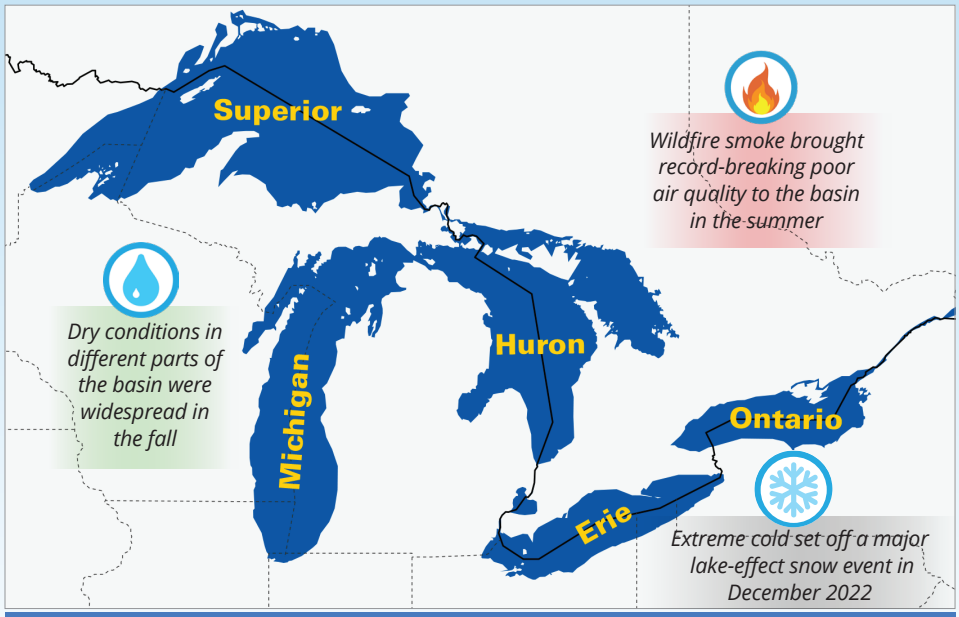
2023 ANNUAL CLIMATE TRENDS AND IMPACTS SUMMARY FOR THE GREAT LAKES BASIN

During the 2023 reporting period, air temperatures were above normal and precipitation was near to below normal for most of the basin. Dry conditions were prevalent in different areas of the basin through 2023, becoming widespread by the fall. These conditions contributed to wildfires in Ontario and Quebec, which drove record-low air quality throughout the basin in the summer months from drifting smoke. Amidst the dry conditions, there were small pockets of above-average precipitation in every season except the fall. Both wet and dry conditions contributed to above-average seasonal shifts in water levels on numerous lakes. At 21.6% areal coverage, Great Lakes maximum ice cover in 2023 was well below the long-term average.



*Arrows indicate how 2023 average values compare to the long-term average for the overall Great Lakes, though numerous 2023 values were near normal or varied by lake.

Above Below Variable

Air Temperature	Basin Precipitation	Water Temperature	Ice Cover	Water Levels
↑	↕	↑	↓	↑

2023 Highlights

Wet and Dry Conditions

Dry conditions began in the northern part of the basin in the winter, then expanded to the western basin in the summer, and to the entire Great Lakes basin in the fall. These dry conditions were interspersed with pockets of above-average precipitation in the western basin in the winter, the northwestern basin in the spring, and southeastern basin in the summer.

Air Quality Diminished by Wildfire Smoke

The basin experienced widespread record-breaking poor air quality in the summer, driven by wildfire smoke from Ontario and Quebec. The air quality index reached 'unhealthy' to 'very unhealthy' levels across the basin.

Unusual Seasonal Water Level Shifts

Warm and wet conditions contributed to above-average water level rises on every lake during the winter or spring. Then, expanding dry conditions led to greater-than-average declines on Lakes Superior and Ontario in the fall. By the end of the year, Lakes Superior and Ontario dropped below average, while Lakes Michigan-Huron and Erie remained above average.

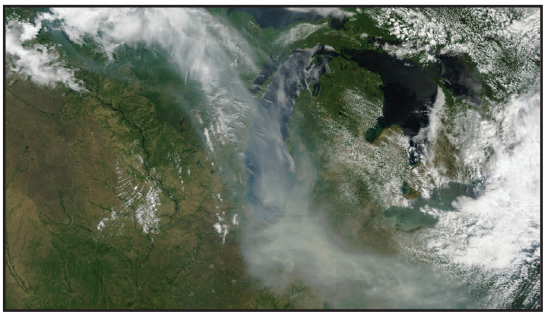


Photo: Great Lakes wildfire smoke on June 9, 2023 (Credit: NASA Goddard Space Flight Center).



Photo: View from Thunder Bay, ON, on March 20, 2023, showing no ice cover on Lake Superior (Credit: NOAA).

2023 ANNUAL CLIMATE TRENDS AND IMPACTS SUMMARY FOR THE GREAT LAKES BASIN

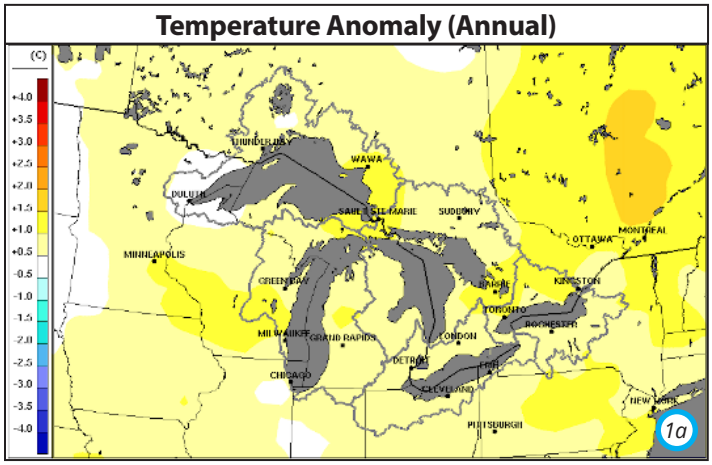
Climate Overview: December 2022–November 2023

During the December 2022–November 2023 reporting period*, mean annual temperatures across the Great Lakes region were above normal by 0.5 to 1°C (Figure 1a). This was heavily driven by warm conditions in the winter and very warm conditions in the fall. Annual precipitation totals were near or below normal for most of the basin (Figure 1b), and above normal in parts of the Erie and Ontario basins. Dry conditions developed in the northern and western portions of the basin in the winter and summer, then spread to the entire basin in the fall. The southeastern portion of the basin was extremely wet in the summer.

Annual water temperatures were above normal for all lakes, except Superior in 2023. Basinwide precipitation and runoff totals were above normal for Lakes Superior and Erie, and below normal for Lakes Michigan-Huron and Ontario. Evaporation totals were above normal on all lakes. Over the period from 1991–2020 across the region, increases in air temperature (+0.14°C/decade), precipitation (+11.5mm/decade), evaporation (+17.4mm/decade), water temperatures (+0.43°C/ decade), and runoff (+20.1mm/decade) have been observed.

This 2023 report utilizes a new climate normal period of 1991–2020 for historical averages, where past reports used the 1981–2010 climate normal period. See more on page 4.

*This report utilizes climatological seasons, which include December from the previous year as part of the winter season.



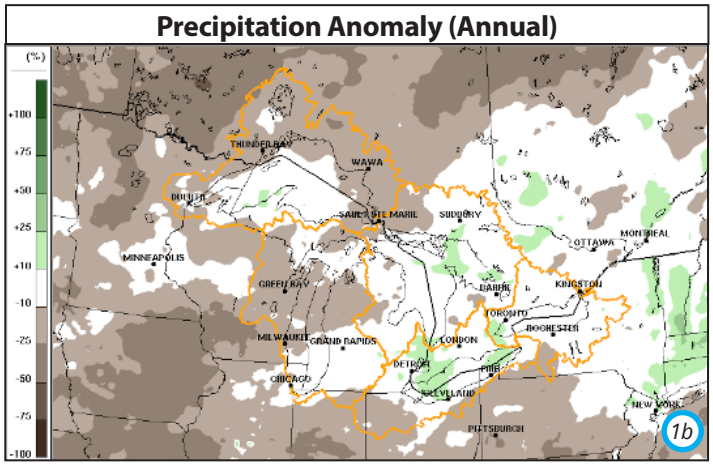


Figure 1. Maps displaying annual anomalies for temperature (1a) and total precipitation accumulation (1b) in the Great Lakes region. Anomalies for temperature are departures from the 1991–2020 mean. Anomalies for precipitation are % departure from the 1991–2020 mean. Gray (1a) and orange (1b) outlines depict the individual lake basins. Data for temperature are from ECCC and NOAA surface observations, and precipitation is a merged dataset containing ECCC model and Numerical Weather Prediction (NWP) model data. Figures created by ECCC.

		SUPERIOR		MICHIGAN		HURON		ERIE		ONTARIO	
		2023	LTA	2023	LTA	2023	LTA	2023	LTA	2023	LTA
Water Temps (°C)	Max	17.83	17.65	22.23	22.59	21.16	21.46	23.92	25.06	22.86	23.59
	Min	1.15	0.60	2.51	1.29	1.46	0.60	0.87	0.33	2.73	1.37
	Avg	6.90	6.56	10.54	9.76	9.81	8.93	12.00	11.43	11.43	10.39
Ice Cover (%)	Max	19.83	54.54	21.51	36.43	34.37	59.90	40.18	79.99	16.38	26.16

		SUPERIOR		MICHIGAN-HURON**		ERIE		ONTARIO	
		2023	LTA	2023	LTA	2023	LTA	2023	LTA
Water Levels (meters)	Max	183.68	183.58	176.70	176.62	174.65	174.40	75.36	75.10
	Min	183.43	183.23	176.41	176.25	174.20	173.91	74.47	74.42
	Avg	183.57	183.41	176.56	176.45	174.47	174.18	74.89	74.77
Precipitation (mm)	Ann Sum	841.9	820.1	832.2	909.9	1042.1	989.5	925.8	955.0
Evaporation (mm)	Ann Sum	702.0	640.1	667.9	585.0	985.0	925.2	747.7	671.2

Table 1: Summary of hydro-climate variables by lake. Long-Term Average (LTA) changes depending on variable: **Water Temps (°C)***–2023: December 2022 through November 2023, LTA: 1995–2022;* **Ice Cover (%)***–2023: December 2022 through May 2023, LTA: 1991–2020;* **Water Levels (m)***–2023: December 2022 through November 2023, LTA: 1918–2022;* **Precipitation (mm)***–2023: December 2022 through November 2023, LTA: 1991–2020;* **Evaporation (mm)***–2023: December 2022 through November 2023, LTA: 1991–2020. Estimated from NOAA Great Lakes Surface Environmental Analysis (water temps), NOAA GLERL CoastWatch (ice cover), U.S. Army Corps of Engineers (lake levels), and NOAA GLERL Great Lakes Hydrologic Data (precipitation and evaporation).*

***Lakes Michigan and Huron are treated as one unit for water levels, precipitation, and evaporation since there is no physical separation between the lake bodies.*

2023 ANNUAL CLIMATE TRENDS AND IMPACTS SUMMARY FOR THE GREAT LAKES BASIN

Historical Trends in Lake Basins

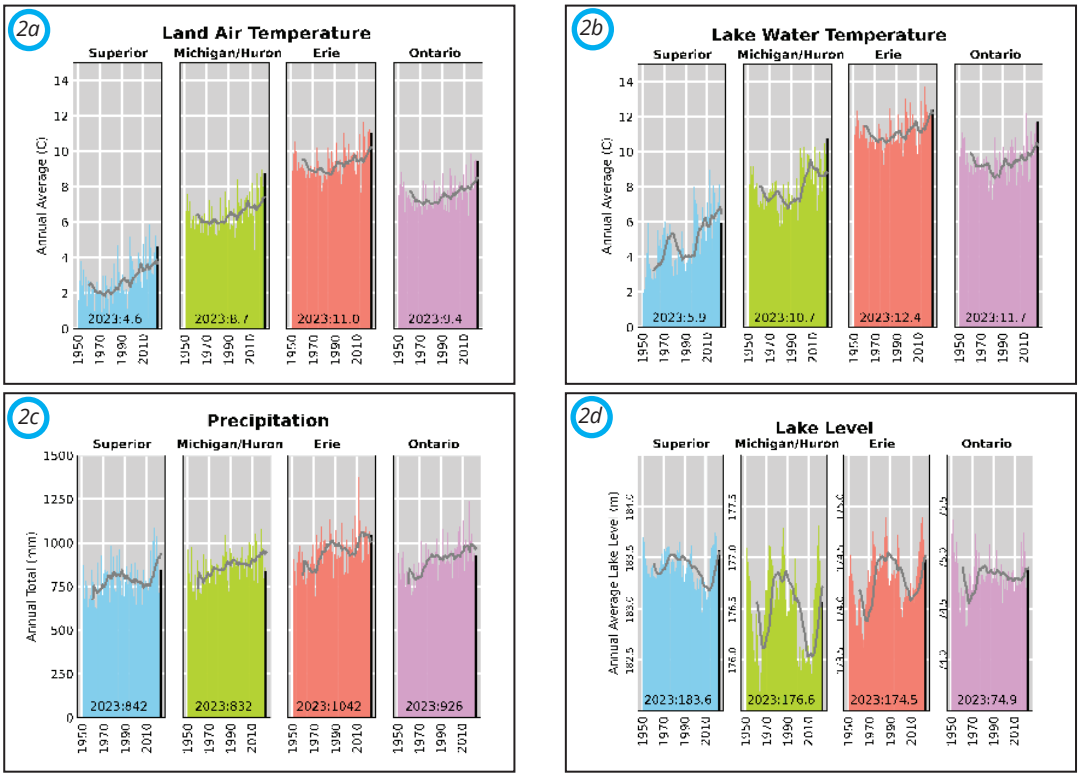
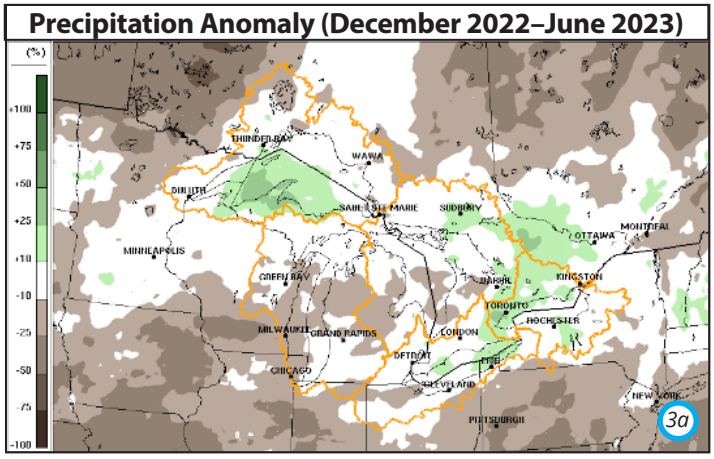


Figure 2. Time series of air temperatures (2a), water temperatures (2b), precipitation (2c), and water levels (2d) by lake basin from 1950–2023. The gray line is a 10-year moving average and the black line is the 2023 average. Estimated from GLERL Great Lakes Monthly Hydrologic Data and Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data.

Air temperatures (Figure 2a) were above the 10-year average for every lake basin in 2023. Water temperatures (Figure 2b) varied by lake, with Superior under, Erie near, and Michigan-Huron and Ontario well above the 10-year average. There has been an upward trend in both air and water temperatures in recent years. Annual precipitation accumulation (Figure 2c) in 2023 was below the 10-year average for all lake basins except Erie, where it was near average. Water levels (Figure 2d) were near the 10-year average on all lakes. Lake levels had risen since 2013 after a period of low lake levels lasting from the 1990s to the mid-2000s and are now near average again.

Wildfires and Air Quality



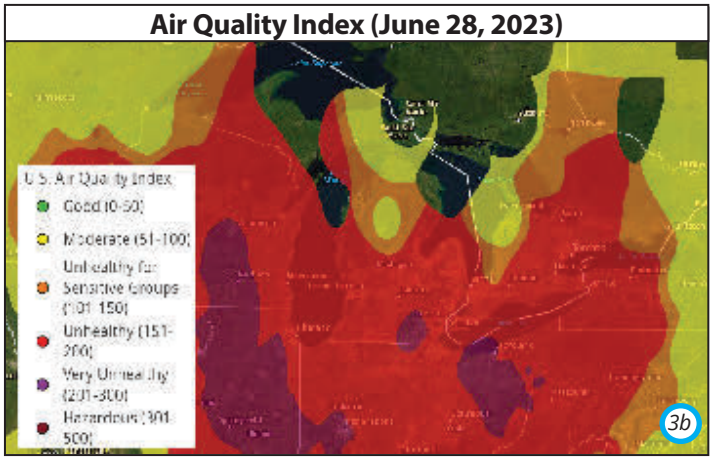


Figure 3. Maps displaying anomalies of total precipitation accumulation for December 2022–June 2023 (4a) and air quality index on June 28, 2023, (3b) in the Great Lakes region. Precipitation anomalies are % departure from the 1991–2020 mean. Figures are from ECCC (3a) and U.S. EPA/AirNow (3b).

The Great Lakes region experienced widespread record-breaking poor air quality in the summer, driven by wildfire smoke from Ontario and Quebec. Dry conditions northeast of the basin from December to June (Figure 3a) contributed to the magnitude of these wildfires. Northerly winds repeatedly pushed smoke from these fires south into the Great Lakes basin during the spring and summer. The air quality index reached 'unhealthy' to 'very unhealthy' levels across the basin during the week of June 28 (Figure 3b) and the week of June 7 for the eastern basin, causing many outdoor events to be canceled or postponed.

2023 ANNUAL CLIMATE TRENDS AND IMPACTS SUMMARY FOR THE GREAT LAKES BASIN

Explaining the New Climate Normal Baseline Period

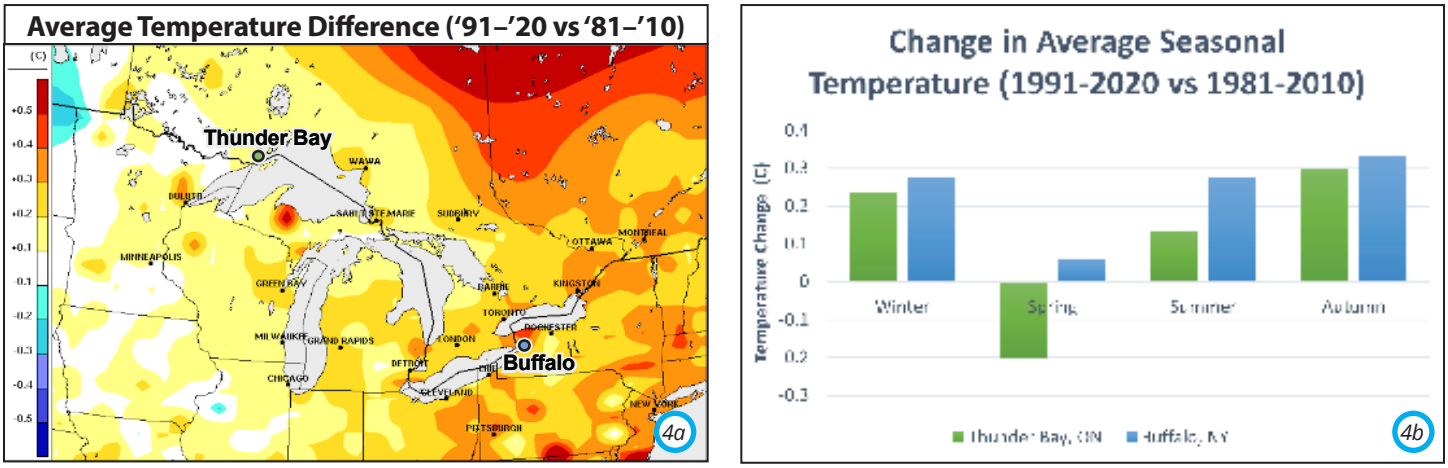


Figure 4. Map displaying the change in annual average temperatures across the basin from the 1981–2010 climate normal period to the 1991–2020 climate normal period (4a) and bar chart of average seasonal temperature changes between the two climate normal periods for Thunder Bay, ON, and Buffalo, NY (4b). Data are from ECCC and NOAA surface observations (4a) and the National Centers for Environmental Information GHCN-D (4b).

This annual climate summary highlights trends for each year in comparison to long-term averages from a historical baseline period. Previous versions of this annual summary used 1981–2010 as the historical baseline period, also called a 30-year 'climate normal.' Starting with this 2023 summary, the new 1991–2020 climate normal will be used as the historical baseline period for numerous variables. The magnitudes of anomalies will not appear as high compared to previous summaries because of the shift to using the warmer '91–'20 period. For example, Toronto's average 2023 temperature is around 1.0°C above the '91–'20 normal (Figure 1a), whereas it would have been 1.3°C above the '81–'10 normal. Average annual temperatures have predominantly increased across the basin from the '81–'10 normal to the '91–'20 normal period, with greater increases in the eastern parts of the basin (Figure 4a). Not all variables, seasons, or individual locations were affected in the same way. For example, when comparing the change from the '81–'10 normal to the 91–'20 normal, average temperature in Buffalo, NY, has increased in every season (Figure 4b). Comparatively, Thunder Bay, ON, has increased at a smaller magnitude in the winter, summer, and fall, and decreased in the spring.

Lake Level Variability Driven by Wet and Dry Conditions

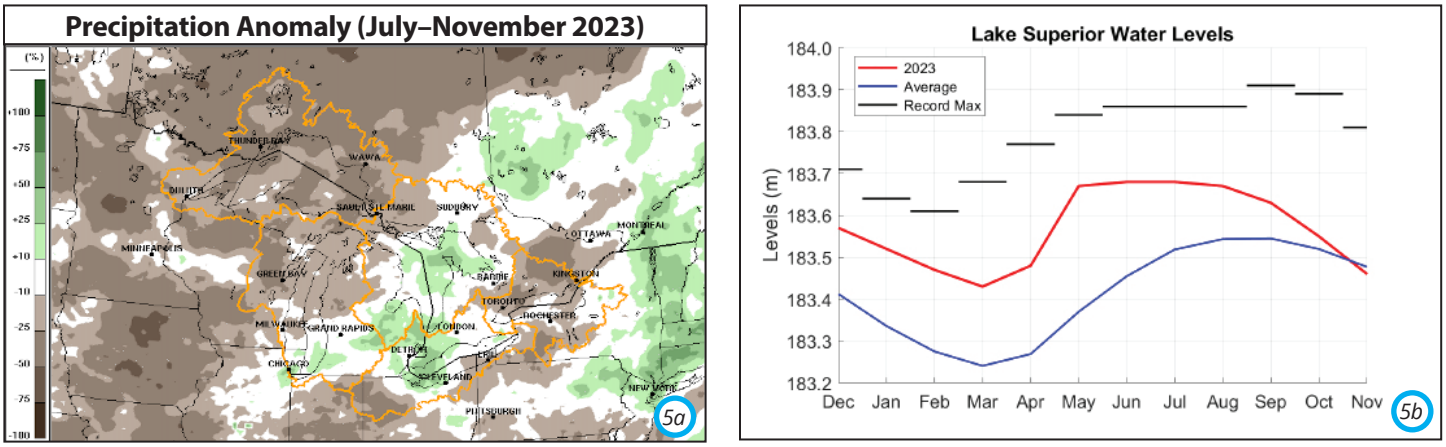


Figure 5. Map displaying anomalies of total precipitation accumulation for July–November 2023 (5a), and values for 2023, historical average, and record lake levels for Lake Superior (5b). Average levels based on 1918–2022 mean. Estimated from U.S. Army Corps of Engineers Data.

Varying precipitation conditions throughout the basin contributed to inter-regional variability in the annual cycle of Great Lakes water levels. Erie and Ontario experienced higher-than-average increases during the winter due to wet and warm conditions. In the spring, water levels rose at a higher-than-average rate mostly due to a very wet April, except on Lake Erie, where drought conditions diminished the spring rise. Widespread dry conditions across most of the basin in the second half of the year (Figure 5a) led to sharper-than-average declines on Lakes Superior and Ontario. As a result, both lakes dropped below average by the end of the year. The seasonal variability was particularly evident on Lake Superior (Figure 5b). Wet conditions contributed to a large spring rise in its water levels, which peaked to their highest point of the year in June and July. This was earlier than the normal peak in August or September, as an abrupt shift to persistent dry conditions led to a relatively stable level after May, rather than continuing to increase. Continued dry conditions resulted in the sixth-highest seasonal decline during the fall months.

2023 ANNUAL CLIMATE TRENDS AND IMPACTS SUMMARY FOR THE GREAT LAKES BASIN

Major Climatic Events

Winter 2022–2023

Only a few deep cold periods briefly affected the Great Lakes, and long warm stretches were widespread. This resulted in above-normal water temperatures and persistently low lake ice extent, which tied for the third lowest on record.

Relatively warm lake temperatures and low ice coverage fueled a massive lake-effect snow event December 23–27 that dumped 131.8cm of snow in Buffalo, New York, and resulted in at least 46 deaths. High winds resulted in dangerous travel conditions and power outages.

The far western portion of the basin had near-record winter snowfall while below-normal snowfall was widespread in the central and eastern basin. Poor snow quality and unsafe ice conditions canceled recreational opportunities and events in Michigan, Ontario, and New York.

The Great Lakes basin had near- to above-normal winter precipitation, with more falling as rain instead of snow. However, dry conditions settled just outside the basin across heavily forested areas of northern Ontario and western Quebec, which would later fuel wildfires and bring dangerous air quality to the Great Lakes and beyond.



Photo: Buffalo, New York, snowstorm in December 2022 (Credit: Ryan Hallock | Flickr).

Spring 2023

An early spring warm-up rapidly melted a deep snowpack in the western basin. This combined with above-normal April precipitation resulted in the second-highest April water level rise for Lake Superior. As the warmth spread east, grapevines, apples, and peaches had earlier-than-usual bud break. Temperatures rose to over 26°C from April 12–16 across a wide swath of the basin.

Early bud break left specialty crops vulnerable to freeze damage on May 18 when temperatures dropped to –5°C for several hours in eastern Ontario and western New York. Farmers sustained yield-reducing damage to apples, grapes, and other fruits.

Rapidly drying conditions were observed across the Great Lakes region in May due to the combined effects of below-normal rainfall and an unusually dry atmosphere. The stalled weather pattern that contributed to basin drying also funneled poor air quality from western Canadian wildfires into the western Great Lakes basin.

Summer 2023

Wildfire smoke and dangerous air quality were persistent issues basinwide in June and July due to atypical northerly wind and a record-breaking Canadian wildfire season.

Dry summer conditions in the western Great Lakes basin kept water levels relatively stable on Lakes Superior and Michigan-Huron when, typically, lakes would continue to rise during summer. Northern Wisconsin reached exceptional drought severity on the U.S. Drought Monitor (USDM) map for the first time since USDM records began in 2000.

While the western basin was locked in drought, rainfall was regular and abundant in July and August for much of the central and eastern Basin. The Cleveland, Ohio, area had its third-wettest summer since 1871.

The annual harmful algal blooms (HABs) that affect western Lake Erie initiated in early July, which is the second-earliest start since records began in 2002. The bloom reached moderately severe intensity and persisted into mid-September.



Photo: Frost damage to fruit crops in New York in May 2023 (Credit: New York Wine & Grape Foundation | Facebook).

Fall 2023

Record warmth settled across the western basin in early September with high temperatures exceeding 32°C for several days. Warm conditions lingered in the west, with Duluth, Minnesota, recording its third-warmest September in 150 years.

Early October had record warmth basinwide with temperatures 5°C to 11°C above normal from October 1–5. The unusual warmth paired with high humidity elevated perceived air temperatures (humidex) to over 30C for about 80% of the basin on October 3. Syracuse, New York, measured its warmest October temperature on record (October 4) and had a record of four consecutive October days with high temperatures at or above 26.7°C.

The eastern basin saw significant drying during the fall. Kingston, Ontario, had its second-driest fall since 1872, with an estimated 112mm of precipitation. Wells ran dry in western New York, and low water supplies affected rural fire fighting operations and agricultural production.

2023 ANNUAL CLIMATE TRENDS AND IMPACTS SUMMARY FOR THE GREAT LAKES BASIN

New Research, Applications, and Activities

This section highlights research findings and various efforts and activities from across the region from the previous year. These efforts have implications for a wide range of sectors across the region, improve the understanding of regional climate, and show promise for informing planning efforts and policy implementation in the Great Lakes.

Modeling, Science, and Natural Resources

- An ensemble of downscaled climate models is paired with a Soil and Water Assessment Tool (SWAT) hydrologic model to evaluate the impact that a changing climate under a moderate greenhouse gas concentration scenario could have on rain-on-snow melt events in the Great Lakes basin watersheds (Myers et al. 2023).
- A study on how the lake sturgeon population in the Great Lakes will be impacted by climate changes in the region analyzes a mix of positive and negative impacts that are seen with spawning and nursery sites, prey availability, activity patterns, and survival for the historically vulnerable species (Embke et al. 2023).
- A newly developed two-way coupled modeling system featuring the Weather Research Forecasting model and a three-dimensional hydrodynamic model was evaluated against observational data, showing progress in more accurately representing lake surface temperatures on the Great Lakes (Kayastha et al. 2023).
- The Indiana Climate Change Impacts Assessment includes a report that applies state climate change projections to see how those changes may impact aspects of water resources, including soil water, evaporation, runoff, snow cover, streamflow, drought, and flooding (Cherkauer et al. 2023).

Communities, Engagement, and Policy

- The Fifth National Climate Assessment includes information on climate change impacts, risks, and responses for the U.S. More localized concerns for the Great Lakes basin are incorporated throughout its Midwest and Northeast chapters. The report emphasizes grounding solutions in local knowledge, Indigenous leadership, and collaboration with tribes and communities (Jay et al. 2023).
- PPGISr, an open source R package for Public Participatory GIS, enables capturing and using spatial information for participatory planning processes and scientific inquiry to address climate change vulnerabilities within a community. With functionality to add a user-defined editable map, basemaps, and mapping categories, the application is highly flexible for guiding decision-making in diverse contexts such as green infrastructure, stormwater management, and increased migration (Berkel et al. 2023).
- Birkholz Fellows from the Great Lakes-St. Lawrence Legislative Caucus (GLLC) met in Detroit to learn about issues affecting Great Lakes communities and to set binational, bipartisan policy priorities for Climate Resiliency in the region. A climate resiliency resolution was then passed by GLLC in September 2023 (GLLC 2023).
- A virtual talking circle was conducted at the 2021 Annual Conference of the International Association for Great Lakes Research to discuss experiences and insights on bridging knowledge systems from Indigenous and non-Indigenous communities from the Great Lakes region and beyond. This article summarizes the discussions to aid others in learning how to equitably utilize both knowledge systems for decision-making (Stirling et al. 2023).
- The inaugural Midwest Climate Resilience Conference brought together hundreds of community leaders, policy makers, resource managers, researchers, and elected officials to focus on preparing for the impacts of climate change across human and natural systems through adaptation (Minnesota CAP).

About This Document

Coordinated by a partnership between climate services organizations in the U.S. and Canada, this product provides a synthesis report summarizing the previous years' climate trends, events, new research, assessments, and related activities in the Great Lakes Region. This product is a contribution to the U.S.-Canada Great Lakes Water Quality Agreement, through Annex 9 on Climate Change Impacts, and to the national climate assessment processes in the U.S. and Canada. It should be cited as: Environment and Climate Change Canada and the U.S. National Oceanic and Atmospheric Administration. 2023 Annual Climate Trends and Impacts Summary for the Great Lakes Basin. 2024.

Contributing Partners

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canada.ca/en/environment-climate-change

Great Lakes Environmental Research Laboratory
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GLISA, NOAA's Great Lakes CAP/RISA Team
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Great Lakes Water Quality Agreement
binational.net

Midwestern Regional Climate Center
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National Oceanic and Atmospheric Administration
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Northeast Regional Climate Center
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U.S. Army Corps of Engineers Detroit District
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For additional information and sources visit: glisa.umich.edu/summary-climate-information/annual-climate-trends