# Sub-Indicator: Ice Cover

## Overall Assessment

**Trends:**

**10-Year Trend (2011-2020):** Increasing

**30-Year Trend (1991-2020):** Decreasing

**Long-term Trend (1973-2020):** Decreasing

**Rationale:** The annual maximum ice cover (AMIC) anomaly (derived from the 1973 to 1990 base period average) for the period of 1973 to 2020 demonstrates a statistically significant (at the 0.05 level) trend of -0.46% annually. This implies a basin-wide ice loss of 22.1% over the period of 1973 to 2020. The 10-year and 30-year trends in maximum ice cover anomalies are 0.63% and -0.04% respectively (Figure 2). As shown below, in addition to overall large, natural interannual variability, the long-term trend is declining quite significantly.

Trend assessment definitions are included following the Lake-by-Lake Assessment section.

Note that the trends calculated within a specific period of time such as 1973-2020 can only be applicable to the same period, and cannot be extrapolated to the future and back to the past. It should not be interpolated to a period shorter than the time series of the data from which the trends are derived, since there are decadal and multi-decadal changes in lake ice cover (Wang et al. 2012b, 2018) and longer time scale of ~50 years (Warner et al. 2021).

So, it is important to note that annual fluctuations can affect trends – especially short-term trends. A 10-year period is relatively short when the climate trend is calculated. For example, recent heavy ice seasons in 2013/2014, 2014/2015, and 2018/2019 have opposed the trend of decreasing ice cover anomalies, which have reduced the statistical significance of the trend in the dataset.

## Lake-by-Lake Assessment

### Lake Superior

**10-Year Trend:** Increasing

**30-Year Trend**: Decreasing

**Long-term Trend (1973-2020):** Decreasing

**Rationale:** The long-term trend for the ice cover anomaly is decreasing at an annual rate of -0.74%, translating into a lake-wide decrease in maximum ice cover of 35.5% from 1973 to 2020. Lake Superior has experienced the highest diminishment of maximum lake ice coverage over the historical period of all the Great Lakes. The trend for the 10-year period is increasing (0.18%) and for the 30-year timeframe is decreasing (-0.42%) (Figure 3).

Note that the long-term record for the whole basin is dominated by Lake Superior, as it is the largest lake and has the strongest long-term downward trend.

### Lake Michigan

**10-Year Trend:** Increasing

**30-Year Trend:** Increasing

**Long-term Trend (1973-2020):** Decreasing

**Rationale:** A similar long-term pattern in the anomaly analysis emerges for Lake Michigan as the trend in maximum ice cover is decreasing at a rate of -0.33% per year for the 1973 to 2020 period. Statistically significant trends of 0.07% for the 10-year period and 0.07% for the 30-year timeframe of maximum ice cover anomalies were noted (Figure 4).

### Lake Huron

**10-Year Trend:** Increasing

**30-Year Trend:** Decreasing

**Long-term Trend (1973-2020):** Decreasing

**Rationale:** Lake Huron exhibits a decreasing trend (-0.39%) in the maximum lake ice coverage anomaly calculated for all the specified long-term period of 1973 to 2020. Maximum ice cover anomalies trend negatively on an annual basis across the 30-year (-0.08%) period of examination as well, but trend positively in the most recent decade (1.49%) (Figure 5).

### Lake Erie

**10-Year Trend:** Decreasing

**30-Year Trend:** Decreasing

**Long-term Trend (1973-2020):** Decreasing

**Rationale:** A statistically significant annual decrease in the maximum ice cover anomaly of -0.50% was noted for the long-term timeframe. Shorter period indicators for Lake Erie were also deemed to be statistically significant, with a trend of -0.63% over the last 30 years and -0.41% for the last 10 years (Figure 6).

Note that as the southernmost and shallowest lake, Erie is the most sensitive and varies from 100% ice-covered to 0% in any given year

### Lake Ontario

**10-Year Trend:** Increasing

**30-Year Trend:** Increasing

**Long-term Trend (1973-2020):** Decreasing

**Rationale:** Lake Ontario maximum ice cover anomalies show a decreasing (-0.24% per year) trend for the long-term period. Statistically significant 10-year and 30-year trends in maximum ice cover anomaly tendencies show an increasing (0.06%) trend for the 10-year period and an increase (0.04%) in the 30-year timeframe (Figure 7).

## Status Assessment Definitions

Climate information in the State of the Great Lakes indicator suite is not assessed in the same manner as other sub-indicators. For example, the ecosystem has adapted to and needs both high and low water levels and neither condition can be assessed as "Good" or "Poor". However, prolonged periods of high or low water levels may cause stress to the ecosystem. Therefore, climate trends for the Precipitation Amounts in the Great Lakes, Surface Water Temperatures, Ice Cover and Water Levels reports are assessed as “Increasing”, “Unchanging”, or “Decreasing” over a defined period of time.

## Trend Assessment Definitions

**Increasing:** Increasing AMIC anomaly (and/or average ice concentrations) over the period of record (1973-2018).

**Unchanging:** No change in AMIC anomaly (and/or average ice concentrations) over the short and/or long term of the reporting cycle.

**Decreasing:** Decreasing AMIC anomaly (and/or average ice concentrations) over the period of record (1973-2018).

**Undetermined:** Data are not available to report on a trend.

## Endpoints and/or Targets

No endpoint is needed for the climate-based sub-indicator reports. The ecosystem adapts to periods of high and low ice coverage, however, a prolonged period of either could pose problems.

## Sub-Indicator Purpose

The overall purpose of this sub-indicator is to assess winter ice cover. The sub-indicator will also help to assess impacts on seasonal and interannual lake temperature (Anderson et al. 2021) and accompanying physical changes to each lake over time by measuring the thermal properties of the Great Lakes. Thermal properties affect the ecosystems’ function (Ozersky et al. 2021) and influence water evaporation and lake effect snow (Wright et al. 2013; Cronewold et al. 2015; Fujisaki-Manome et al. 2017) from the lakes that affects water levels. This sub-indicator tracks the extent of winter ice cover for each of the five Great Lakes by measuring spatial extent of water temperature and ice cover using long-term data, which can be compared with future claimate change in the Great Lakes region (ECCC 2021; Wang, X. et al. 2017). This sub-indicator is also used to infer potential impact of climate change on wetlands since ice cover affects water levels and protects the shorelines, including wetlands (Dehghan 2019), from erosion by waves and winter storms. In addition, the role of wind in ice formation and stability is an important factor on landfast ice. Wind mixing and upwelling, as well as driving intermittent breakup of shoreline-attached ice, keep Lake Michigan and Lake Ontario from freezing in most years due to lake orientation and depth.

## Ecosystem Objective

Change in lake ice cover during the winter due to climate change will affect water temperature and biomass abundance (Ozersky et al. 2021) on the Great Lakes in the following spring and summer and, in turn, affect lake ecosystems. Awareness of occurrence will encourage human response to reduce the stressor towards minimizing biological disruption.

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.”

## Measure

This sub-indicator will measure annual maximum and average ice concentrations on each of the Great Lakes. The data are collected by National Oceanic and Atmospheric Administration (NOAA) and the Canadian Ice Service (CIS) of Environment and Climate Change Canada from 1973 to 2020 for the purposes of this report.

The satellite measurement of lake ice started in 1979. Quality control was applied to the dataset to remove the outliers (usually greater than 2 standard deviations). Then spatial ice cover maps and ice cover time series can be obtained (Wang et al. 2012b). From 1973 to 2020, ice cover of each lake and total ice cover for all five Great Lakes can be calculated. Furthermore, the decadal average can be constructed for reporting purposes.

According to Assel (2005), the daily spatial average ice cover for each Great Lake is calculated from daily grids. Daily grids are generated by linear interpolation of observed ice cover grids between adjacent dates for a given winter season from the date of the first ice chart to date of the last ice chart (Assel and Norton, 2001). Lake-averaged ice cover prior to date of first ice chart and after date of last ice chart is assumed to be zero. The daily lake-averaged ice cover on each Great Lake is used to calculate the seasonal average ice cover. The seasonal average ice cover is the sum of the daily lake-averaged ice cover over a winter divided by 182 (the number of days between 1 December to the following 31 May). The seasonal average ice cover is calculated using days when the lake-averaged ice cover was greater than or equal to 5%.

The seasonal average ice cover is an index of the severity of an annual ice cycle. Ancillary ice cycle variables calculated for each winter are the Julian dates that the first and last observed lake-averaged ice cover were greater than or equal to 5% and the duration of the ice cover, that is, the difference between dates of last and first ice.

Annual maximum ice cover (AMIC) is defined as a maximum percentage of ice cover in one day during an ice season (winter). This snapshot of the ice season is a realization that can be measured, and reflects the overall atmospheric cumulative effects on lake ice. Furthermore, its seasonal and interannual variability can be accurately recorded and analyzed (Bai et al. 2012). The trend of AMIC for a specified period can be calculated (Wang et al. 2012a,b; 2017a,b). However, the trend varies with different length of the time series included, because there is multi-decadal variability in lake ice caused by multi-decadal atmospheric and water thermal forcings (Wang et al. 2018). The AMIC anomaly is defined as the difference between the daily AMIC and the climatological mean of daily AMIC over the period of 1973-1990.

An anomaly-based approach to reporting on the climate trend sub-indicators, which include water levels, precipitation amounts, ice cover and surface water temperatures, has been implemented since the 2019 State of the Great Lakes reporting cycle.

The approach includes identifying a defined base period and comparing the most recent 10-year, 30-year and long-term trends (the full period of record) to this base period to identify "anomalies" or "deviations" from the base period. The base period includes up to 1990 but not beyond as it is expected that accelerated “climate change” effects would be occurring after 1990. The base period varies in length for these 4 reports, but includes a minimum of 15 years of data that are reliable and comprehensive to calculate the base values. An anomaly-based approach puts the longer periods of record into context and compares the historical data to more recent changes that are occurring in the ecosystem. This approach provides more telling information as it identifies whether the deviations or extremes are increasing or decreasing over the various time periods which is valuable in reporting on recent climate changes and impacts in the Great Lakes. Previously, the increasing and/or decreasing trends provided in the State of the Great Lakes climate trend reports looked at the historical period of record and whether long-term trends were increasing or decreasing over that time.

A moving average (length determined by the authors) for the climate trend sub-indicators is used because these measures of precipitation, ice cover, water levels and surface water temperatures, in most cases, are non-linear (e.g., there is no inherent link in precipitation amounts from one year to the next). The moving average smooths the variation in the year-to-year fluctuations to help show the trends in the data over the longer period (Wang et al. 2018).

## Ecological Conditions

This sub-indicator is used as a potential assessment of climate change, particularly within the Great Lakes basin. Changes in water and air temperatures will influence ice development on the lakes and, in turn, affect coastal wetlands, nearshore aquatic environments, and inland environments. Ice cover directly influences lake water temperature change, duration of stratification, and fish behavior. Based on the observations (Figure 1), the highest maximum ice cover for each Great Lake occurred in 1977-1979, 1994, 2014, and 2015. For Lakes Michigan, Erie and Ontario, the highest maximum ice over took place in 1977, 1978 and 1979 (Figures 4, 6 and 7), respectively, depending on the spatial variability of air temperature and water depth (i.e., heat content) of each lake.

There is spatial variability in the AMIC trend. The steepest trends occur along heavily ice-covered coasts in Lake Superior, Georgian Bay, northern Lake Huron, and northern Lake Michigan. Offshore ice cover has more gradual trends, as ice cover is not continuous. Research is needed to map the grid points of a lake using GIS to calculate each grid point trend. This on-going research will reveal spatial trend distributions over the Great Lakes (Mason et al. 2016).

During the 2015/16 and 2016/17 winters, AMIC was observed to be 34% and 19%, respectively, significantly below the long-term average of 55% (Figure 1), mainly due to the simultaneous occurrence of a strong El Niño, positive North Atlantic Oscillation (NAO), warm phase of Atlantic Multi-decadal Oscillation (AMO), and warm phase of Pacific Decadal Oscillation (PDO).

Air temperatures over a lake are among the few factors that control the formation of ice on that surface. Colder winter temperatures increase the rate of heat release by the lake, thereby increasing the freezing rate of the water. Milder winter temperatures have a similar controlling effect--only the rate of heat released is slowed and the ice forms more slowly. Globally, some inland lakes appear to be freezing up at later dates, and breaking-up earlier, than the historical average, based on a study of 150 years of data (Magnuson et al. 2000). These trends add to the evidence that the earth has been in a period of global warming for at least the last 150 years.

## Linkages

This sub-indicator links directly to the other sub-indicators in the Watershed Impacts and Climate Trends indicator. It is indirectly linked to other sub-indicators that track trends in wetland area, habitat change and fish species.

The freezing and thawing of lakes is a very important aspect to many aquatic and terrestrial ecosystems. Many fish species rely on the ice cover or ice duration to give their eggs protection against strong wind stirring during the late part of the ice season. Nearshore ice has the ability to change the shoreline as it can encroach upon the land during winter freeze-up times. Even inland systems are affected by the amount of ice that forms, especially within the Great Lakes basin. Less ice on the Great Lakes allows for more water to evaporate and be spread across the basin in the form of snow. This can have an effect on the foraging animals (such as deer) that need to dig through snow during the winter in order to obtain food.

Under the business as usual emission scenario (IPCC RCP 8.5), annual average air temperature over the Canadian portion of the Great Lakes basin is projected to be about 5°C warmer by the 2080s (2070-2099) than it was in the 1990s (1986-2005) (Zhu et al 2018). These changes could affect the formation of ice on the Great Lakes and could result in changes in the ecosystem as noted below.

Under the decreasing ice conditions, however, there are some benefits such as lengthened shipping duration (Kubat et al. 2021) and less destruction of infrastructure around the Great Lakes, including offshore wind farm development. Declining ice cover may not be a universally negative phenomenon for all constituencies.

Linkages to other sub-indicators in the indicator suite include:

- Surface Water Temperature – ice cover has high correlation with water temperature (r = 0.5).
- Water Levels – ice cover can influence heat and moisture exchange between the lake and the atmosphere.
- Precipitation Amounts – ice cover can strongly influence lake-effect snow.
- Coastal Wetlands: Extent and Composition – ice cover can protect coastal wetlands and reduce erosion.
- Hardened Shorelines – less ice cover exposes the shoreline to waves generated by winter storms that accelerate erosion.
- Dreissenid Mussels – ice cover can influence the water stability, vertical temperature structure and spring warming and summer stratification.
- Harmful Algal Blooms – higher water temperatures and less ice cover may be related to more and earlier algal blooms.
- Toxic Chemicals in Herring Gull Eggs – a link has been shown between contaminant levels in Herring Gull eggs and ice cover.
- Lake white fish, lake herring, and yellow perch species are dependent on ice cover, as ice cover can protect the eggs from wind mixing.

## 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 | Data can be found here: https://www.glerl.noaa.gov/data/ice/ | | |

## Additional Information

Ice cover is a very understandable feature. Lake ice indicates coastal wetland ice and itself affects wetlands (e.g., winter storm severity). Less ice cover exposes the shoreline to waves generated by winter storms that accelerates erosion. Ice cover reflects temperature, wind, and heat stored in a lake, and therefore, this is a good indicator of climate effects. These data are already collected annually for each lake by NOAA and CIS using satellite imagery. There is a natural variability in maximum ice extent accounted for in the interpretation.

On-going research will improve our understanding of lake ice and related climate changes, as well as its implications for ecosystems in the Great Lakes (Bai et al. 2015; Wang et al. 2012b, 2018).

## Acknowledgments

Ice dataset was obtained from NOAA Great Lakes Environmental Research Laboratory (https://www.glerl.noaa.gov/data/ice/)

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All data analyzed and charts created by the authors.

## Information Sources

Anderson, E.J., Stow, C.A., Gronewold, A.D., Mason, L.A., McCormick, M.J., Qian, S.S., Ruberg, S.A., Beadle, K., Constant, S.A. and Hawley, N., 2021. Seasonal overturn and stratification changes drive deep-water warming in one of Earth's largest lakes. Nature communications, 12(1), pp.1-9.

Austin, J.A., and S. Colman, 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: a positive ice-albedo feedback. Geophys. Res. Lett., 34, L06604, doi:10.1029/2006GL029021.

Assel, R. 2005. Classification of Annual Great Lakes Ice Cycles: Winters of 1973–2002. Journal Of Climate 18: 4895-4905.

Bai, X., J. Wang, C. Sellinger, A. Clites, and R. Assel, 2012. Interannual variability of Great Lakes ice cover and its relationship to NAO and ENSO. *J. Geophys. Res.*, doi:10.1029/2010JC006932

Bai, X., J. Wang, R. Assel, D.J. Schwab, A. Clites, J. Bratton, M. Colton, J. Lenters, B. Lofgren, T. Wohlleben, S. Helfrich, J. Austin, 2015. A record breaking low ice cover over the Great Lakes during winter 2011/2012, Clim. Dyn. 44, 5: 1187-1213.

Dehghan, A. (2019). Projections of key climate variables for use in wetlands vulnerability assessment. Environment and Climate Change Canada.

Environment and Climate Change Canada (ECCC). 2021. Adapting to Climate Change: Solutions to Enhance Great Lakes Coastal Wetland Resilience. Mayne, G., Hazen, S., Milner, G., Rivers, P., MacMillan, K., Zuzek, P. and Mortsch, L. 144 p.

Fujisaki-Manome, A., Fitzpatrick, L.E., Gronewold, A.D., Anderson, E.J., Lofgren, B.M., Spence, C., Chen, J., Shao, C., Wright, D.M. and Xiao, C., 2017. Turbulent heat fluxes during an extreme lake-effect snow event. Journal of Hydrometeorology, 18(12), pp.3145-3163.

Gronewold, A.D., Anderson, E.J., Lofgren, B., Blanken, P.D., Wang, J., Smith, J., Hunter, T., Lang, G., Stow, C.A., Beletsky, D. and Bratton, J., 2015. Impacts of extreme 2013–2014 winter conditions on Lake Michigan's fall heat content, surface temperature, and evaporation. Geophysical Research Letters, 42(9), pp.3364-3370.

Kubat, I., Fowler, C.D. and Sayed, M., 2021. Floating ice and ice-pressure challenge to ships. In *Snow and ice-related hazards, risks, and disasters* (pp. 641-669). Elsevier.

Magnuson, J.J., Robertson, D.M., Benson, B.J., Wynne, R.H., Livingston, D.M., Arai, T., Assel, R.A., Barry, R.G., Carad, V., Kuusisto, E., Granin, N.G., Prowse, T.D., Stewart, K.M., and Vuglinski, V.S. 2000. Historical trends in lake and river ice covering the Northern Hemisphere. Science 289(9):1743-1746.

Mason, L.A., C.M. Riseng, A.D. Gronewold, E.S. Rutherford, J. Wang, A. Clites, S.D. P. Smith, and P.B. McIntyre, 2016. Fine-scale spatial variation in ice cover and surface temperature trends across the surface of the Laurentian Great Lakes. Climate Change, 1-13.

Wang, J., M. Ikeda, S. Zhang, and R. Gerdes, 2005. Linking the northern hemisphere sea ice reduction trend and the quasi-decadal Arctic Sea Ice Oscillation**.** *Climate Dyn.*, *24*: 115-130, DOI: 10.1007/s00382-004-0454-5.

Wang, J., R.A. Assel, S. Walterscheid, A. Clites, and X. Bai, 2012a. Great lakes ice climatology update: winter 2006 – 2011 description of the digital ice cover data set, NOAA Technical Memorandum GLERL-155, 37 pp. 2012.

Wang, J., X. Bai, H. Hu, A. Clites, M. Colton, and B. Lofgren, 2012b. Temporal and spatial variability of Great Lakes ice cover, 1973-2010. *J. Climate*, DOI: 10.1175/2011JCL14066.1

Wang, J., J. Kessler, F. Hang, H. Hu, A.H. Clites, and P. Chu, 2017a. Great Lakes Ice Climatology Update of Winters 2012-2017: Seasonal Cycle, Interannual Variability, Decadal Variability, and Trend for the period 1973-2017, NOAA Technical Memorandum GLERL-170, 25 pp. 2017.

Wang, J., J. Kessler, F. Hang, H. Hu, A.H. Clites, and P. Chu, 2017b. Analysis of Great Lakes Ice Cover Climatology: Winters 2012-2017, NOAA Technical Memorandum GLERL-171, 15 pp. 2017.

Wang, J., J. Kessler, A. Assuncao, X. Bai, Z. Yang, A. Clites, B. Lofgren, J. Bratton, P. Chu, and G. Leshkevich, 2018. Decadal variability of Great Lakes ice cover in response to AMO and PDO, 1963-2017. *J. Climate*, DOI: 10.1175/JCLI-D-17-0283.1

Wang, X., Huang, G., Baetz, B. W., & Zhao, S. (2017). Probabilistic projections of regional climatic changes over the Great Lakes Basin. Climate Dynamics, 49(7–8), 2237–2247. https://doi.org/10.1007/s00382-016-3450-7

Warner SM, Jeffries SJ, Lovis WA, Arbogast AF, Telewski FW. Tree ring-reconstructed late summer moisture conditions, 1546 to present, northern Lake Michigan, USA. Climate Research. 2021 Mar 11;83:43-56.

Wright, D.M., Posselt, D.J. and Steiner, A.L., 2013. Sensitivity of lake-effect snowfall to lake ice cover and temperature in the Great Lakes region. Monthly Weather Review, 141(2), pp.670-689.

## List of Figures



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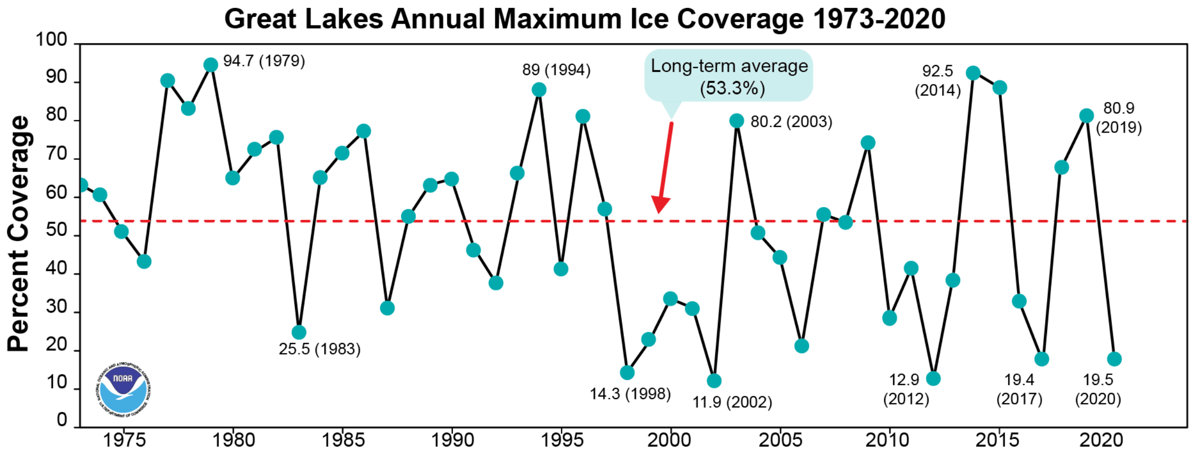


**Figure 1.** Time series of five Great Lake AMIC for the period 1973-2020, which is based on the binational NIC and CIS dataset. Source: NOAA Great Lakes Environmental Research Laboratory (GLERL), National Ice Service (NIC) and Canadian Ice Service (CIS).

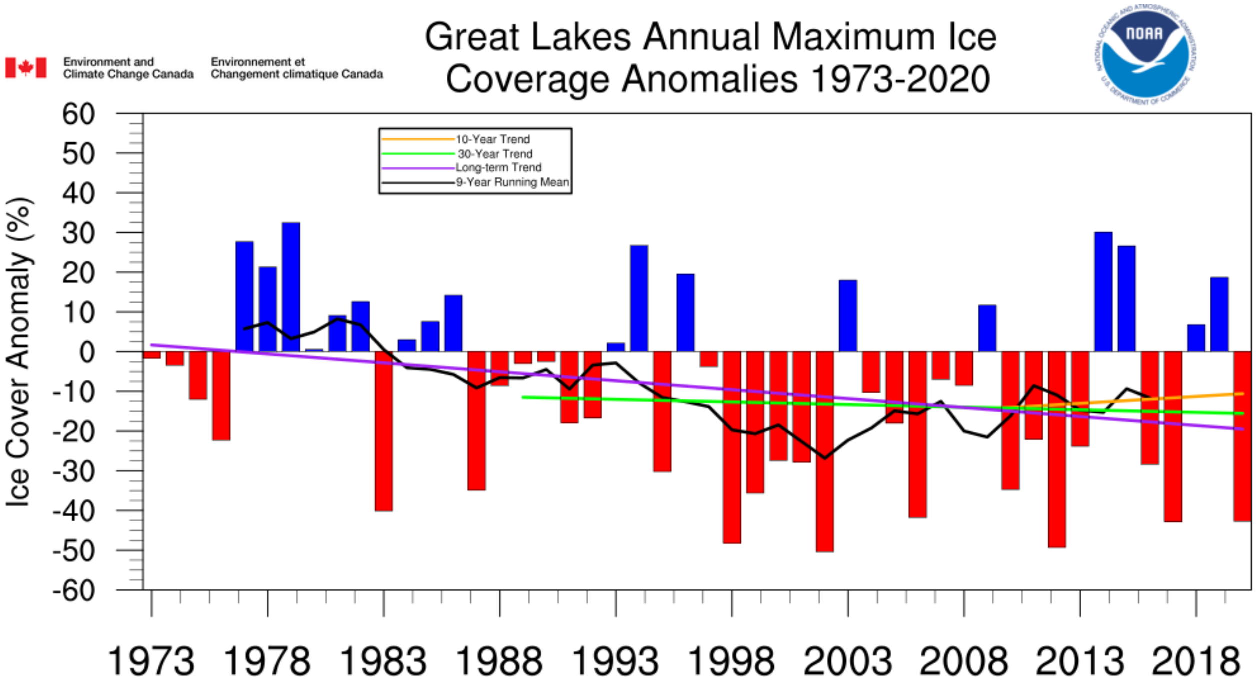


**Figure 2.** Time series of five Great Lakes AMIC anomalies for the periods 1973-2020, based on the binational NIC and CIS dataset. 10-year trend (orange), 30-year trend (green), long-term trend (purple) and 9-year running mean (black) of anomalies also shown. Source: ECCC and NOAA.

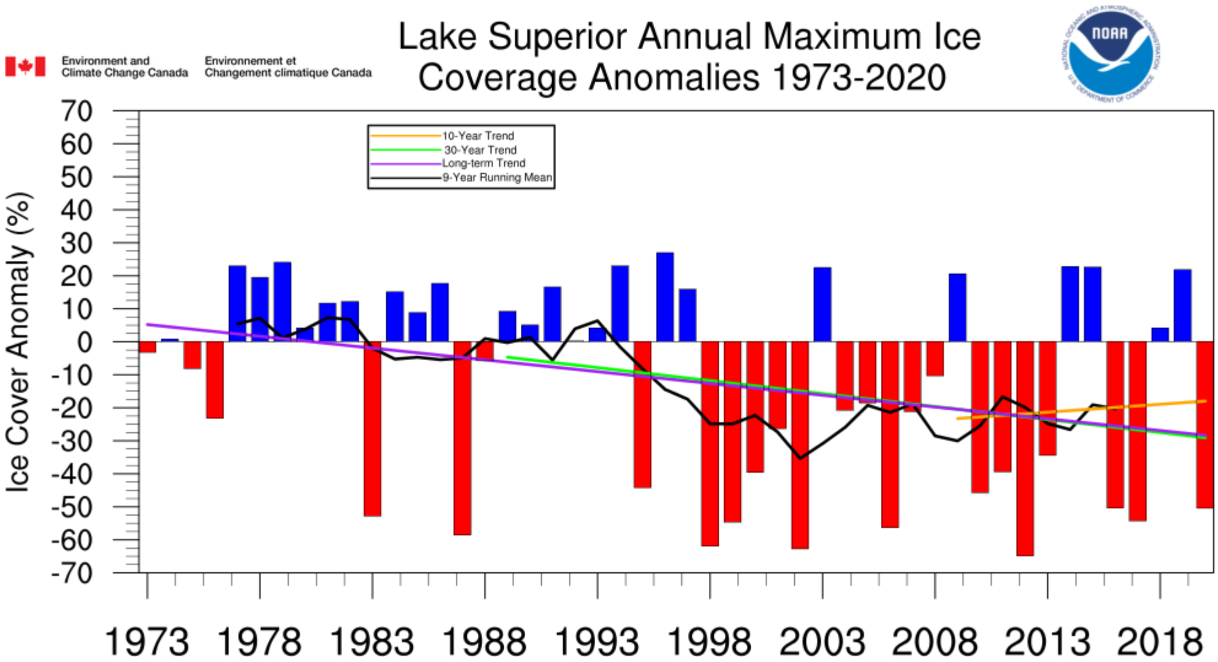


**Figure 3**. Time series of Lake Superior AMIC anomalies for the periods 1973-2020, based on the binational NIC and CIS dataset. 10-year trend (orange), 30-year trend (green), long-term trend (purple) and 9-year running mean (black) of anomalies also shown.
Source: ECCC and NOAA.

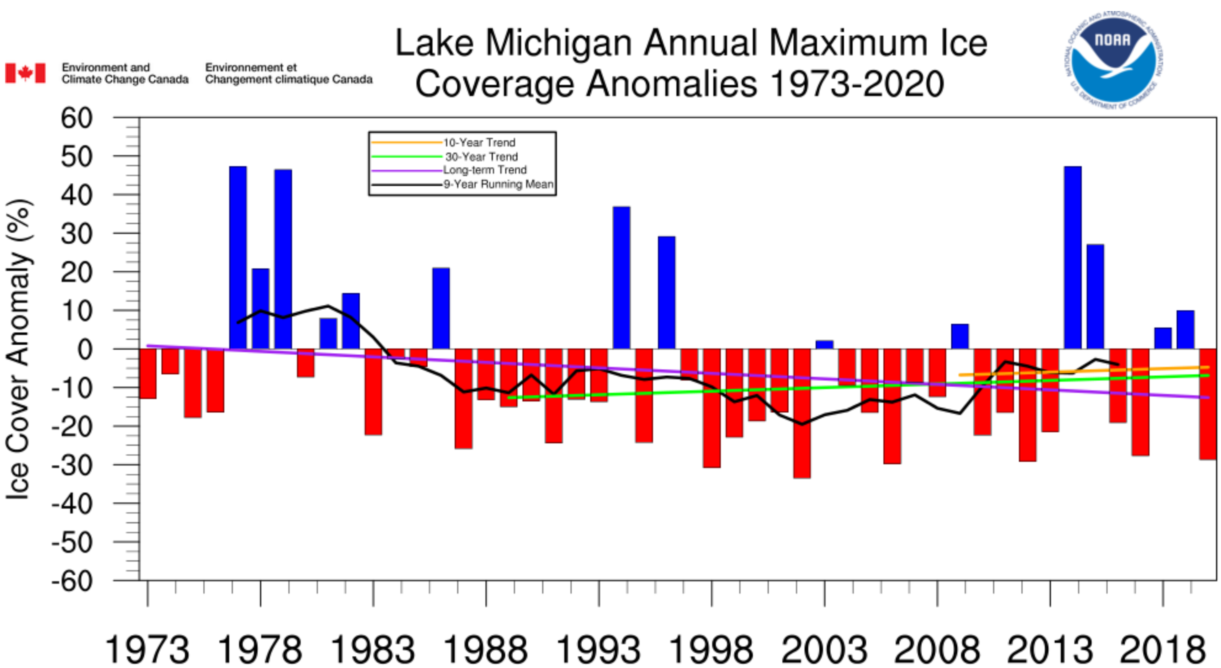


**Figure 4**. Time series of Lake Michigan AMIC anomalies for the periods 1973-2020, based on the binational NIC and CIS dataset. 10-year trend (orange), 30-year trend (green), long-term trend (purple) and 9-year running mean (black) of anomalies also shown. Source: ECCC and NOAA.

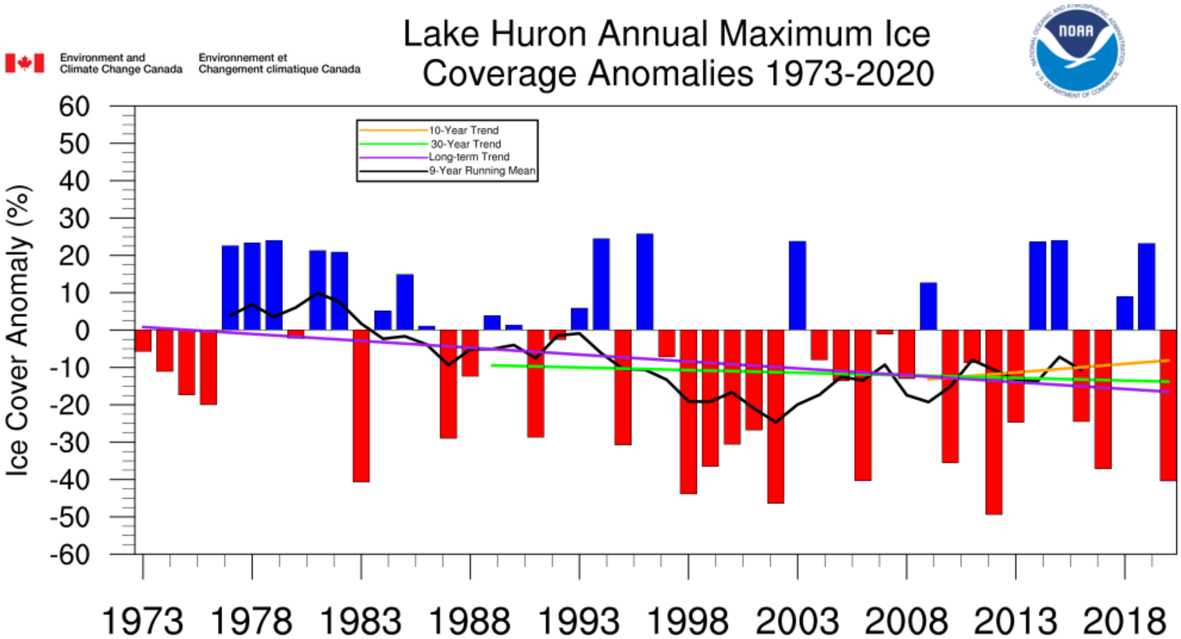


**Figure 5**. Time series of Lake Huron AMIC anomalies for the periods 1973-2020, based on the binational NIC and CIS dataset. 10-year trend (orange), 30-year trend (green), long-term trend (purple) and 9-year running mean (black) of anomalies also shown. Source: ECCC and NOAA.

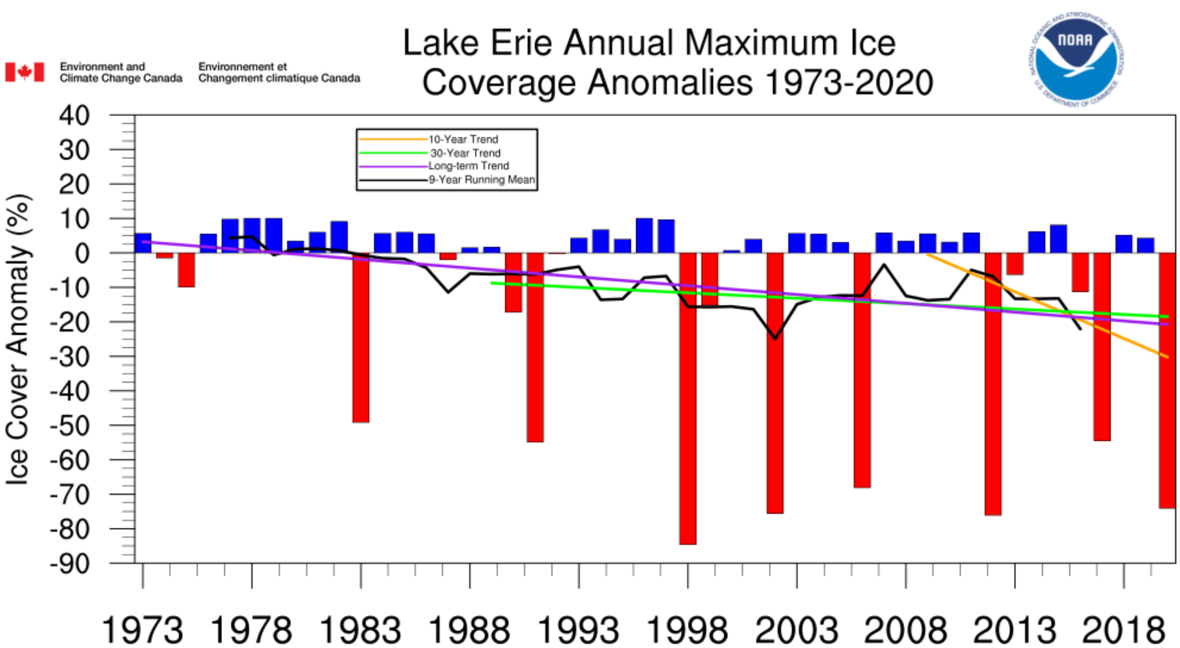


**Figure 6**. Time series of Lake Erie AMIC anomalies for the periods 1973-2020, based on the binational NIC and CIS dataset. 10-year trend (orange), 30-year trend (green), long-term trend (purple) and 9-year running mean (black) of anomalies also shown. Source: ECCC and NOAA.

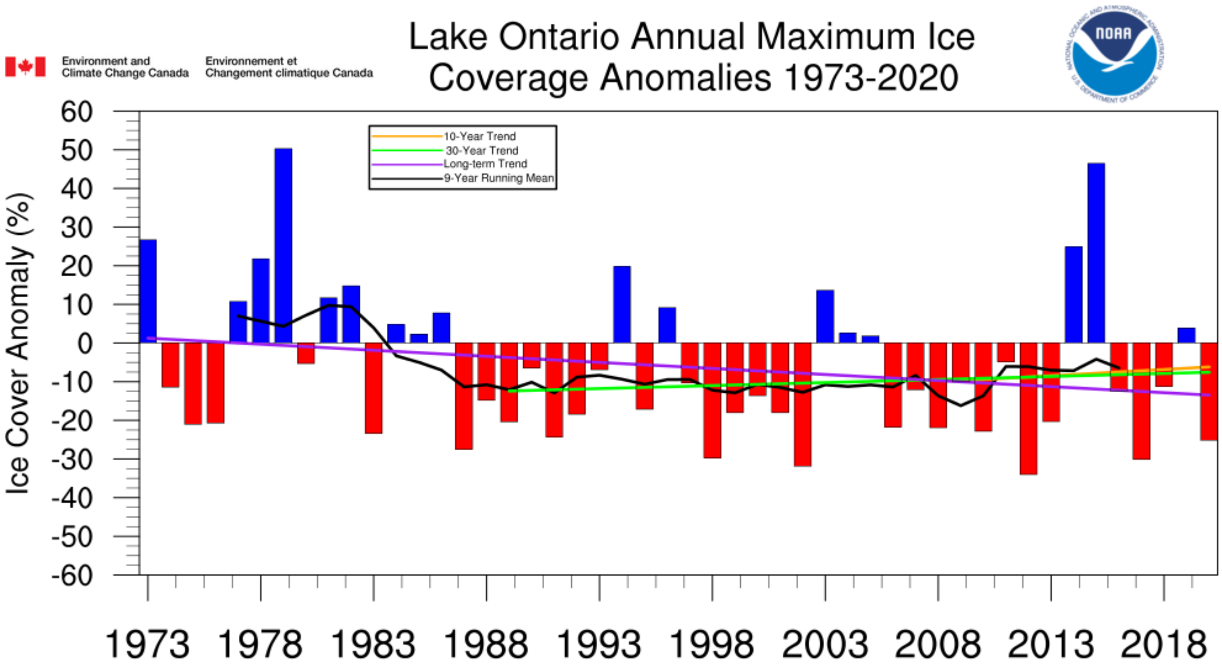


**Figure 7**. Time series of Lake Ontario AMIC anomalies for the periods 1973-2020, based on the binational NIC and CIS dataset. 10-year trend (orange), 30-year trend (green), long-term trend (purple) and 9-year running mean (black) of anomalies also shown.
Source: ECCC and NOAA.