Sub-Indicator: Precipitation Amounts in the Great Lakes Basin

Overall Assessment

Trends:

10-Year Trend (2014-2023): No Trend

30-Year Trend (1994-2023): Increasing

Long-term Trend (1950-2023): Increasing

Rationale: Annual precipitation anomalies based on US and Canadian stations aggregated across the entire Great Lakes basin relative to 1961-1990 means display a statistically significant trend for both the 30-year period (+2.8% per decade) and for the long-term period (+1.9% per decade). Total precipitation during 2014-2023 exceeded that of any other 10-year period in the data record (1950-2023). Although the overall assessment is based on annual values, there was evidence of long-term increasing trends in summer (+1.5% per decade) and fall (+3.2% per decade). Summer precipitation was found to be increasing over the long-term (+1.5% per decade), but with a less statistical significance (90% significance). No significant trends in seasonal precipitation anomalies were determined for the 10-year or 30-year periods ending in 2023.

Lake-by-Lake Assessment

Note: The lake-by-lake trend assessments are based solely on the annual precipitation anomalies, and not on seasonal precipitation anomalies. Some additional information on seasonal trends are included in the rationale sections; however this is only to provide additional context.

Lake Superior

10-Year Trend (2014-2023): No Trend

30-Year Trend (1994-2023): No Trend

Long-term Trend (1950-2023): No Trend

Rationale: The precipitation anomaly trend was positive for both the long-term and 30-year trend, but not statistically significant. The relatively dry years of 2023, 2021, and 2020 in the Lake Superior basin resulted in an overall negative trend for the 10-year period ending in 2023, but that trend was not determined to be statistically significant. No significant trends were found for seasonal precipitation anomalies on Lake Superior apart from a 3.1% per decade increase in fall precipitation over the long-term period with 90% significance.

Lake Michigan-Huron

10-Year Trend (2014-2023): No Trend

30-Year Trend (1994-2023): No Trend

Long-term Trend (1950-2023): Increasing

Rationale: The annual precipitation anomaly trend for the Lake Michigan-Huron basin was statistically significant for the long-term period (+2.1% per decade). No significant trends were discovered in the seasonal precipitation anomalies apart from a 2.3% increase per decade in spring precipitation over the long-term period and, with less

statistical significance (90%), an increase in summer and fall precipitation (+1.5% and +3.1% per decade, respectively).

Lake Erie

10-Year Trend (2014-2023): No Trend

30-Year Trend (1994-2023): No Trend

Long-term Trend (1950-2023): Increasing

Rationale: The annual precipitation anomaly trend for the Lake Erie basin was statistically significant for the long-term period (+2.4% per decade). Over the long-term period, significant increasing trends were also found in summer precipitation (+3% per decade) and, with less significance in the winter precipitation (+3% per decade, at 90% significance). No significant trends in annual or seasonal precipitation anomalies were discovered in the 10-year or 30-year periods ending in 2023.

Lake Ontario

10-Year Trend (2014-2023): No Trend

30-Year Trend (1994-2023): No Trend

Long-term Trend (1950-2023): Increasing

Rationale: The annual precipitation anomaly trend for the Lake Ontario basin was statistically significant for the long-term period (+2.5% per decade). Positive seasonal precipitation anomaly trends were found to be significant for winter, summer, and fall over the long-term period (+2.3%, +3.3%, and +3.4% per decade, respectively) and for winter and summer over the 30-year period (+4.5% and +8.1% per decade, respectively). In addition, a 13.5% per decade increase in winter precipitation was identified over the 10-year period, but with less statistical significance (90% significance).

Trend Assessment Definitions

Increasing: The calculated historical trend in annual precipitation amount is positive and large enough to be distinguished from the variability of the data (is statistically significant at the 0.05 level).

Unchanging: The calculated historical trend in annual precipitation amount is too small to be distinguished from the natural variability of the data (is not statistically significant at the 0.05 level).

No Trend: The calculated historical trend in annual precipitation is not statistically increasing or decreasing due to high variability in the data. No Trend is different from Unchanging (which would be used when the trend is not statistically significant and has low variability (i.e., stable)).

Decreasing: The calculated historical trend in annual precipitation amount is negative and large enough to be distinguished from the variability of the data (is statistically significant at the 0.05 level).

Undetermined: Sufficient data are not available to report on a trend.

Note that significant trends in seasonal precipitation are also described in the rationale, but trend assessment definitions are based on annual precipitation.

Sub-Indicator Purpose

The purpose of the Precipitation Amounts sub-indicator is to assess whether the amount of precipitation falling within the Great Lakes basin is above or below a reference period, both annually and seasonally, both Great Lakes wide and for individual lakes and to infer the potential impact that varying precipitation amounts will have on ecosystem components.

Ecosystem Objective

This sub-indicator best supports work towards General Objective #9 of the 2012 Great Lakes Water Quality Agreement, which states that the Waters of the Great Lakes should "be free from other substances, materials, or conditions that may negatively impact the chemical, physical, or biological integrity of the Waters of the Great Lakes." This sub-indicator also relates to all of the General Objectives in the Agreement because it has broad ecosystem implications.

In addition, an objective of the precipitation amounts sub-indicator is to report on a component of the hydrologic system of the Great Lakes and surrounding region to determine if the hydrologic system of the Great Lakes basin continues to follow historic patterns. Changes in the frequency, seasonal distribution, or magnitude of precipitation will affect the hydrologic system of the entire Great Lakes basin, resulting in impacts such as altered water levels or changes in the rates and patterns of storm runoff, thereby influencing the distribution of pollutants, nutrients, and invasive species.

Methods

This sub-indicator estimates the annual and seasonal precipitation anomalies (from the 1961-1990 reference period) for each period of study (1950–2023, 1994-2023 and 2014-2023) in the Great Lakes basin as well as each individual lakes' basin ("basin" hereafter refers to the combined area including both the land-surface of the watershed and the lake surface). Data from 1950-2021 are from the Coordinating Committee for Great Lakes Basic Hydraulic and Hydrologic Data (for details on the Coordinating Committee, see Gronewold et al., 2018). Data for 2022-2023 come from the U.S. Army Corps of Engineers (USACE). Both the Coordinating Committee and USACE compute basin precipitation using tools that are packaged with the Great Lakes Seasonal Hydrologic Forecast System (GLSHyFS, described in Gronewold et al. 2017). GLSHyFS calculates basin-wide precipitation values using a Thiessen Polygon weighting technique to derive historical precipitation over sub-basins which can then be aggregated into lake basin averages for the entire lake (Croley and Hartmann 1985).

This sub-indicator, as well as the other Physical Conditions sub-indicators (Water Levels, Ice Cover, and Surface Water Temperatures), have been determined using an anomaly-based approach for estimating trends. An anomaly-based approach is a more representative way of describing the state of an ecosystem variable where the typical value is not necessarily common knowledge. It also allows for easy comparison of the state of variables that are not necessarily similar, such as precipitation in different seasons or different geographic locations. In addition, the anomaly-based approach helps put the longer periods of record into context by identifying whether the deviations or extremes are increasing or decreasing over the various time periods. For this sub-indicator, an annual or seasonal precipitation anomaly is the difference between the precipitation amount and the reference value, which is then divided by the reference value and multiplied by 100. The anomaly is therefore represented by a percentage of deviation from the reference value and the trend is expressed as a percent rate of change. Since the

precipitation mean of the base period is a constant, the trends within the anomalies are identical to the trends determined from the original data.

The reference values used in this sub-indicator are the annual and seasonal precipitation totals for the base period of 1961–1990. Seasons are defined as winter (December, January, February); spring (March, April, May); summer (June, July, August); and fall (September, October, November). The 1961–1990 base period was selected following the World Meteorological Organization recognition as a standard reference period (WMO 2007). Moreover, this period includes a relatively high fraction of manual and rigorously quality controlled observations before the automation of observations (Mekis et al, 2018).

The significance of trends was evaluated using a Mann-Kendall test (Kendall, 1955). For a computed trend to be deemed statistically significant, it must be large enough to stand out from the variability of the data. Statistical significance was computed at the 0.05 level. While trends that were not significant at the 0.05 level may still be true, there is also a tangible chance that they instead represent cyclic or other variations in the data.

A 9-year moving average for the Physical Conditions sub-indicators is displayed on the figures, as an aid for visualizing trends.

Discussion

Overall

Annual precipitation anomalies for the Great Lakes Region for 1950–2023 is shown in Figure 1. It displays a statistically significant (at the 0.05 level) increasing trend of 1.9% per decade (Table 1, 13.9% total over the period). The trend for the 30-year period (1994-2023) was also found to be significant and had an increasing trend of 2.8% per decade (8.4% total over the period). While the trend during the 10-year period (2014-2023) was not statistically significant, it is important to note that, similar to the 2022 report, it was the wettest 10-year period since 1950. This recent 10-year period is an example of how extrapolation of long-term and recent trends does not constitute a projection of future conditions.

Precipitation anomalies can also be analyzed on a seasonal basis. The 9-year running means of the seasonal precipitation anomalies for the Great Lakes basin over the period of record (1950-2020) are shown in Figure 2. Summer and fall were found to have statistically significant trends of increase for the long-term period but not the 30- or 10-year period.

Lake-by-Lake

The four lakes' trend analysis results can be found in Table 1. The 9-year running means of anomaly series are plotted for annual and seasonal precipitation in Figures 3 and 4, respectively. The long-term annual precipitation trends for individual lakes were statistically significant for Michigan-Huron, Erie and Ontario. (Though a p-value of 0.05 was used for this study, please note that all three lakes above were also significant at the 0.01 level.) There were also significant trends found for long-term seasonal precipitation as shown in Table 1.

For the 30- and 10-year periods fewer significant trends were found: No significant trends in annual precipitation anomalies were found for any of the lakes over these shorter periods. Seasonal precipitation anomaly trends were only identified for Lake Ontario winter and summer precipitation over the 30-year period, and no seasonal trends were identified in the 10-year period.

Linkages

Increased precipitation amounts seen over the long-term record in the Great Lakes basin is the result of both increasing frequency and magnitude of precipitation. An increase in global temperature enhances the ability of the atmosphere to store and transport water vapour which intensifies the hydrologic cycle and affects storm evolution and geographical distribution of precipitation (Wuebbles et al, 2020). This change, which is projected to continue into the future (Wuebbles et al., 2020) affects the hydrological system of the entire basin. The impacts of such changes would be numerous; some examples specific to an increase in precipitation event magnitude (precipitation extremes) include crop loss due to storm-damage, erosion, and flooding.

Locally, changes in ice cover and surface water temperature will directly impact precipitation event magnitude and frequency through mechanisms such as lake-effect precipitation.

Precipitation Amounts in the Great Lakes Basin link directly to almost all other sub-indicators in the suite given their role as a driving force in hydrology, nutrient and toxin distribution, and shoreline and wetland health. An increase in intense precipitation events increase the risk of flooding and higher soil erosion rates, causing entrainment and delivery of sediments, nutrients, pesticides and other contaminants in surface waters (Cooney et al, 2018).

Some specific examples include:

- Beach Advisories – runoff following precipitation events and related bacteria loading is a major concern to beach safety and human health.
- Algal Bloom Extent – more rain in the future over the Great Lakes basin means more runoff and sewer discharge into the lakes, increasing the potential occurrence of algal blooms and hypoxia.
- Coastal Wetland Sub-indicators (Coastal Wetland Amphibians, Coastal Wetland Birds, Coastal Wetland Fish, Coastal Wetland Invertebrates, Coastal Wetland Plants, Coastal Wetland: Extent and Composition) – change in precipitation event frequency or intensity will have a direct impact on coastal wetlands by altering the extent and quality of wetland ecosystems through processes such as altering water levels, changing nutrient availability, or affecting pollutant concentrations. Extreme precipitation events could also lead to additional upstream erosion resulting in increased sedimentation, loss of wetland vegetation, and habitat loss.
- Invasive Species – cumulative stresses related to precipitation amounts, may encourage the spread of invasive species in coastal wetlands.
- Water Quality in Tributaries – precipitation events, especially extreme ones, can increase and/or change the flow of contaminants resulting in reduced water quality.

In addition, Precipitation Amounts in the Great Lakes Basin potentially have direct or indirect impacts on all 14 Beneficial Use Impairments included in Annex 1 (Areas of Concern) of the Great Lakes Water Quality Agreement Protocol of 2012.

Assessing Data Quality

Data Characteristics	Agree	Neutral or Unknown	Disagree	Not Applicable

Data are documented, validated, or quality-assured by a recognized agency or organization	X			
Data are from a known, reliable and respected generator of data and are traceable to original sources	X			
Geographic coverage and scale of data are appropriate to the Great Lakes Basin	X			
Data obtained from sources within the U.S. are comparable to those from Canada	X			
Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X			
Data used in assessment are openly available and accessible	Yes	https://zenodo.org/records/10479324 *valid for 1950-2021		

Data Limitations

Precipitation data suffers from geographic and temporal discontinuities due to factors such as lack of observing sites, changes in observation method, equipment wear and replacement, station relocation and automation. Additionally, the solid precipitation undercatch due to mainly windy conditions can lead to further missing precipitation amount in all downstream applications. To mitigate the effect of discontinuities, station data undergo QA/QC prior to use as input for the Thiessen Polygon weighting algorithm run by GLSHyFS.

Precipitation naturally varies greatly on multiple time-scales including daily, seasonally, and annually. This is a challenge in precipitation trend analysis, especially when analyzing time series of a few decades or even shorter, as only very large trends will be deemed statistically significant by tests.

Additional Information

In the next century, annual precipitation is expected to increase by up to 20% across the Great Lakes basin with greater annual precipitation projected for Lake Superior (Lofgren et al. 2002; McKenney et al. 2011). Lake-effect precipitation continues to be observed in future projections and is expected to increase due to decreasing ice cover on lakes (Burnett et al. 2003; Notaro et al. 2014). The form of precipitation is also expected to change, with more precipitation falling as rain and freezing rain and less as snow. Shifts in the timing of precipitation are expected, where rainfall will increase in the spring but decrease in the summer (Kling et al. 2003; Hayhoe et al. 2010).

Future reporting cycles could benefit from an analysis of the number of extreme storms—defined as any extratropical cyclone-related event occurring during ice-free and ice-breakup periods which meets two of the following three criteria:

- Total daily precipitation that exceeds the 95th percentile of the reference period.
- Central atmospheric pressure less than 980mb.
- Recorded maximum wind gusts in a 24hr period exceeding the 95th percentile.

Report Authors

Deanna Fielder, U.S. Army Corps of Engineers Detroit District (Deanna.C.Fielder@usace.army.mil)

Lauren Fry, NOAA Great Lakes Environmental Research Lab (lauren.fry@noaa.gov)

James Kessler, NOAA Great Lakes Environmental Research Lab (james.kessler@noaa.gov)

Frank Seglenieks, Environment and Climate Change Canada (Frank.Seglenieks@ec.gc.ca)

Report Contributors

Victor Isaac (previous report author), Environment and Climate Change Canada

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List of Tables

Table 1: The slope of the linear trend (units: % anomaly per decade) for each period and lake. The anomaly is based on the deviation from the reference value which is shown in table 2. The trends that are statistically significant at the 0.05 level are colored dark green. Though the 0.05 level is used exclusively to determine statistical significance throughout this report, two more significance levels, 0.01 (bold) and 0.1 (light green) are also shown for additional context.

Table 2: The reference value (mean 1961-1990) for each lake expressed as total annual and seasonal precipitation in millimeters.

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Figure 2. Nine-year running means of seasonal precipitation anomalies (from the 1961–1990 seasonal means) for the Great Lakes basin during the period of record (1961–2023). Note that the mean for a particular 9-year interval is centered on the middle year, meaning the first year for which the running mean can be defined is 1954 and the last is 2019.

Figure 3. Annual precipitation anomaly (from the 1961–1990 mean) and nine-year running mean for each Great Lake during the 1950–2023 period. Note that the mean for a particular 9-year interval is centred on the middle year, meaning the first year for which the running mean can be defined is 1954 and the last is 2019.

Figure 4. Nine-year running means of seasonal precipitation anomalies (from the 1961–1990 seasonal means) for each Great Lake individually during the period of record (1950–2023).

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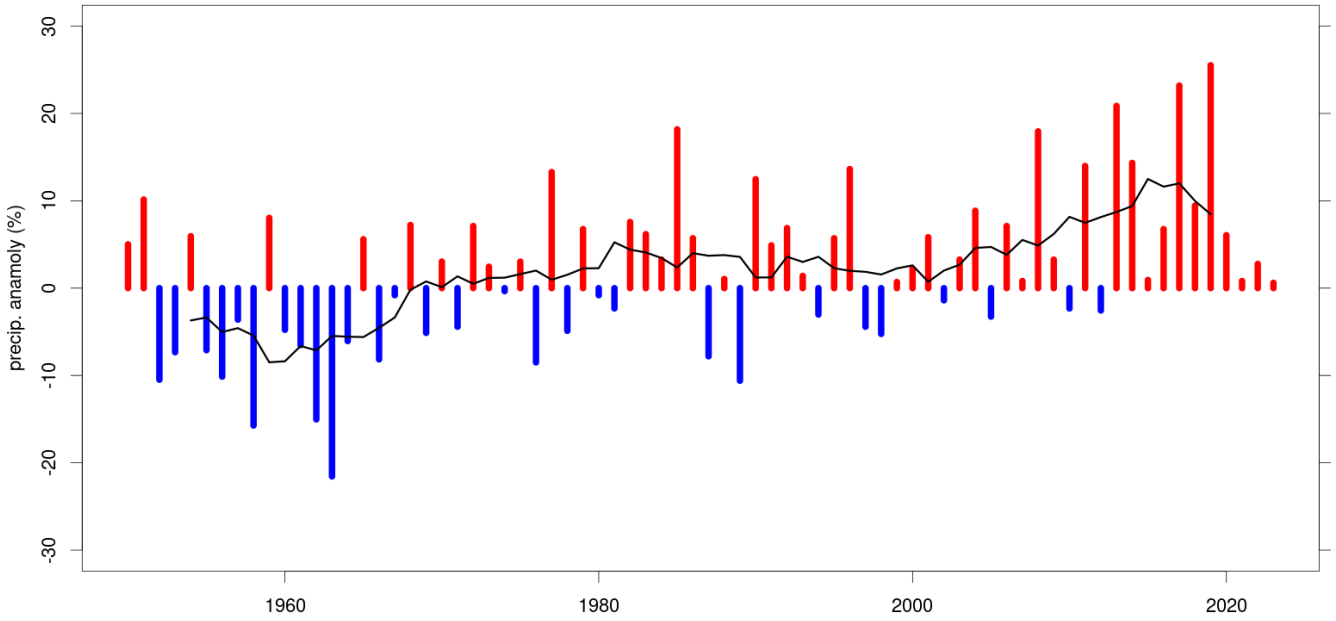
Table 1: The slope of the linear trend (units: % anomaly per decade) for each period and lake. The anomaly is based on the deviation from the reference value which is shown in table 2. The trends that are statistically significant at the 0.05 level are colored dark green. Though the 0.05 level is used exclusively to determine statistical significance throughout this report, two more significance levels, 0.01 (bold) and 0.1 (light green) are also shown for additional context.

	Annual	Winter	Spring	Summer	Fall
LONG TERM: (1950-2023)					
Great Lakes Basin-Wide	**1.9**	1.6	1.7	1.5	3.2
Superior	0.9	0.3	0.6	-0.2	3.1
Michigan-Huron	**2.1**	1.7	2.3	1.5	3.1
Erie	**2.4**	3	1.6	**3**	4.3
Ontario	**2.5**	2.3	1.1	**3.3**	3.4
30 year: (1994-2023)					
Great Lakes Basin-Wide	2.8	2.4	3.4	3.4	2.4
Superior	2.8	9.1	3.8	-0.2	2.2
Michigan-Huron	2.3	-2	4.1	2.7	3.9
Erie	3.6	3.7	1	5.7	5
Ontario	3.1	4.5	1.4	8.1	-1.6
10 year: (2014-2023)					
Great Lakes Basin-Wide	-8.5	-8.2	-1.7	-2.5	-28.6
Superior	-19.3	-18.2	7.9	-30.9	-35.1
Michigan-Huron	-10	-24.8	-7	4	-28.4
Erie	-1.6	6.8	-7.9	6.4	-24.4
Ontario	2.1	13.5	-2.5	5	-14.3

Table 2: The reference value (mean 1961-1990) for each lake expressed as total annual and seasonal precipitation in millimeters.

	Annual	Winter	Spring	Summer	Fall
Great Lakes Basin-Wide	858	167.2	196.5	251.5	242.8
Superior	805.8	147.1	166.8	258.6	233.4
Michigan-Huron	853.9	165.1	198.1	245.5	245.2
Erie	925.7	182.9	236.2	267.8	238.8
Ontario	935.4	207.7	218.6	245.7	263.4



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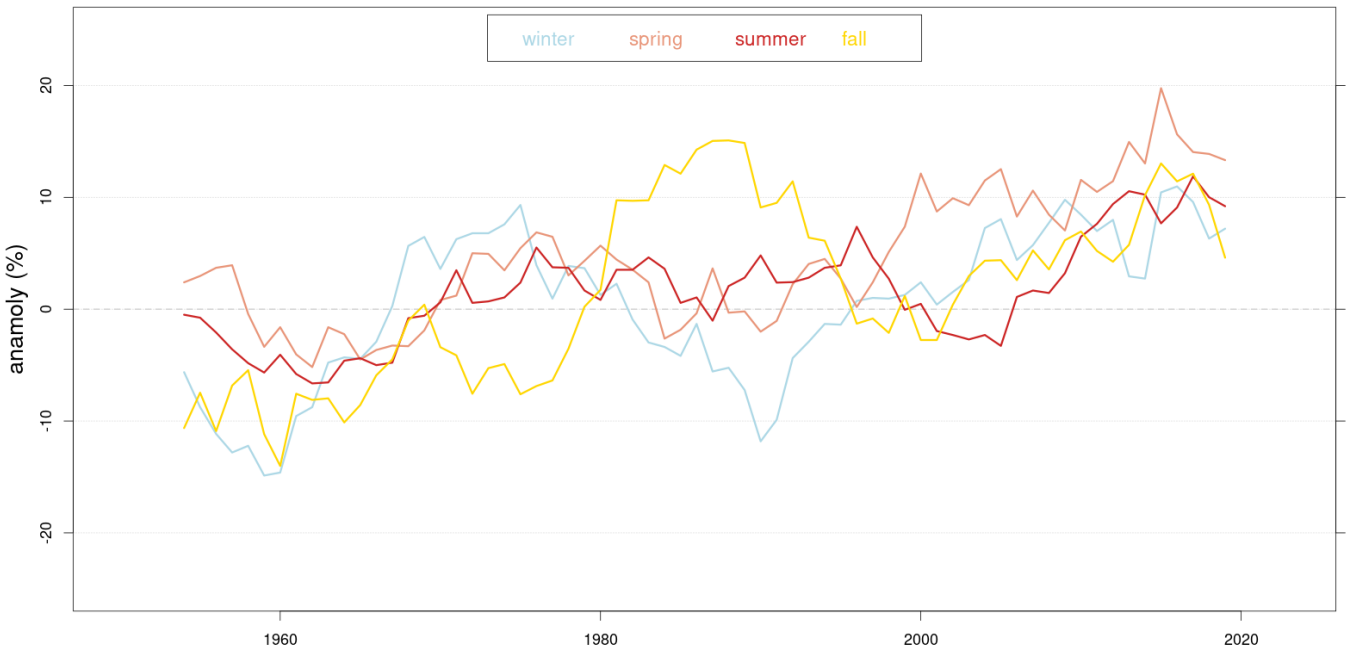

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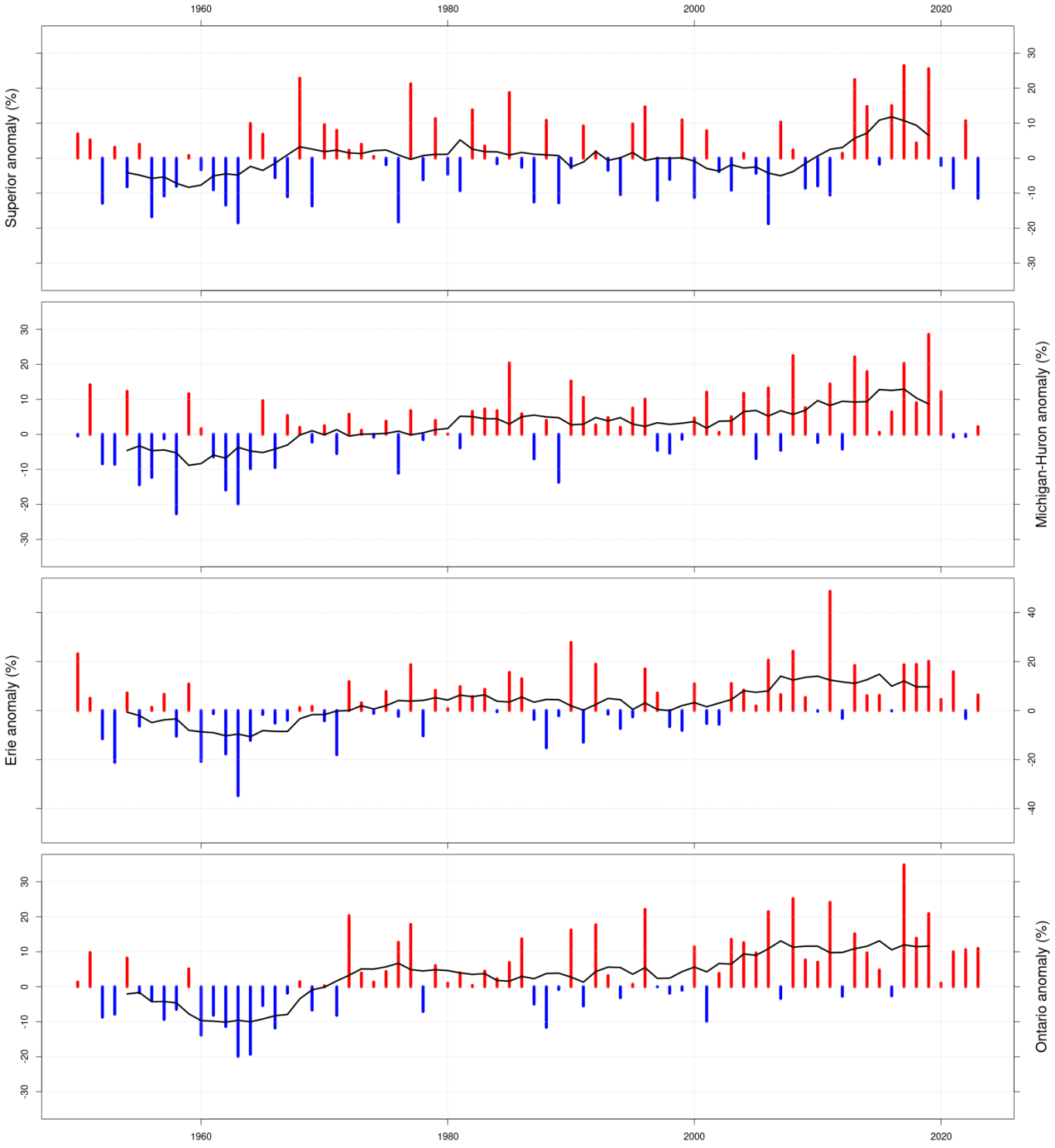

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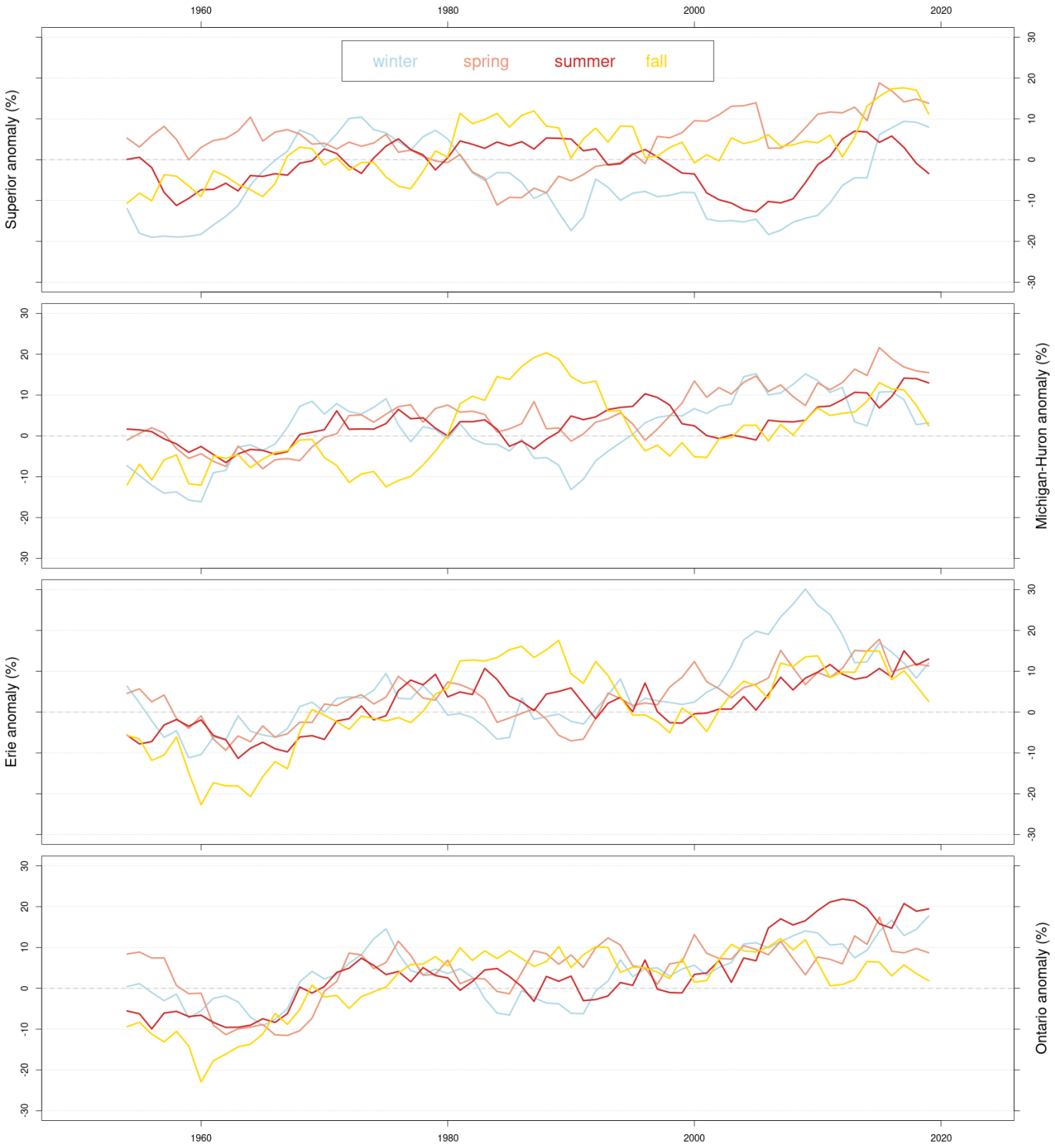

Figure 4. Nine-year running means of seasonal precipitation anomalies (from the 1961–1990 seasonal means) for each Great Lake individually during the period of record (1950–2023).