A Historical Monthly Hydrometeorological Database for the Great Lakes

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Background

Starting in 1983, the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) has been developing and maintaining a historical time series of North American Great Lakes basin-scale monthly hydrometeorological data. This collection of data sets, which we hereafter refer to as the NOAA-GLERL monthly hydrometeorological database (GLM-HMD) is, to our knowledge, the first (and perhaps still the only) to assimilate hydrometeorological measurements into model simulations for each of the major components of the water budget across the entirety (i.e. both United States and Canadian portions) of the Great Lakes basin for a period of record dating back to the early and mid 1900s.

Figure 1. The North American Laurentian Great Lakes and the boundary of the Great Lakes drainage basin. Credit: USACE Detroit District.

Precipitation and Air Temperature

The GLM-HMD-I historical precipitation estimates range from the mid 1800s to present and are divided into three time periods. Air temperature estimates are only developed for the most recent of these three periods. The beginning and end of each time period correspond with significant changes in the number of stations in the monitoring network (Figure 2) and in the algorithms used to interpolate measurements from that network.

We estimate monthly total over-lake and over-land precipitation, as well as minimum, maximum, and average monthly (dry bulb) air temperature from 1948 to present using daily monitoring station data from NOAA's NCDC daily data sets including the Global Historical Climate Network - Daily, as well as MSC's DLY04 and DLY02 data sets. We also develop estimates of daily precipitation and temperature values at individual stations from NOAA's NCDC hourly Integrated Surface Data.

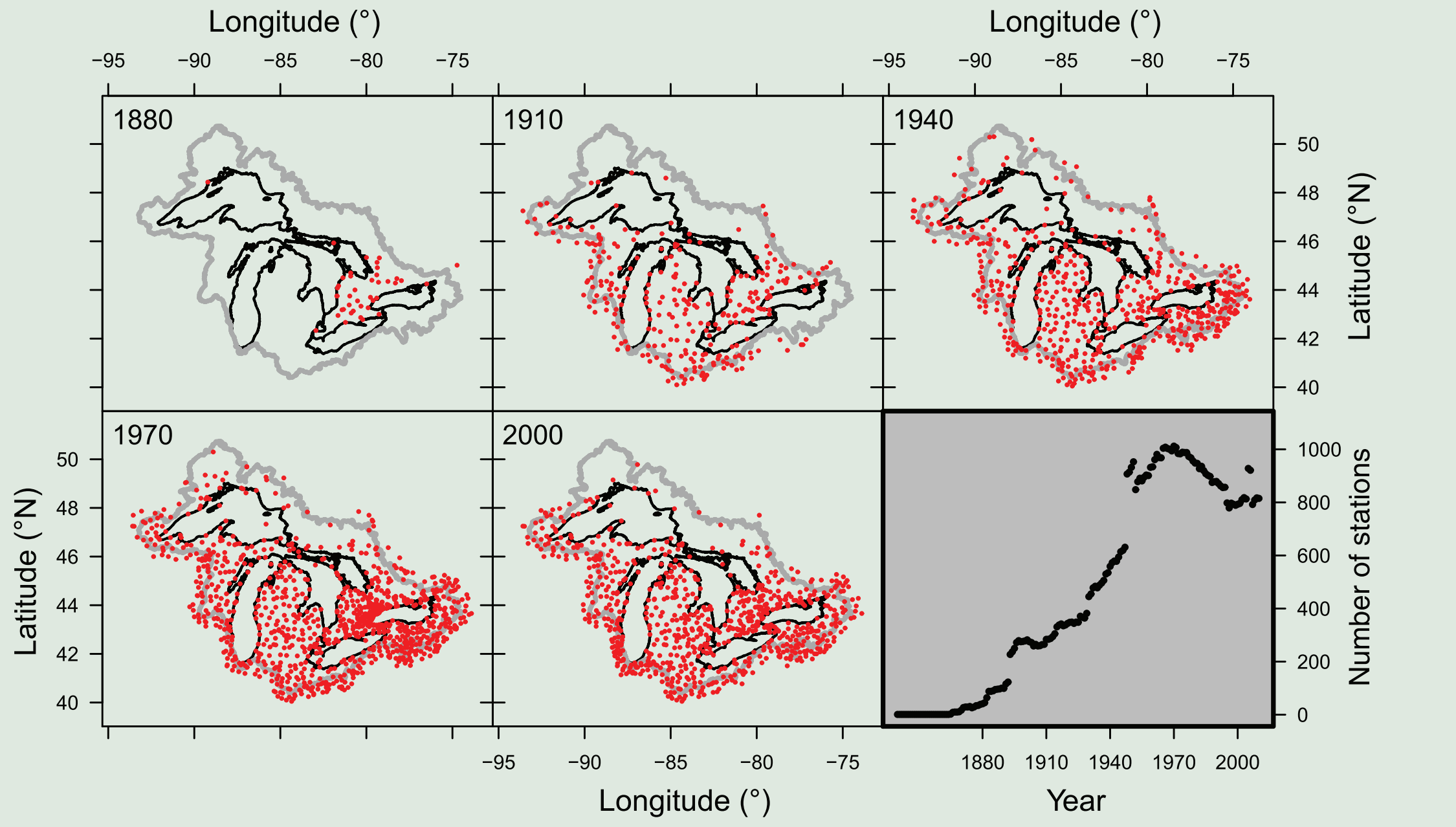

Figure 2. Spatial distribution of meteorological stations within the Great Lakes basin (boundary represented by gray line), and outside but within 50 km of the Great Lakes basin, reporting daily precipitation totals in 1880, 1910, 1940, and 2000. Bottom right-hand panel indicates total number of corresponding meteorological stations from 1840 to present.

Availability

The database is freely-available from NOAA-GLERL at the following web-site:

www.glerl.noaa.gov/data/arc/hydro/mnth-hydro.html

and through the Great Lakes Dashboard project:

www.glerl.noaa.gov/data/dashboard/portal.html

We develop precipitation and temperature basin-scale estimates by first interpolating daily precipitation and daily minimum and maximum air temperature measurements across a NOAA-GLERL defined set of subbasins and lake surface areas using a modified version of conventional Thiessen weighting, hereafter referred to as the GLERL-DTP (or daily Thiessen polygon) method.

Over-lake Evaporation

We estimate total monthly evaporation over each lake by aggregating daily simulations from NOAA-GLERL's one-dimensional Large Lake Thermodynamics Model (or LLTM). While the LLTM has been employed in both research-oriented and operational programs for decades, we recently implemented several important improvements. First, in 2012, we began implementing an alternative formulation of over-lake cloud cover (one of the inputs to the LLTM) that, relative to the pre-2012 methodology, draws from the relatively broad range of meteorological stations in the NOAA NCDC Integrated Surface Hourly Database. Second, we recalibrated (also in 2012) the LLTM using the most recent set of lake surface water temperature estimates from NOAA's Coastwatch Great Lakes Surface Environmental Analysis, and the most recent set of ice cover measurements from the NOAA-GLERL Great Lakes Ice Atlas. Third, and finally, we changed the beginning of the period of record for the over-lake evaporation estimates from 1948 to 1950, setting aside simulations from 1948 and 1949 as a model initialization period.

Tributary Runoff

We estimate historical monthly runoff by extrapolating daily streamflow measurements from both the United States Geological Survey (USGS) and Water Survey of Canada (WSC) across NOAA-GLERL subbasins (Figure 3) using a conventional flow-per-unit area ratio approach. We hereafter refer to this method as the NOAA-GLERL area ratio method, or GLERL-ARM.

We begin by identifying a set of USGS and WSC gages that have a relatively long (roughly five years or more) uninterrupted period of record and that are far downstream but are not influenced by significant "backwater" effects. For every day in our period of record (from the late 1880s to present) we then identify the subbasins that have at least one station meeting our selection criteria. For each subbasin with at least one station, we estimate the cumulative daily flow from that subbasin by dividing the total gaged flow by the total gaged area, and then multiplying the resulting subbasin-specific flow-area ratio by the total subbasin area. We estimate the total flow from all subbasins that do not contain at least one gage meeting our criteria (i.e. "ungaged subbasins") by multiplying the average flow-area ratio of all gaged by the lake basin's total ungaged area.

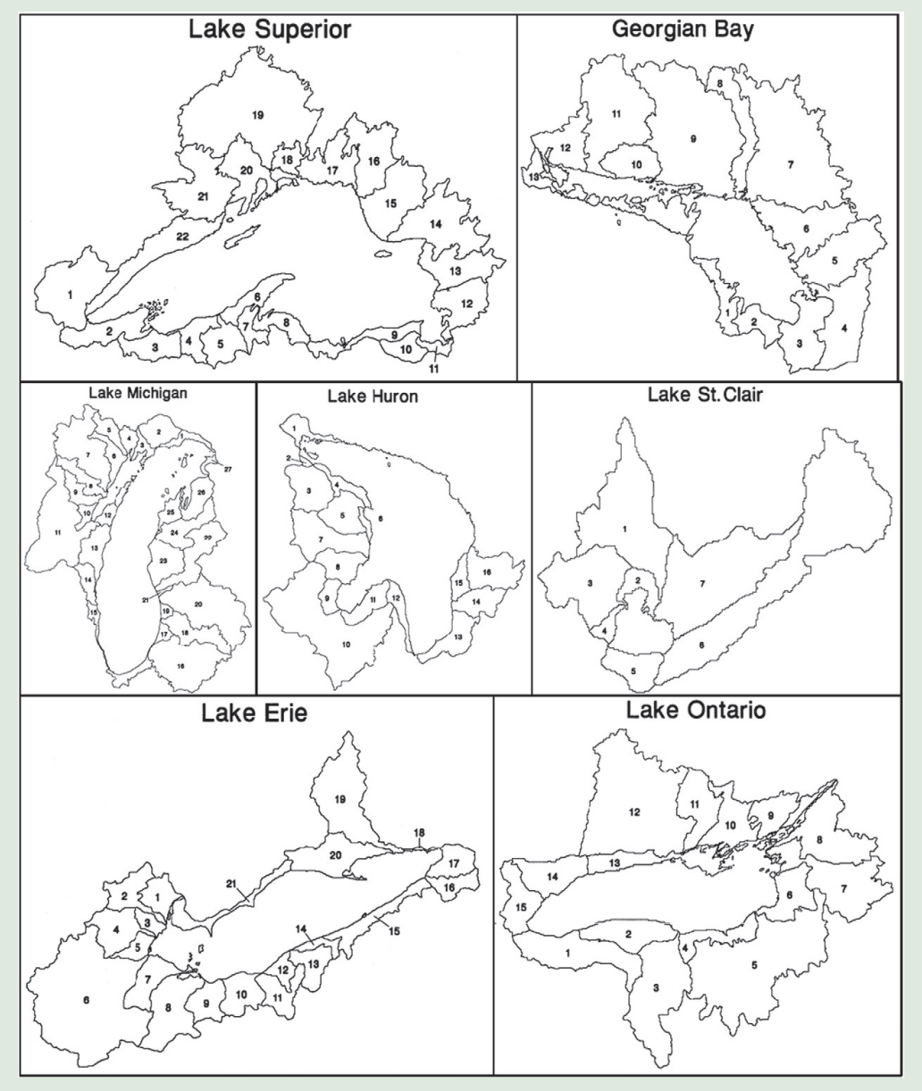

Figure 3. Historical NOAA-GLERL subbasin delineations (not to scale) that serve as a basis for spatial interpolation of precipitation, temperature, and runoff measurements for the 1948–present period of record.

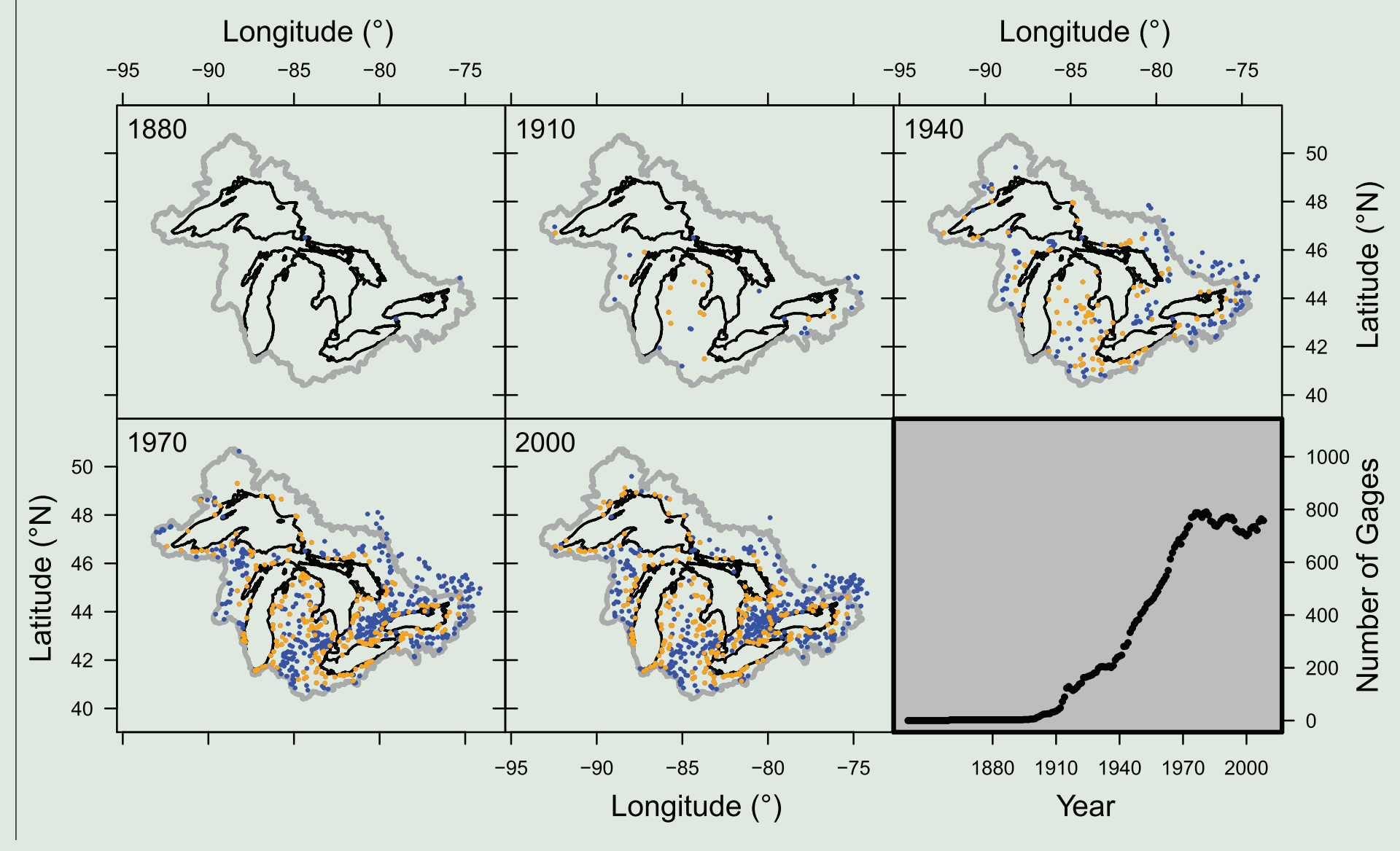

Figure 4. Spatial distribution of USGS and WSC stream flow gages across the Great Lakes basin (boundary represented by gray line) reporting daily measurements in 1880, 1910, 1940, 1970, and 2000. Yellow dots represent the subset of stations that meet GLERL-ARM selection criteria (blue dots represent stations that do not meet the criteria). Bottom right-hand panel indicates total number of gages reporting daily values from 1840 to present

Application: Understanding historical trends in the annual water budget and annual average surface air temperature of the Great Lakes basin

The time series of annual data from the GLM-HMD-I indicates periods of both significant interannual variability and long-term trends in historical over-lake precipitation and evaporation (top two rows of Figure 5); however, the variability and trends are not necessarily the same for each of the lake systems. For example, the GLM-HMD-I indicates that over-lake precipitation on Lakes Superior and Michigan-Huron is, on average, less than that on Lakes Erie and Ontario and that, beginning in the early 1970s, precipitation over Lakes Michigan-Huron, Erie, and Ontario transitioned from a period with predominantly below average values to predominantly above average values. Precipitation over Lake Superior for the past 10 years, however, has predominantly been below its long-term average.

Simulated annual evaporation rates in the GLM-HMD-I (second row Figure 5), though they constitute a shorter period of record than the precipitation estimates, also reflect a significant long-term trend with noticeably less interannual variability than over-lake precipitation estimates. More specifically, the GLM-HMD-I indicates an extended period of below-average evaporation rates across all of the Great Lakes between the early 1950s and the early 1980s, with evaporation rates rising gradually through the 1980s. The GLM-HMD-I then indicates, particularly for Lakes Superior, Michigan-Huron, and Erie, abrupt increases in over-lake evaporation beginning in the late 1990s and relatively persistent above-average evaporation rates since then.

The net effect of variability and trends in over-lake evaporation and over-lake precipitation is reflected by their sum (third row Figure 5), quantifying precipitation as a positive contribution and evaporation as a negative contribution). This time series of the difference between over-lake precipitation and over-lake evaporation (which we periodically refer to as "net precipitation") provides insight into some of the drivers behind significant shifts in the water budget of the Great Lakes over time. For example, we observe that decreasing precipitation over Lake Superior for the past 20 years, and increasing evaporation for an even longer period, collectively propagate into a relatively consistent decrease in net precipitation over Lake Superior over the past fifty years. The net precipitation on the other lakes appears to have more of a cyclical pattern, with oscillations between periods of low and high net over-lake precipitation. Of particular note are the pronounced recent decreases in net over-lake precipitation on Lakes Superior and Michigan-Huron, both of which, when presented alongside the contributions of both over-lake precipitation and over-lake evaporation, provide insight into drivers behind recent changes in Great Lakes water levels (Sell et al. 2007, Lamon and Stow 2010, Gronewold et al. 2013). While data for much of 2014 are still preliminary, we expect future updates to the GLM-HMD, coupled with the analysis presented here, to serve as an important stepping stone towards improving understanding of the hydrologic impacts of the recent extreme cold winter of 2013-2014 on the Great Lakes (Wang et al. 2014).

Finally, our analysis of GLM-HMD-I Great Lakes regional air temperatures (bottom row Figure 5) indicates significant warming over the past several decades, though the records also indicate that current air temperatures may not be entirely dissimilar from the temperature measurements in the 1950s over the basins of Lakes Michigan-Huron, Erie, and Ontario. Air surface temperatures in the Lake Superior basin also appear to have been above average in the 1950s, though the duration and intensity of the current warming period is particularly pronounced given the abrupt shift from below- to above-average temperatures in the late 1990s.

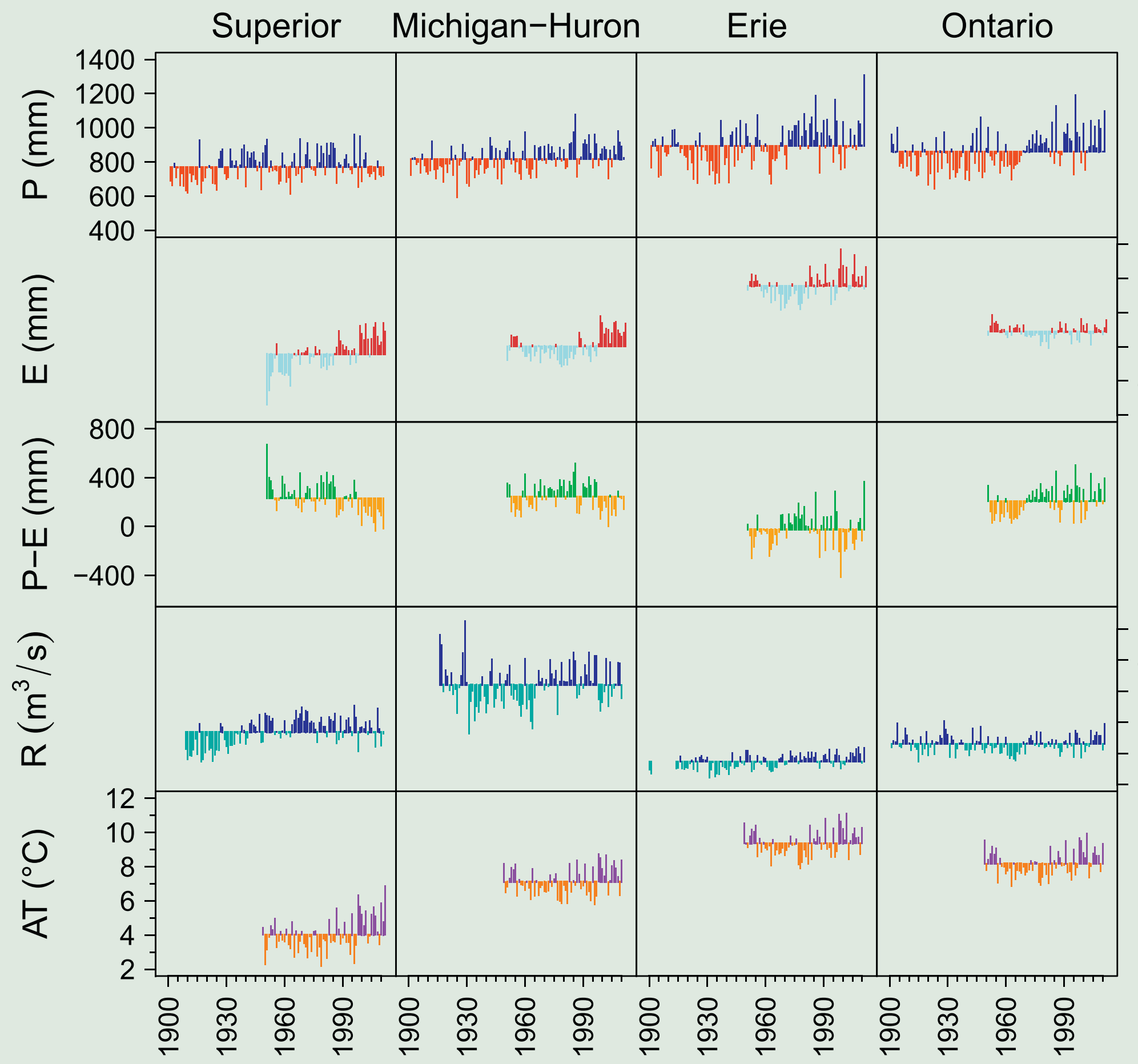

Figure 5. Time series of historical data from the GLM-HMD-I including total annual over-lake precipitation (P), total annual over-lake evaporation (E), the difference between over-lake precipitation and evaporation (P–E), average annual runoff rates (R), and average annual over-lake air temperature (AT) for each of the four major Great Lake systems. Alternating colors for each data set reflect values either above or below the long-term average for each lake.

Application: Changes in the Lake Superior seasonal water budget

Our estimates of historical (1950 to present) Lake Superior monthly NBS (top row Figure 6) provide insight into potential origins of annual and decadal NBS trends. More specifically, our estimates indicate a persistent shift over the past 60 years from a positive to negative NBS in February, as well as a tendency for December NBS to be increasingly negative. Our estimates indicate particularly pronounced decreasing trends in December and August NBS beginning roughly 15 years ago.

Visual analysis of individual components of Lake Superior NBS (rows 2-4 of Figure 6) offers additional insight into potential drivers behind the trends in the Lake Superior seasonal NBS. For example, our estimates indicate that runoff has (relative to the other NBS components) changed little over time. Changes in over-lake evaporation, however, are more pronounced, particularly in the mid-winter (December and February) and late summer (e.g. August) months, and underscore the impact of changes in over-lake precipitation and over-lake evaporation on seasonal changes in the Lake Superior water budget. The tendency for significant increased evaporation in both the mid-winter and late summer months represents not only a profound change in Lake Superior's water budget, but in the climatology of the Lake Superior basin as well, and is a critical component of broader scale changes taking place across the entire Great Lakes ecosystem.

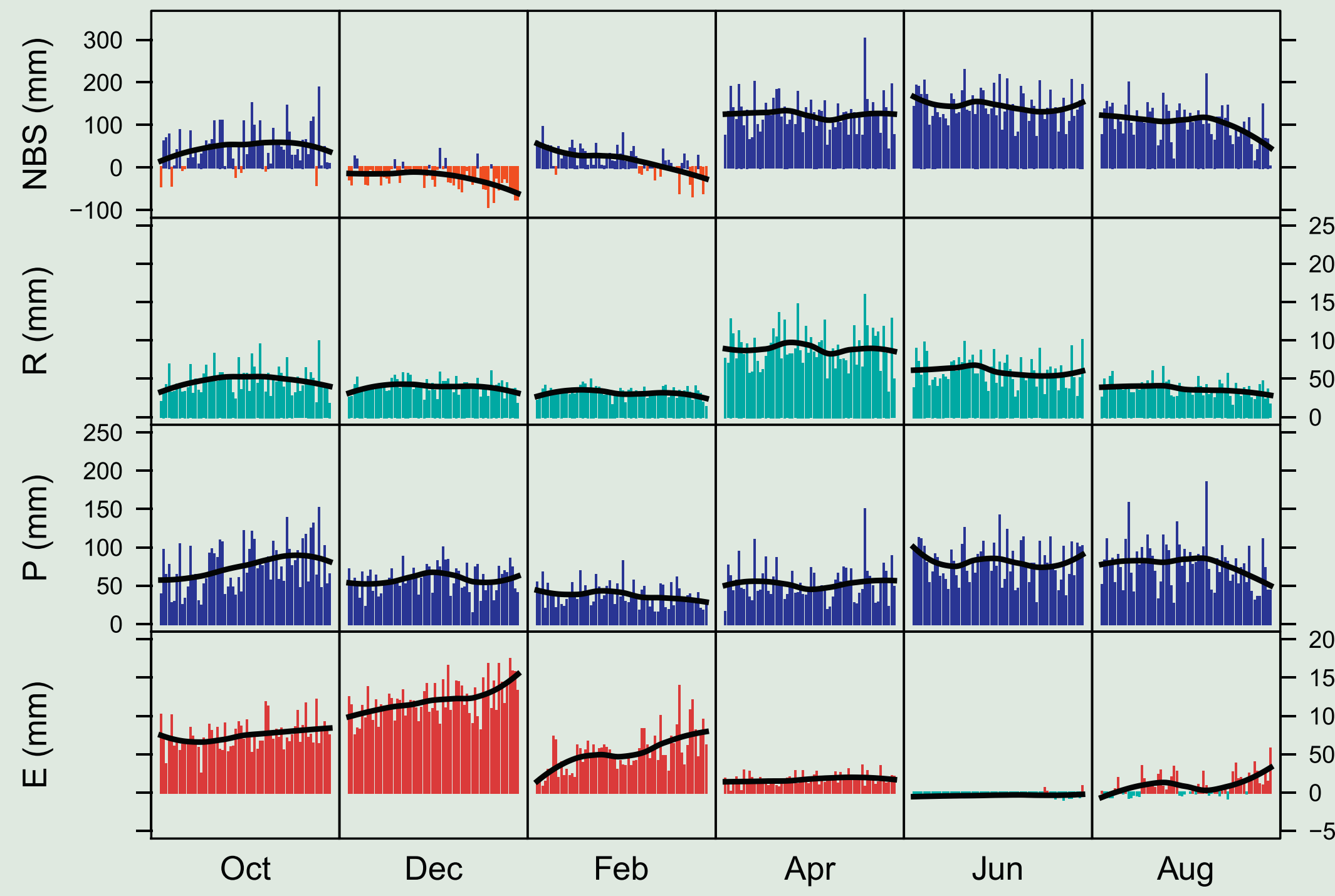

Figure 6. Monthly data from the GLM-HMD-I for Lake Superior including net basin supply (NBS), runoff (R), over-lake precipitation (P), and over-lake evaporation (E). The vertical bars in each panel represent monthly total values from 1950 to 2013. Coloring in each panel differentiates positive from negative values. Horizontal black lines in each panel represent the smoothed trend.

For Further Reading:

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