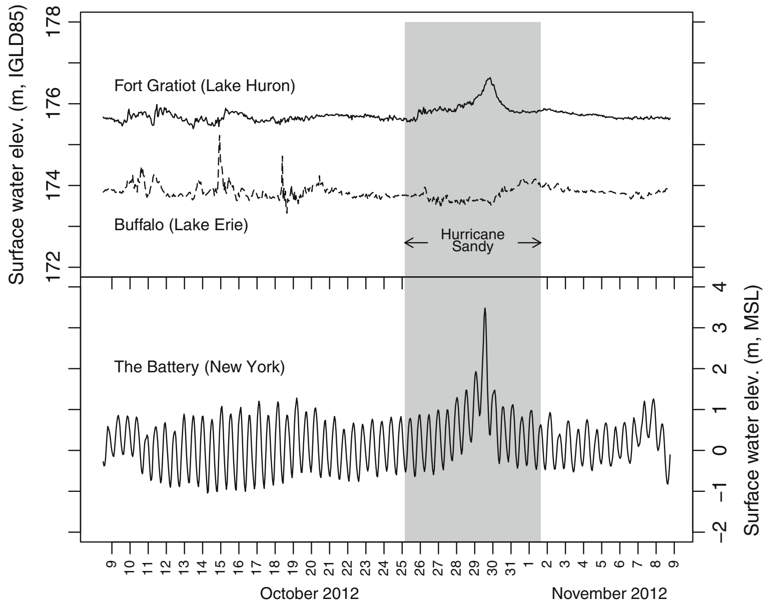

Fig. 4 Times series of hourly water level gauge measurements from two gauges on the Great Lakes (*top panel*) and the gauge at The Battery (New York). The range of the vertical axis (6 m) is the same for both panels

Hurricane Sandy (Fig. 4) when water levels at The Battery rose roughly 2–4 m, while water levels at the southern end of Lake Huron rose roughly 1–2 m. Aside from the fact that Hurricane Sandy was not centered over the Great Lakes, the surge in water levels on Lake Huron is intriguing because much of the water accumulating at Fort Gratiot was able to flow out of Lake Huron through the St. Clair River and (via Lake St. Clair and the Detroit River) into Lake Erie. Without this natural outlet, it is likely that the Hurricane Sandy-induced storm surge at Fort Gratiot would have been noticeably higher.

2 A Great Lakes perspective on drivers behind long-term coastal water level variability

Roughly one-third of the surface area of the Great Lakes basin is water and, because the Great Lakes are the largest fresh surface water on the planet, no similarly-sized basin has such a high proportion of surface water. More specifically, Lakes Victoria, Tanganyika, Baikal, and Malawi, for example (all of which reside in separate basins), each constitute between roughly 1 and 5 percent of their respective basin areas (Revenga et al. 1998; Lehner and Döll 2004). Consequently, unlike other large-lake systems, the major components of the water budget (and the major drivers of surface water level dynamics) of the Great Lakes include overlake precipitation and overlake evaporation, as well as land surface runoff. In addition to a long record of surface water elevation measurements, the Great Lakes region has a relatively long record of these water budget components and other meteorological measurements as well

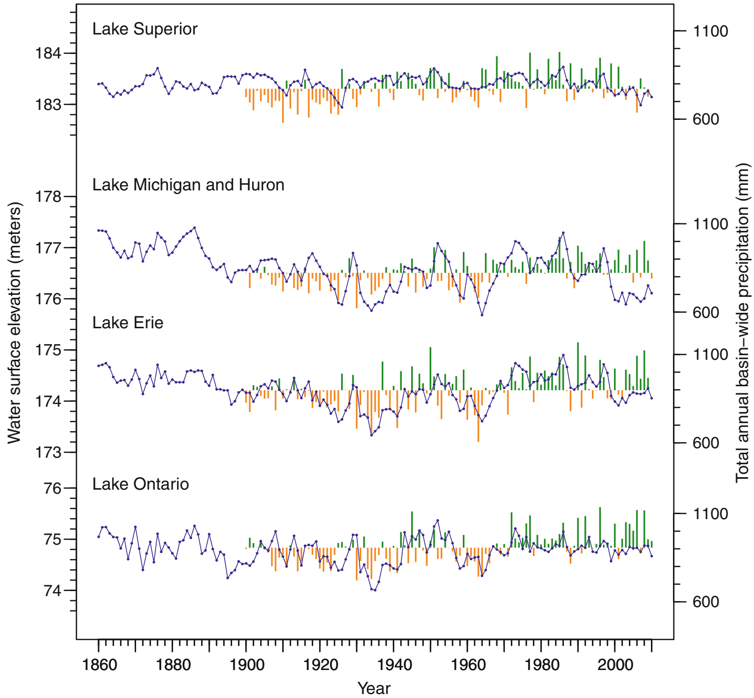

Fig. 5 Historical gauge-based basin-wide precipitation estimates (in *mm*) for the North American Laurentian Great Lakes and, for comparison, water level observations (for details, see Fig. 3). *Green* and *orange bars* represent annual basin-wide precipitation values (in *mm*) above and below (respectively) 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; Stow 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

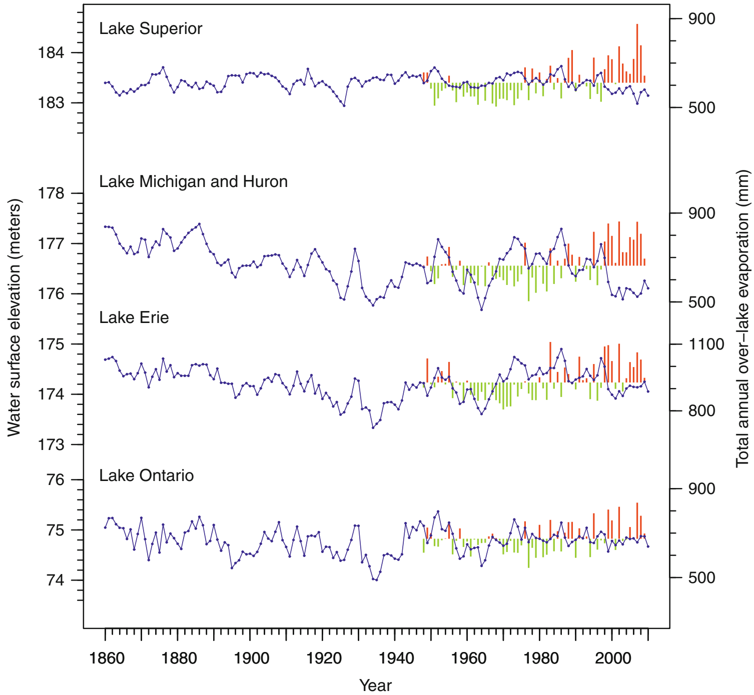

Fig. 6 Simulated annual overlake evaporation (in *mm*) based on Croley (1992) and Croley and Assel (1994) and historical annual lake-wide average water levels. *Orange vertical bars* represent annual evaporation rates greater than the average over the simulation period (1948–2010), while *green vertical bars* represent annual evaporation rates below the average

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 and Hartmann 1985) that has evolved over time. Additional potential sources of precipitation data and model simulations for the Great Lakes region include satellite imagery (Augustine et al. 1994), radar and combined radar and gauge-based products (Wilson 1977; Watkins Jr et al. 2007), and other reconstructed datasets including, most notably, the North American regional reanalysis, as described in Mesinger et al. (2006). Each of these sources could lead to a different representation of precipitation patterns in Fig. 5, yet none of these relatively new analysis tools extrapolate precipitation estimates for the Great Lakes basin over the entire period of record for which direct (i.e. gauge-based) measurements are available. As indicated in Holman et al. (2012) and Gronewold et al. (2013), we view extending these new tools over the relatively long period of record for direct gauge-based measurements as a potential area for future research.

Historical Great Lakes surface water evaporation estimates (Fig. 6), in contrast, are based primarily on model simulations (Croley 1989; Croley and Assel 1994), in part because direct measurements of the energy budget over the Great Lakes (and, subsequently, of evaporative loss) had not been collected until roughly five years ago (Spence et al. 2011). Thus, while simulations of overlake evaporation provide important insights into potential causes of recent changes in Great Lakes water levels, they also underscore the critical need for supplementing model simulations with additional monitoring. A robust evaporation monitoring infrastructure would not only contribute to an improved historical record, but would also provide a basis for calibrating, and improving forecasts from, models that simulate and forecast the water budget and water levels of the Great Lakes (Gronewold et al. 2011; Gronewold and Fortin 2012).

2.2 Other factors influencing Great Lakes water levels

Water level measurements are affected by several extrinsic factors that need to be recognized in water level assessments and in the interpretation of historical water level data. Glacial isostatic rebound, which refers to ongoing changes in ground surface elevation following the release of pressure from retreating glaciers (for details, see Mainville and Craymer 2005), is one example. Importantly, land surface elevation changes that exceed the rate of elevation change at a lake outlet, known as differential glacial isostatic rebound, can be perceived as a change in water surface elevation. For example, relative to the outlet of Lake Superior at Point Iroquois (Michigan), the shoreline at Duluth (Minnesota) is falling at a rate of roughly 25 cm per 100 years, while the shoreline at Rossport, Ontario (the northern shore of Lake Superior) is rising at a rate of roughly 30 cm per 100 years (Mainville and Craymer 2005). Assessments of long-term trends in Great Lakes water levels and water level forecasts must acknowledge that isostatic rebound is altering the Great Lakes coastline, and the studies that document this accounting provide yet another basis for applying coastal water resource management practices from the Great Lakes to other coastal systems.

Outflow regulations on Lakes Superior and Ontario also influence water level dynamics, though to a lesser extent than the changes induced through the regional climate patterns. Regulation of Lake Ontario outflows, for example, is visually apparent in the time series data (Fig. 3) with sustained deviations from the overall mean becoming infrequent after 1960. In contrast, regulation of Lake Superior (beginning in the early 1920s) is visually difficult to discern; despite regulation, water levels in Superior reached a near-record high in 1986 and a near-record low in 2007. To put these changes into perspective, ever since water levels in Lakes Superior and Ontario have been regulated, the ranges of their annual averages (0.8 m and 0.9 m, respectively) have still exceeded the range of annual averages (0.5 m) experienced at the Battery over the entire period of record. Additionally, the largest annual rise (<0.1 m) and fall (<0.1 m) recorded at the Battery is considerably less than the annual rise (0.5 m) and fall (0.5 m) that the Lake Michigan-Huron system experienced in nearly successive years (1927 and 1929).

3 Communicating climate change impacts on coastal water levels

Over the past 30 years, numerous studies have projected changes in the Great Lakes water budget under alternative climate scenarios (see, for example, Bruce 1984; Cohen 1986; Croley 1990). The methodology pioneered by Croley (1990), in particular, hereafter referred to as an "off-line" hydrological model, projected future changes in lake levels associated with changes in anthropogenic greenhouse gases. These changes, represented primarily by changes in precipitation and air temperature, were propagated through a cascade of lake thermodynamics (Croley 1989) and rainfall-runoff (Croley 2002) models to project the overall water budget of the Great Lakes basin and, ultimately, water levels (Croley 2003). This suite of models is collectively referred to as the Great Lakes Advanced Hydrologic Prediction System (or AHPS, as described in Gronewold et al. 2011). We refer to most of these models as "off-line" because their output is not fed back into the models that simulate precipitation and temperature when, in reality, processes over the lakes themselves do have an influence on these regional drivers. Models that explicitly acknowledge this feedback loop are often referred to as "coupled".

Of particular importance is the use of the Croley (1990) methodology in numerous follow-on studies (Lofgren et al. 2002; Angel and Kunkel 2010; Hayhoe et al. 2010) to project Great Lakes water levels using several general circulation models (GCMs) of global climate as input. While the magnitude of projected water level change in each of these studies differs depending on the GCM input, most projected drops in lake levels, in many cases very large drops (Fig. 7a). These studies have been both widely reported (Hartmann 1990; Changnon 1993; Magnuson et al. 1997) and used in many projections of climate change effects on the Great Lakes (Hobbs et al. 1997; Mortsch 1998; Schwartz et al. 2004; Millerd 2011). Consequently, the notion that lower water levels will accompany future climate change is ingrained throughout the Great Lakes region. Importantly, the use of multiple GCM simulations as input (Angel and Kunkel 2010) has created the perception of independent verification of these results. However, the underlying hydrologic models and method of forcing them remained the same throughout all of these projections. Furthermore, these studies do not provide a clear indication of the baseline water levels, nor do they offer reference to the historical water level record as a context for these projections. Doing so (Fig. 7b) impacts perceptions of the relative magnitude of future water level changes and the extent to which those changes should guide water resource management planning decisions relative to intrinsic interannual water level variability.

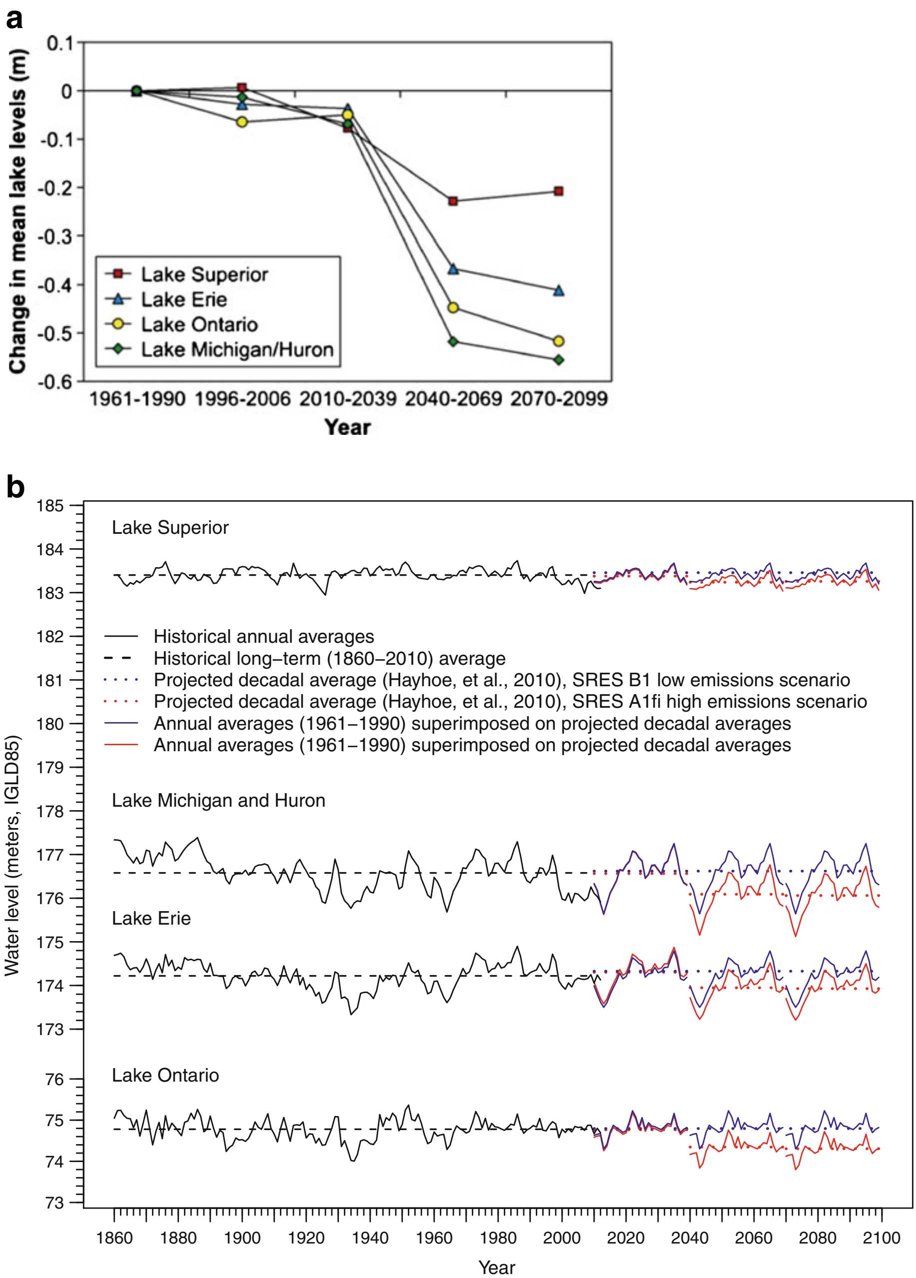

Fig. 7 Two representations of Great Lakes water level forecasts from Hayhoe et al. (2010) which employed the methodology originally presented in Croley (1990). **a** includes a version reproduced with permission from Hayhoe et al. (2010) which significantly impacted public perceptions of potential future trends in Great Lakes water levels. These projections are based on IPCC SRES A1fi high emissions scenarios; projections based on SRES B1 low emissions scenarios, as indicated in the text of Hayhoe et al. (2010) but not explicitly acknowledged in (**a**), resulted in insignificant changes in mean water levels relative to the 1961–1990 reference period. **b** places forecasts from both scenarios into the context of the Great Lakes water level historical record

3.1 Note on advancements in Great Lakes climate-scale water level forecasting

Interestingly, there are numerous published projections of the Great Lakes water budget that do not employ "off-line" hydrologic models to project the Great Lakes water budget. Manabe et al. (2004), Kutzbach et al. (2005), and Milly et al. (2005), for example, all use relatively novel modeling tools which project increases in either the atmospheric moisture convergence or the net outflow from the Great Lakes basin. These are metrics that, in the long term, are equivalent to net basin supply, and necessarily imply rises in lake levels. However, because these (and similar) studies did not propagate water budget projections explicitly into lake levels, their results gathered relatively little attention in both the regional research community and Great Lakes water level impacts assessments.

To resolve this gap in regional research, Lofgren et al. (2011) presented a critical assessment of the modeling approach originating in Croley (1990), looking particularly at the implications of alternative expressions of the energy budget of the surface. They found that the surface energy budget implied in the land portions of the basin under the method of Croley (1990) differed substantially from the surface energy budget of the GCMs that were driving the "off-line" hydrologic model. Put differently, the methods of Bruce (1984), Cohen (1986), and Croley (1990), which all used air temperature as a proxy for potential evapotranspiration, projected large increases in evapotranspiration. As noted in Lofgren et al. (2011), however, GCM simulations indicate that the energy required to support this magnitude of evapotranspiration will likely not be available in the future, and that conventional approaches (i.e. those which employ "off-line" hydrological models) introduce inconsistencies between these two components (i.e. energy and evapotranspiration) of the overall projection (for further discussion, see Milly and Dunne 2011). Finally, Lofgren et al. (2011) proposed an alternate method with greater fidelity to the surface energy budget of the GCMs resulting in future water level scenarios ranging from smaller decreases than those published previously to increases in projected water levels.

4 Concluding remarks

The Great Lakes comprise a large coastal system which continuously experiences interannual water levels increases and decreases that are of a greater magnitude than the changes experienced by many marine coastal systems over the past century. Intrinsic dynamics of the Great Lakes and the Great Lakes regional climate have required a large proportion of the North American population to adapt to the type of coastal water level variability projected for marine coasts over the next century.

The Great Lakes system includes two countries, two provinces, tribal nationals, and eight states with a focal point being the International Joint Commission between the US and Canada. There is a long history of joint water resource management including the regulation of Lakes Superior and Ontario and the diversion of waters into and out of the lakes for public health, water supply, hydro-power, and navigation. Over the last ten years, there has also been an effort to include environmental impacts in lake regulation. A current emphasis is to include climate change and variability into developing adaptive management for both Lakes Superior and Ontario. This requires not only the existing long hydro-climate data base and the maintenance of the current monitoring infrastructure, but also a robust hydro-climate research program. Research is necessary to examine and adapt to the impact of potential climate scenarios and to explain current climate surprises and their impact on water resources.

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