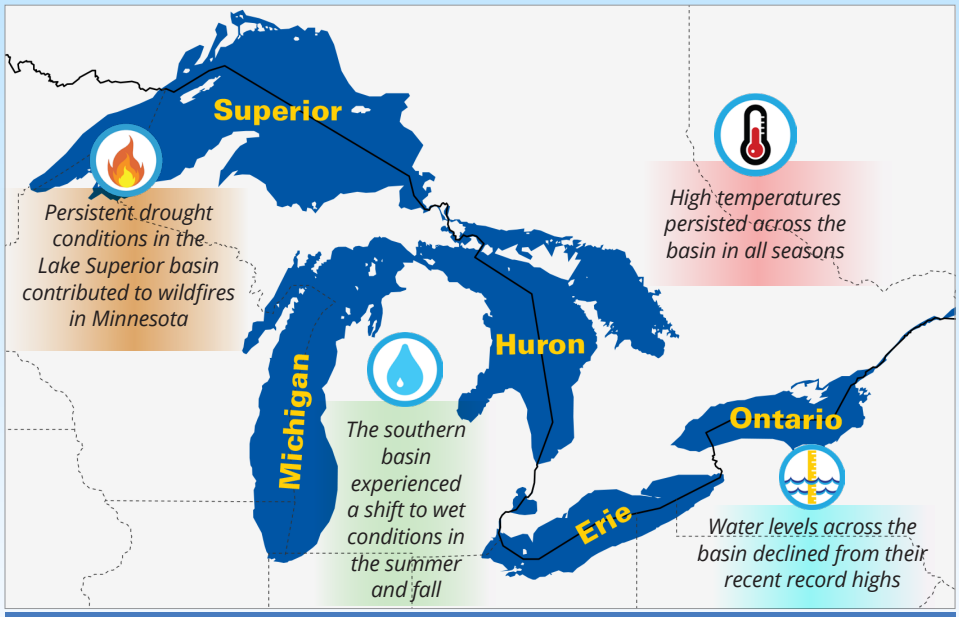
2021 ANNUAL CLIMATE TRENDS AND IMPACTS SUMMARY FOR THE GREAT LAKES BASIN

During the 2021 reporting period, several notable events and trends were observed across the Great Lakes basin, including warm air and water temperatures throughout the year, drought conditions, and flooding. Winter and spring drought contributed to wildfires and diminished the springtime rise in water levels. Water levels on the upper-Great Lakes began a return to near-average conditions, after years of above average water levels. For the southern basin, dry conditions gave way to above-average precipitation for the second half of the year. At 45.8% areal coverage, Great Lakes maximum ice cover in 2021 was below the long term average of 53.3%.



Arrows indicate how 2021 average values compare to long-term average (LTA, defined on page 2).

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

Above *Below* *Variable*

2021 Highlights

Dry to Wet Conditions

Basin-wide dry conditions in the winter and spring contributed to summer wildfires across northern Minnesota. While Superior basin drought conditions worsened through the remainder of 2021, the rest of the basin experienced a wet summer and fall, with several extreme precipitation and flooding events occurring.

Water Levels Returning Closer to Average

As a result of the warm and dry conditions seen in the basin during 2021, all of the Great Lakes saw declines in their water levels from the record highs that occurred in 2019 and 2020. Lakes Superior and Ontario predominately returned to or approached near-average water levels during 2021, while water levels of the other lakes remained above average, but much lower than the past few years.

High Air and Lake Temperatures

Air temperatures across the basin were above average for every season of 2021. Lake surface temperatures were also above average for every Great Lake. These warm conditions contributed to well below-average ice cover, until a cold arctic air intrusion caused rapid ice formation and led to a maximum areal coverage of 45.8% for the year. Snow cover was also below average due to a combination of warm and dry conditions in the winter.

Photo: Greenwood Fire in Superior National Forest, Minnesota, August 20, 2021 (Credit: USDA Forest Service)

Photo: Several miles of I-94 were flooded in and around Detroit, Michigan, June 2021 (Credit: Russ McNamara, Dorothy Hernandez/WDET)

2021 ANNUAL CLIMATE TRENDS AND IMPACTS SUMMARY FOR THE GREAT LAKES BASIN

Climate Overview: December 2020 - November 2021

During the December 2020 – November 2021 reporting period*, mean annual temperatures across the Great Lakes region were above average by +1 to +3°C (Figure 1a). The highest anomalies, above +3°C, were recorded in the Lake Michigan basin. Every season of 2021 was warmer than average. Annual precipitation totals were below normal across the basin (Figure 1b), with the exception of the northern Lake Erie and southern Lake Ontario basins, which experienced above-normal precipitation. Dry conditions characterized the winter and spring of 2021 for most of the basin, including the driest January on record basin-wide. These conditions gave way to wet conditions in the summer and fall for the lower portion of the basin, including a number of extreme rainfall events.

Annual water temperatures for all of the Great Lakes were above their long-term averages. In 2021, basin-wide precipitation and runoff totals were below average for Lakes Superior and Michigan-Huron, but above average for Lakes Erie and Ontario and evaporation totals were above average on all lakes. Over the period from 1991-2020 across the region, air temperature (+0.14°C/decade), precipitation (+11.5 mm/decade), evaporation (+17.4 mm/decade), water temperatures (+0.43°C/ decade), and runoff (+20.1 mm/decade) have all increased.

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

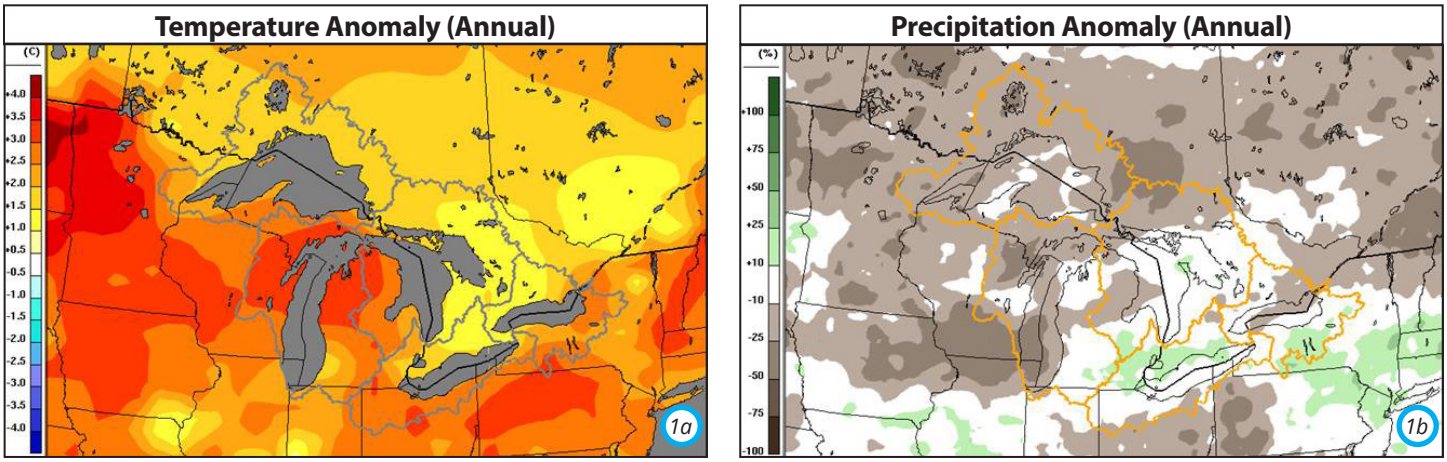


Figure 1. Maps displaying annual anomalies for temperature (1a) and total precipitation accumulation (1b) in the Great Lakes region. Anomalies for temperature are departures from the 1981-2010 mean. Anomalies for precipitation are % departure from the 1991-2020 mean. Gray (1a) and yellow (1b) outlines 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	
		2021	LTA	2021	LTA	2021	LTA	2021	LTA	2021	LTA
Surface Water Temps (°C)	Max	19.39	17.68	23.41	22.62	23.20	21.45	25.86	25.05	24.94	23.57
	Min	0.75	0.61	1.77	1.28	0.98	0.61	0.23	0.34	2.17	1.34
	Avg	8.12	6.59	10.99	9.76	10.13	8.92	12.42	11.42	11.65	10.36
Ice Cover (%)	Max	50.62	61.47	33.27	39.97	48.28	64.61	86.65	81.24	20.63	29.81

		SUPERIOR		MICHIGAN-HURON**		ERIE		ONTARIO	
		2021	LTA	2021	LTA	2021	LTA	2021	LTA
Water Levels (meters)	Max	183.63	183.58	177.14	176.61	174.81	174.39	74.86	75.10
	Min	183.38	183.23	176.77	176.24	174.57	173.90	74.49	74.42
	Avg	183.51	183.41	176.97	176.44	174.67	174.17	74.70	74.77
Precipitation (mm)	Ann Sum	712.2	780.5	797.7	888.0	1062.4	973.9	943.8	930.7
Evaporation (mm)	Ann Sum	676.4	556.8	657.9	504.0	1002.6	896.4	739.3	650.4

Table 1: Summary of hydro-climate variables by lake. Long Term Average (LTA) changes depending on variable: Water Temps (°C) - 2021: December 2020 through November 2021, LTA: 1995-2020; Ice Cover (%) – 2021: December 2020 through May 2021, LTA: 1973-2020; Water Levels (meters) - 2021: December 2020 through November 2021, LTA: Period of Record (1918-2020); Precipitation (mm) - 2021: December 2020 through November 2021, LTA: 1981-2010; Evaporation (mm) - 2021: December 2020 through November 2021, LTA: 1981-2010. Estimated from NOAA Great Lakes Surface Environmental Analysis (surface water temps), NOAA GLERL CoastWatch (ice cover), US Army Corps of Engineers (water levels), 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.*

2021 ANNUAL CLIMATE TRENDS AND IMPACTS SUMMARY FOR THE GREAT LAKES BASIN

Historical Trends

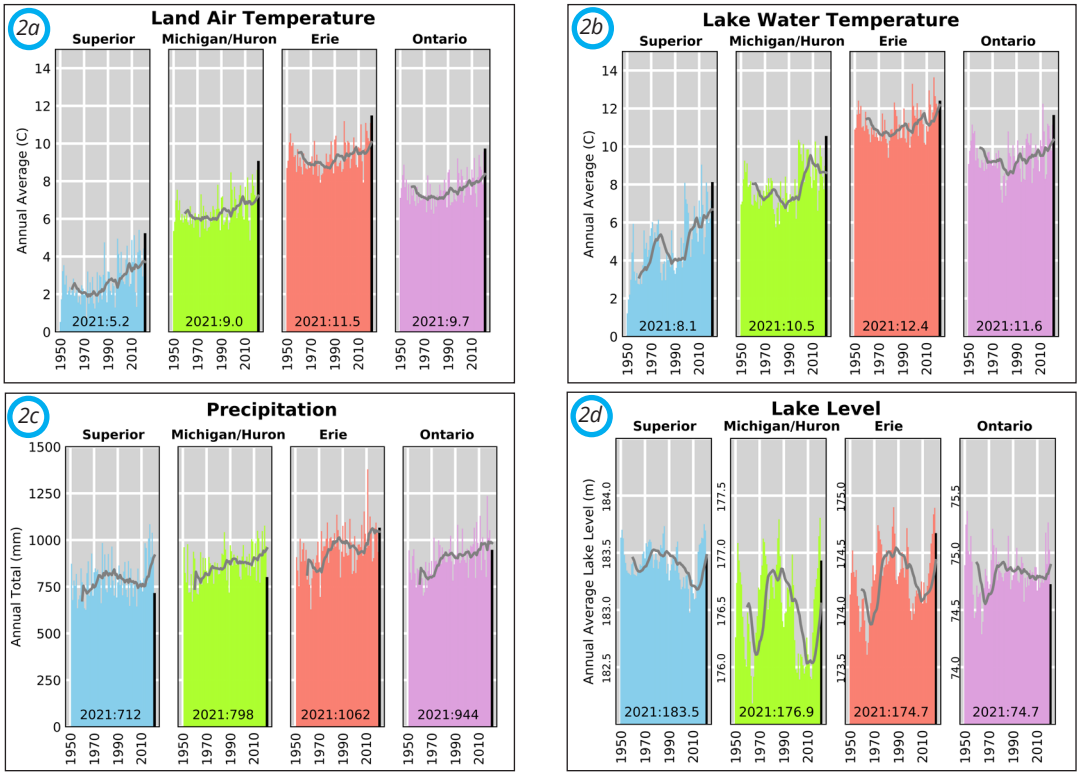


Figure 2. Time series of air temperatures (2a), water temperatures (2b), precipitation (2c), and water levels (2d) by lake basin from 1950-2021. The grey line is a 10-year moving average and the black line is the 2021 average. Estimated from GLERL Great Lakes Monthly Hydrologic Data, and Coordinating Committee on Great Lakes Basin Hydraulic and Hydrologic Data.

Air (Figure 2a) and water temperatures (Figure 2b) were above the 10-year average for each lake basin in 2021. There has been an upward trend in both air and water temperatures in recent years that is particularly notable in the upper Great Lakes and their basins. Annual over-lake precipitation accumulation (Figure 2c) in 2021 was below the 10-year average for all lake basins except Erie. This is a departure from the general upward trend observed in recent years, though substantial interannual variability is common. Water levels (Figure 2d) remained above the 10-year average on Lakes Michigan-Huron and Erie, near average on Lake Superior, and below average on Lake Ontario. Lake levels had risen since 2013 after a period of low lake levels lasting from the 1990s to the mid-2000s, and are now falling again.

Precipitation

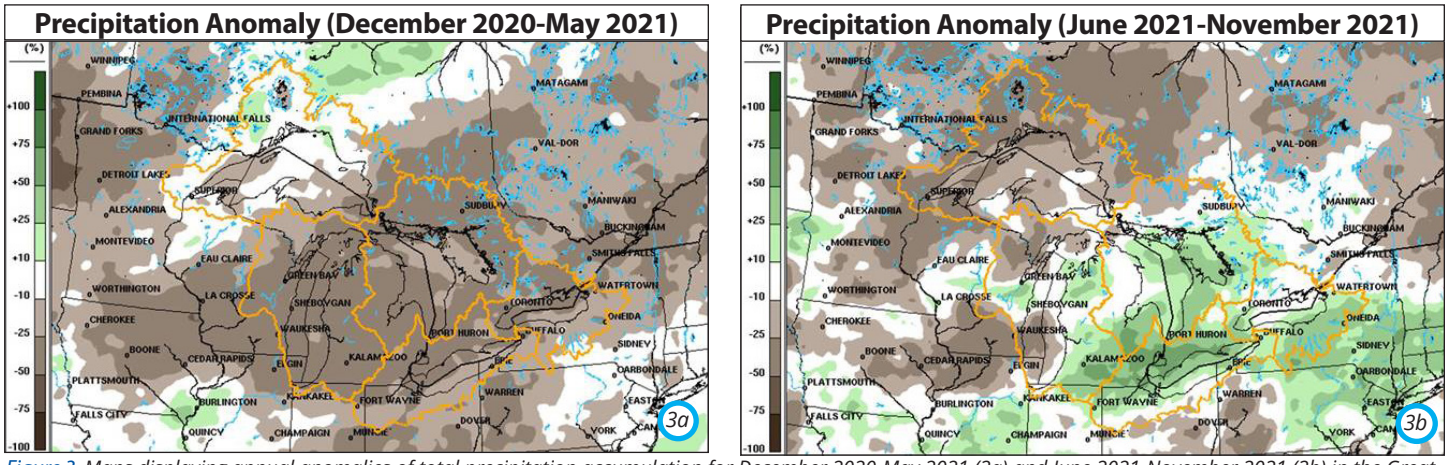


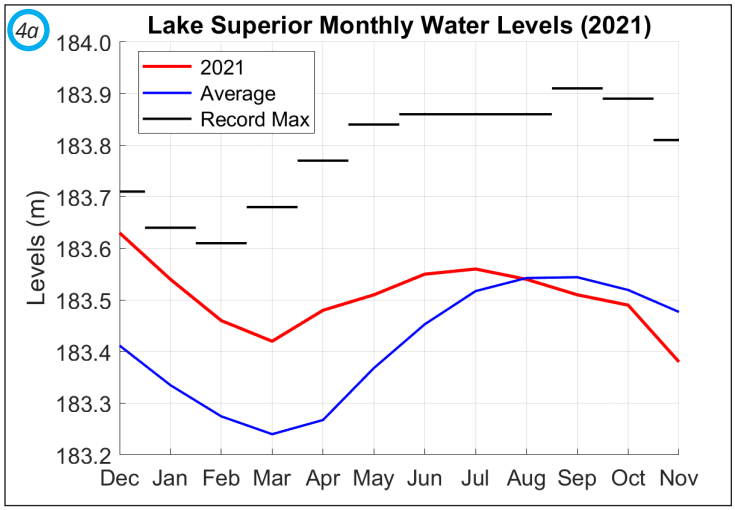
Figure 3. Maps displaying annual anomalies of total precipitation accumulation for December 2020-May 2021 (3a) and June 2021-November 2021 (3b) in the Great Lakes region. Anomalies are % departure from the 1991-2020 mean. Figures created by ECCC.

Dry conditions in the winter and spring (Figure 3a) gave way to wet conditions in the summer and fall for the southern portions of the basin (Figure 3b). Lack of precipitation created winter drought conditions that worsened in the spring, and that contributed to wildfires across northern Minnesota and northwestern Ontario. Smoke from these fires combined with fires in the Mountain West and led to air quality issues throughout the entire Great Lakes basin.

Above-average precipitation characterized the southern basin for the second half of 2021, with several single-day precipitation records broken. Many areas of southern Ontario and southeastern Michigan experienced flash flooding during extreme precipitation events in the summer. The exception to these wet conditions was the Superior basin, which remained drier than average throughout the year and was upgraded to the "extreme-drought" category.

2021 ANNUAL CLIMATE TRENDS AND IMPACTS SUMMARY FOR THE GREAT LAKES BASIN

Lake Levels



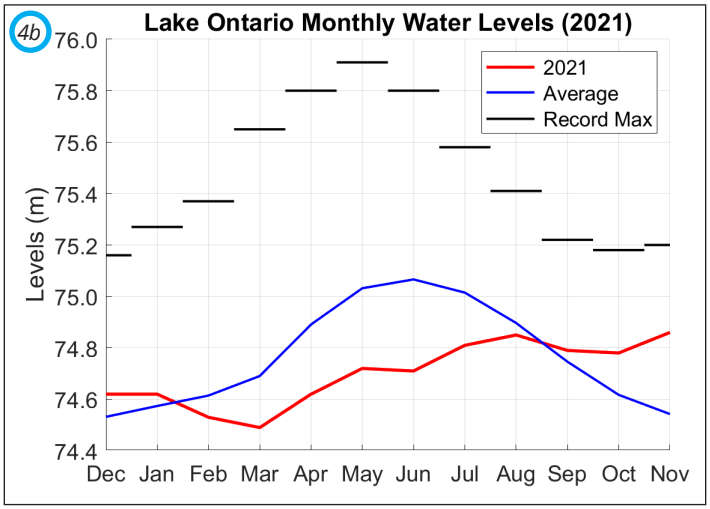


Figure 4. Values for 2021, historical average, and record lake levels for Lake Superior (4a) and Lake Ontario (4b). Average levels based on 1918-2020 mean. Estimated from US Army Corps of Engineers Data.

Varying precipitation conditions throughout the basin contributed to inter-regional variability in the annual cycle of Great Lakes water levels. Water levels on Lake Superior (Figure 4a) began above average in December (start of the Dec. 20' - Nov. 21' climatological year). On average, water levels on Lake Superior have historically reached their highest point of the year in the summer. Persistent drought conditions throughout 2021 diminished the springtime rise enough that water levels did not reach their highest point during the summer peak, but rather in the preceding winter months. By the fall, Lake Superior water levels fell below average.

Lake Ontario water levels (Figure 4b) briefly began the year above average, but dry conditions caused them to remain below average from mid-winter through the end of the summer. Unlike the persistently dry Superior basin, the Ontario basin shifted to wet conditions in the second half of 2021, contributing to a rise in water levels. On average, water levels on Lake Ontario historically reach their highest point of the year in the early-summer and then begin their fall decline. Rather than following this average cycle in 2021, Ontario water levels continued to rise through the end of the year and reached their highest annual levels in November.

Snow and Ice

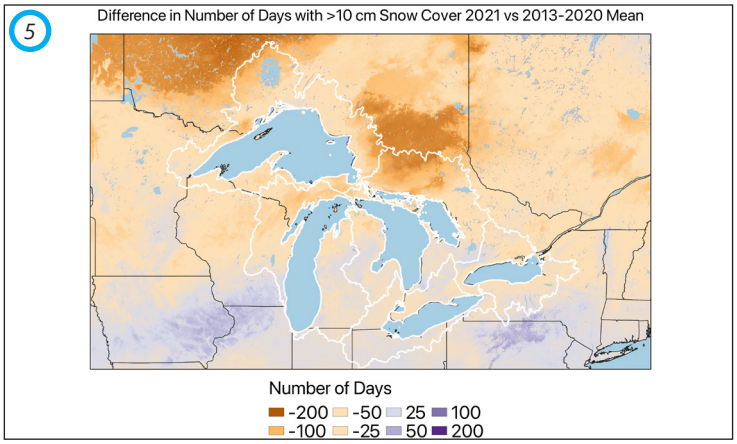


Figure 5. Difference in number of days with > 10 cm snow cover for July 2020-June 2021 compared to the 2013-2020 mean. White outlines depict the individual lake basins. Estimated from the NOAA National Operational Hydrologic Remote Sensing Center (NOAA NOHRSC) model output.

The number of days with substantial snow cover (> 10 cm) across the region was below the 8-year average for most of the basin, particularly in the north (Figure 5). This can be partially attributed to warmer temperatures and dry conditions, particularly in the Lake Superior basin, though snow cover did persist into the spring.

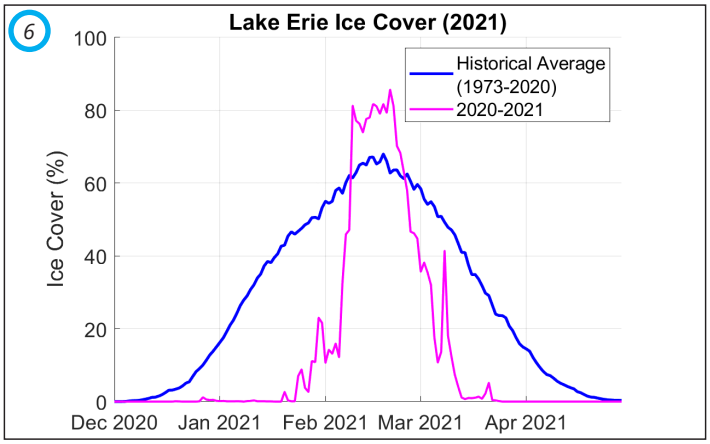


Figure 6. Daily 2021 and historical average ice cover concentrations for Lake Erie. Estimated from NOAA GLERL Great Lakes CoastWatch.

Above average air and water temperatures in the basin contributed to a shorter ice season and below-average lake ice cover for much of the winter (Figure 6). In February, a cold arctic air intrusion caused a large spike in ice cover that briefly brought most lakes near their long-term averages. There has been a declining ice cover trend over the past several decades, though there remains strong year-to-year variability.

2021 ANNUAL CLIMATE TRENDS AND IMPACTS SUMMARY FOR THE GREAT LAKES BASIN

Major Climatic Events

Winter 2020-2021

The Great Lakes basin had its driest January on record dating back to 1900.

Extreme temperature swings in February, from up to 16°C above normal then falling to as much as 16°C below normal, resulted in ice jam flooding on rivers and cold injury to specialty crops.

February was near normal or snowier than average for many locations, including Grand Rapids, Michigan, which received twice as much snow as normal for the month. The three-week period ending on February 17 was the snowiest three weeks for Chicago since 1978-79.

From December to February, winter conditions were warmer than average, with below-average snowfall and below-average lake ice cover.

Photo: Ice breaking along the St. Clair River, February 20, 2021 (Credit: Mike Mulholland / MLive).

Spring 2021

Record high temperatures were set or tied from March 10-11, stretching from Michigan to Toronto, Ontario, and as far east as Watertown, New York. Temperatures surpassed 21°C and spurred the early development of agricultural crops.

Several late-season freezes and snow events occurred in April and May, leading to pollination issues as bees were less active during these stretches of colder weather.

Record warmth in Toronto-Pearson (Ontario) on May 25 was followed by the latest snowfall on record on May 28.

Drought intensified during the spring, with moderate and severe drought conditions emerging across much of the basin due to low precipitation paired with above-normal temperatures and high evaporation.

Summer 2021

Reduced precipitation and high temperatures caused drought conditions to intensify in the western portion of the basin.

The basin experienced unusually warm temperatures in June and August. June was the third hottest on record for Minnesota and Wisconsin, while Buffalo and Syracuse, New York broke their records for the hottest August. Lake temperatures were also very warm during the summer, with Lake Huron reaching a record-breaking 23.2°C on August 26th.

Excess precipitation affected the eastern portion of the basin, with New York having its wettest July on record. Several heavy rain events led to flash flooding across western New York, southern Ontario, and southern Michigan, including Detroit.

Elevated temperatures and drought conditions led to an increased risk of wildfires. Over 25,000 acres of forest and wetlands burned across northern Minnesota and northwestern Ontario, prompting evacuations and shuttering recreational areas. Smoke from these fires resulted in dangerous air quality across the basin.

Photo: Fire in Quetico Provincial Park, Ontario, August 26, 2021 (Credit: Ontario Ministry of Northern Development, Mines, Natural Resources and Forestry, Aviation, Forest Fire and Emergency Services Branch).

Autumn 2021

The basin experienced record to near-record high overnight temperatures for October, which helped fuel above-normal lake temperatures. Moderately-severe harmful algal blooms (HABs) developed in Lake Erie, and the unseasonable October warmth extended the blooms by about one month compared to normal.

The first fall freeze was 2-4 weeks later than normal for most. Thunder Bay's first fall freeze was the latest on record (dating back to 1941).

Above normal precipitation continued in the eastern basin, slowing corn and soybean harvest and resulting in several flash flood events.

Drought continued to affect northern and western areas across the basin. For instance, drought-induced low water levels in Wisconsin and Minnesota led to a difficult wild rice harvest and reduced yields.

For only the 3rd time since 1900, Lake Ontario water levels rose from the start of September to the end of November.

2021 ANNUAL CLIMATE TRENDS AND IMPACTS SUMMARY FOR THE GREAT LAKES BASIN

New Research, Applications, and Activities

This section highlights research findings from across the region from the previous year. Findings from 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 & Natural Resources

- A study used several CMIP5 models to drive an ensemble of high-resolution WRF simulations over the Great Lakes region to analyze changes in extreme heat events. It found that although the lakes have a mitigating effect downwind, a significant increases in extreme heat events can be expected (Xie et al., 2021).
- Researchers analyzed projected changes to heavy lake-effect snowfall (HLES) in the Great Lakes Basin and found that the frequency and amount of HLES may be decreasing overall, even with climate change. Lake ice fraction was also found to have a weaker impact on HLES in future climates (Huziy et al., 2021).
- Toronto and Region Conservation Authority and Ryerson University partnered to create a process-based integrated watershed model for studying the impacts of future climate change and land use scenarios on the water quality of an urban watershed draining into Lake Ontario (TRCA, 2021).
- A study aims to connect climate change impacts and groundwater systems by examinging both spatial and temporal variability in groundwater responses to climate. The research found that large variability is anticipated, especially for groundwater recharge, quantity, quality, discharge, and surface interactions (Costa et al., 2021).
- The Ontario Lakes and Climate Change Database summarizes projected changes in the thermal conditions (surface temperatures and thermal habitat available for key fisheries species) of inland lakes in Ontario including those within the Great Lakes Basin (Smith et al., 2021).
- The Great Lakes Integrated Sciences and Assessments team published a set of climate model report cards that aim to provide users with technical details about how specific models are constructed, and help them to better understand if the model offers a suitable representation of the climate for their application (GLISA, 2021).
- A study examines the cold season performance of the high-resolution NASA-Unified Weather Research and Forecasting (NU-WRF) ensemble and identifies limitations to address in future generations of Great Lakes climate models (Notaro et al., 2021).
- A study examined the spatial and temporal patterns of extreme minimum temperatures in the Great Lakes region to assess the impacts on mortality of an invasive insect harming hemlock trees. Findings support that proximity to water, surface elevation, and latitude are important controls for extreme minimum temperatures (Kiefer et al., 2021).
- A fully integrated surface/groundwater model called the Canada Continental Scale Model (CCSM) demonstrated large-scale ground/surface water interactions and balances, including regions in Canada's far north; where climate change impacts are anticipated to be most severe, but hydrologic monitoring data is extremely sparse (Canada1Water).

Communities, Engagement & Policy

- A large interdisciplinary project aims to assess the current knowledge of observed and projected impacts of climate change in Illinois. The assessment is divided into 7 chapters and examines impacts on hydrology and water resources, agriculture, human health, and ecosystems (Wuebbles et al., 2021).
- The American Society of Adaptation Professionals hosted a climate migration workshop that explored new research findings on potential migration into and out of the Great Lakes region, and considered how such findings can help receiving communities plan for socially just and environmentally responsible growth (ASAP, 2021).
- Researchers explore the connections between Indigenous health, climate change and land in a paper analyzing interviews from members of the Fort William First Nation in Ontario. The research uses an approach called Two-Eyed Seeing, where Indigenous and non-Indigenous people work together to gather and share knowledge (Galway et al., 2021).

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. 2021 Annual Climate Trends and Impacts Summary for the Great Lakes Basin. 2022. Available at https://binational.net.

Contributing Partners

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canada.ca/en/environment-climate-change

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Great Lakes Integrated Sciences and Assessments
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Great Lakes Water Quality Agreement
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For additional figures, information, and sources visit:
glisa.umich.edu/summary-climate-information/annual-climate-trends