# Sub-Indicator: Surface Water Temperature

## Overall Assessment

**Trends:**

**10-Year Trend 2014-2023:** Undetermined

**30-Year Trend 1994-2023:** Increasing

**Long-term Trend (1979-2023):** Increasing

**Rationale:** All of the lakes have experienced increased summer surface water temperatures over the period of direct observation, although the strength of the trend varies between lakes, due to the great geographical extent of the lakes and differences in lake morphometry (e.g. depth). In general, based on buoy observations made since 1979, the open waters of the upper Great Lakes (Superior, Michigan, and Huron) have experienced statistically significant rates of warming on the order of $0.05^{o}Cyr^{-1}$ ($0.5^{o}C$ per decade, or roughly $2^{o}C$ over the period of the modern directly measured record), as measured at multiple sites on each lake. The trend on Lake Erie, while still positive, is much weaker, on the order of $0.02^{o}Cyr^{-1}$. Data from Lake Ontario is limited, with the longest time series starting in 1990. In general, there is enough interannual variability in water temperature relative to long term change that assessing the trend over a 10-year period is not statistically meaningful.

## Lake-by-Lake Assessment

### Lake Superior

**10-Year Trend 2014-2023:** Undetermined

**30-Year Trend 1994-2023:** Increasing

**Long-term Trend (1979-2023):** Increasing

**Rationale:** All three buoys deployed on Lake Superior show trends towards warmer summer surface water temperature, all on the order of $0.06 \pm 0.03°C\ yr^{-1}$. The average temperature over the last 10 years, estimated by the Large Lakes Thermodynamic Model (LLTM), is approximately 3°C higher than the baseline period (1960-1990) average. As determined by the model, the average date on which the lake reached the temperature of 3.98°C ($T_{MD}$, the temperature of maximum density) over the last 10 years is 23 days earlier than during the baseline period of 1960-1990.

### Lake Michigan

**10-Year Trend 2014-2023:** Undetermined

**30-Year Trend 1994-2023:** Increasing

**Long-term Trend (1980-2023):** Increasing

**Rationale:** Both buoys deployed on Lake Michigan show trends towards higher summer surface water temperatures, on the order of $0.05 \pm 0.02\ °C\ yr^{-1}$, similar to Lake Superior trends. The average temperature over the last 10 years, estimated by the LLTM, is approximately 4°C higher than the baseline period average. The average date of the lake reaching $T_{MD}$ over the last 10 years is 37 days earlier.

### Lake Huron

**10-Year Trend 2014-2023:** Undetermined

**30-Year Trend 1994-2023:** Increasing

**Long-term Trend** (1980-2023): Increasing

**Rationale:** Both buoys in Lake Huron show trends towards higher summer surface water temperatures on the order of 0.06 ± 0.02°C $yr^{-1}$. The average temperature over the last 10 years estimated by the numerical model is approximately 2°C higher than the baseline period average. The average date of the lake reaching $T_{MD}$ over the last 10 years is 13 days earlier.

### Lake Erie

**10-Year Trend 2014-2023:** Undetermined

**30-Year Trend 1994-2023:** Increasing

**Long-term Trend** (1980-2023): Increasing

**Rationale:** Three buoys (one NDBC, two ECCC) show trends towards warmer summer surface water temperatures. The trend at the NDBC buoy (0.03± 0.02°C $yr^{-1}$) is substantially weaker than those observed in the upper lakes. The two ECCC buoys have significantly shorter periods of reporting, both starting in 1994. The average temperature over the last 10 years estimated by the LLTM is approximately 1°C higher than the baseline period average. The average date of the lake reaching $T_{MD}$ over the last 10 years is 11 days earlier.

### Lake Ontario

**10-Year Trend 2014-2023:** Undetermined

**30-Year Trend 1994-2023:** Increasing

**Long-term Trend** (1994-2023): Increasing

**Rationale:** Of the three buoys on Lake Ontario, two (45012, 45135) displayed positive trends in summer surface water temperature; at a third buoy (45159), the uncertainty in the estimate of the slope exceeded the best estimate of the slope. The time series at all three buoys are significantly shorter than those available for other lakes, so the 30-year trend carries less weight than it does on other lakes. The average temperature over the last 10 years, estimated by the numerical model, is approximately 1°C higher than the baseline period average. The average date of the lake reaching $T_{MD}$ over the last 10 years is 17 days earlier than during the baseline period.

## Trend Assessment Definitions

**Increasing:** The calculated historical trend in annual surface water temperature 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 surface water temperature is too small to be distinguished from the natural variability of the data (is not statistically significant at the 0.05 level)

**No Trend:** Data are available but the trend is not statistically increasing or decreasing due to high variability

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

**Undetermined:** Data are not available to report on a trend or the time period is too short for viable surface water temperature trend analysis

## Sub-Indicator Purpose

The purpose of this sub-indicator is to assess trends in summer surface water temperature for each of the five Great Lakes.

## Ecosystem Objective

This sub-indicator best directly and indirectly supports general objectives in Article 3 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"

## Methods

The purpose of the surface water temperature sub-indicator is to assess the long-term changes in Great Lakes thermal conditions. Two sources of data are used: data collected from a set of nine buoys operated by the National Data Buoy Center (hereafter NDBC, operated by the US National Oceanic and Atmospheric Administration), which goes back as far as 1979, and data collected from a set of four buoys operated by Environment and Climate Change Canada. The U.S. National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) and the Canadian Environment and Climate Change Canada (ECCC) operate surface buoys in the spring, summer, and fall in all five Great Lakes. Information on NDBC sensors and calibration schedules can be found at https://www.ndbc.noaa.gov/faq/instr.shtml. Among other fields, the buoys measure near-surface (within the upper meter) water temperature. Most deployments have water temperature available on an hourly basis; starting around 2016, some NDBC buoys started sampling at 10-minute intervals. For each year, small gaps (<5 days) are interpolated. If data is present for more than 90% of the July-September period, a mean of summer water temperature (July, August, September; JAS) is determined to provide a yearly value. Most of these buoys are far enough offshore that they are not affected by coastal processes such as upwelling, which could result in anomalously low estimates of surface water temperature, although there is evidence of this at some of coastal sites; data used in this report are all collected from offshore sites. Simple linear regression was used to assess the trends, and the standard errors of the trends were used to make the determination as to the nature of the trend. Trends in the date of onset of summer stratification are determined by finding the first day on which the average water temperature exceeds the temperature of maximum density ($T_{MD}$, 3.98°C).

While we present the results in terms of anomalies from the mean, we subtract the mean of all of the data, rather than attempting to use a fixed baseline period due to the relatively short time period available for the buoy data. Output from the Large Lake Thermodynamic Model (LLTM; Croley 1989a,b) is operated by the Great Lakes Environmental Research Laboratory (GLERL) and is used to estimate trends over a longer time interval, as output from this model goes back to 1950. The LLTM is a basin-averaged model- i.e., it models the lake in one dimension and does not account for lateral variability. The LLTM estimates the lake response to available meteorological data around and over the lakes, which is available over a much longer timer period than is water temperature. For the numerical model output, 1960-1990 will be used as a baseline period in order to display results in terms of anomaly. We do not intend to suggest that this baseline period was "normal" in any sense of the word. As an

additional metric, the last day in the spring when the surface water temperature is below 4 °C is used. On this date, the heat content of the entire water column is highly constrained and is a robust measure of the thermal condition of the lake. In deep lakes like the Laurentian Great Lakes, this corresponds to the onset of summer stratification; in shallower lakes this may not be the case. This is used as supporting information rather than for the determination of trends. In general, the date of onset of stratification plays a significant role in mean and maximum temperatures in the subsequent summer (Austin and Colman 2007).

## Discussion

Overall, Great Lakes surface water temperatures have increased from 1980 to 2023, although the rates vary between lakes. Specifically, the rate for Erie is significantly less than rates observed on the other lakes. Meanwhile, lakes are experiencing earlier onset of stratification ($T_{MD}$ = 3.98°C) over the last 10 years ranging from 37 days earlier for Lake Michigan to 10 days earlier for Lake Ontario: indicating earlier adverse or favorable environmental conditions for a variety of physical, biochemical, and biogeochemical processes. For example, a likely temporal shift in the development of seasonal stratification with the ability to limit the vertical transport of dissolved oxygen and nutrients, a possible temporal shift in optimum temperature for seasonal algal blooms, and the fact that the dissolved oxygen concentrations in water decreases with temperature – i.e., effects of changes in water temperature on oxygen solubility (Wetzel 2001; Chapra 2008).

Surface water temperature is directly dependent on regional air temperatures. Upward trends in surface water temperatures have been documented on the Laurentian Great Lakes (e.g., Austin and Colman 2007, Huang et al. 2012) as well as on lakes around the world (O'Reilly et al. 2015). Water temperature is a primary ecosystem driver, affecting a wide range of processes, including nutrient uptake, metabolism rates, and defines fish habitat. Surface heat and moisture fluxes (evaporation) are also a strong function of surface water temperature. Summer surface water temperatures are a reflection of not only summer air temperatures but ice conditions the previous winter (Austin and Colman 2007). In addition, the onset of summer stratification provides a robust, integrated measure of winter conditions, in which higher-ice winters tend to result in a later onset of stratification and low-ice winters result in earlier onset of stratification. In lakes without significant ice formation (e.g., Michigan, Ontario), the onset of stratification is a reflection more of the winter thermal storage of the lake, again with colder years resulting in a later onset of stratification. The date of the onset of stratification is a strong predictor of the summer surface water temperature, and the results in this report are consistent with each other: the date of the onset of stratification is getting earlier, and summer surface water temperatures are increasing.

There is a great deal of natural inter-annual variability superimposed on top of the warming trend, resulting in relatively low values of the correlation coefficients for most linear fits. Several features are consistent across the

lakes. First and perhaps most importantly, a significant jump occurs between 1997 and 1998, a strong El Niño year. It has been pointed out (van Cleave et al. 2014) that taken separately, summer water temperature prior to 1998 and from 1998 to the present have no significant trends, but a strong discontinuity between the average water temperature between these two time periods. The offset between these two time periods for the upper lakes is on the order of 2°C.

In the absence of historical field observations, we rely on LLTM simulated lake water temperature since 1950. It is worth noting that while the LLTM results suggest that the past decade has been anomalously warm, the same could be said for the decades *preceding* the baseline period as well. In fact, it appears that for the span of available model output (i.e., 1950, which is in turn limited by the availability of meteorological data with which to force the model) appears to be an anomalously cold period, with lower average temperatures and later stratification onset. This may somewhat bias the anomalies for recent years towards higher values.

## Linkages

There is a clear link between the onset of summer stratification and average summer water temperatures. Further, the onset of summer stratification is closely tied to ice cover in lakes that form ice cover (Austin and Colman 2007). Taking this a step further, recent work (Titze, 2016; Anderson et al., 2021) has shown a strong but unsurprising link between average winter air temperatures and the amount of ice cover, suggesting a series of causal linkages (winter air temperatures → winter ice cover/heat content → onset of stratification → summer water temperatures) which may prove to be a useful predictive tool for resource managers. It should be noted that winter air temperatures are increasing faster than the annual average. Due to the connectivity noted, this suggests that winter air temperature changes are going to impact not only winter conditions such as ice cover, but summer water temperatures as well, as measured in this report. The impact of lake level on water temperature, or the reverse, is not clear.

Trends towards earlier stratification onset (and later breakdown) imply that the period of stratification is increasing. Separate research (Austin and Colman 2008) suggests that over the period 1906-2006, the length of the period of summer stratification on Lake Superior has increased from roughly 145 days to 170 days, an increase of about 20%. This has implications for primary productivity in the lakes, as well as oxygen depletion in shallower, more productive parts of the Great Lakes.

## 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 | US data:<br><br>www.ndbc.noaa.gov<br><br>Canadian data:<br><br>https://www.isdm-gdsi.gc.ca/ |

## Notes on Accessing Data

Data from US sources are available at ndbc.noaa.gov and are available in ASCII format. Data from Canadian sources are available upon request.

## Data Limitations

Given that temperature is a relatively easy measurement to make well, there is surprisingly little long-term data available. The buoy data used in this report are all collected near-surface and at offshore sites, and typically only from late spring to fall. While offshore measurements are most likely to reflect trends of the lakes as a whole, a great deal of thermal variability is neglected.

LLTM simulated lake water temperature since 1950 are only available until 2020. The LLTM would need to be updated, or an alternative model used to simulate results beyond 2020.

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Source: NOAA NDBC.

**Figure 2**. Summer surface water temperature anomalies at buoys in Lake Huron (first column) and Lake Erie (second column). Solid line is the best estimate of linear trend; shaded area is region of one standard error for fit.

Source: NDBC and ECCC.

**Figure 3.** Summer surface water temperature anomalies at buoys in Lake Ontario. Solid line is the best estimate of linear trend; shaded area is region of one standard error for fit.

Source: NDBC and ECCC.

**Figure 4.** Mean summer (JAS) surface water temperature anomalies from LLTM output, 1950 to 2020. Shaded region represents baseline period.

Source: Large Lake Thermodynamic Model.

**Figure 5**. Date of reaching the temperature of maximum density (4°C) from LLTM model output, 1950 to 2020. Shaded region represents baseline period.

Source: Large Lake Thermodynamic Model**.**

**Figure 6.** Model output- buoy data comparison, 1981-2020. WT = Water Temperature.

Source: data: NDBC and ECCC. Model: Large Lake Thermodynamic Model.

**Figure 7.** Location of surface buoys used in this report.

Source: National Data Buoy Center (NDBC) and Environment and Climate Change Canada (ECCC).

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**Table 1.** Great Lakes buoys operated by NOAA and ECCC with a summary of surface water temperature trends.

| Designation | Location | Trend ± 1 S.E., °C $yr^{-1}$ | Correlation coeff. r | Start of years operational | number of years of data | Source |
|---|---|---|---|---|---|---|
| 45006 | W. Superior | 0.05 ± 0.02 | 0.32 | 1981 | 39 | NDBC |
| 45001 | C. Superior | 0.05 ± 0.04 | 0.23 | 1979 | 36 | NDBC |
| 45004 | E. Superior | 0.07 ± 0.04 | 0.28 | 1980 | 38 | NDBC |
| 45002 | N. Michigan | 0.05 ± 0.02 | 0.43 | 1980 | 39 | NDBC |
| 45007 | S. Michigan | 0.05 ± 0.02 | 0.42 | 1982 | 39 | NDBC |
| 45003 | N. Huron | 0.06 ± 0.02 | 0.44 | 1980 | 39 | NDBC |
| 45008 | S. Huron | 0.05 ± 0.02 | 0.44 | 1982 | 37 | NDBC |
| 45005 | W. Erie | 0.02 ± 0.01 | 0.32 | 1980 | 39 | NDBC |
| 45132 | C. Erie | 0.04 ± 0.02 | 0.38 | 1995 | 26 | ECCC |
| 45142 | E. Erie | 0.03 ± 0.02 | 0.39 | 1994 | 28 | ECCC |
| 45159 | W. Ontario | (0.01 ± 0.06) | 0.04 | 2002 | 12 | ECCC |
| 45012 | E. Ontario | 0.05 ± 0.03 | 0.34 | 2002 | 21 | NDBC |
| 45135 | E. Ontario | 0.08 ± 0.02 | 0.68 | 1992 | 24 | ECCC |

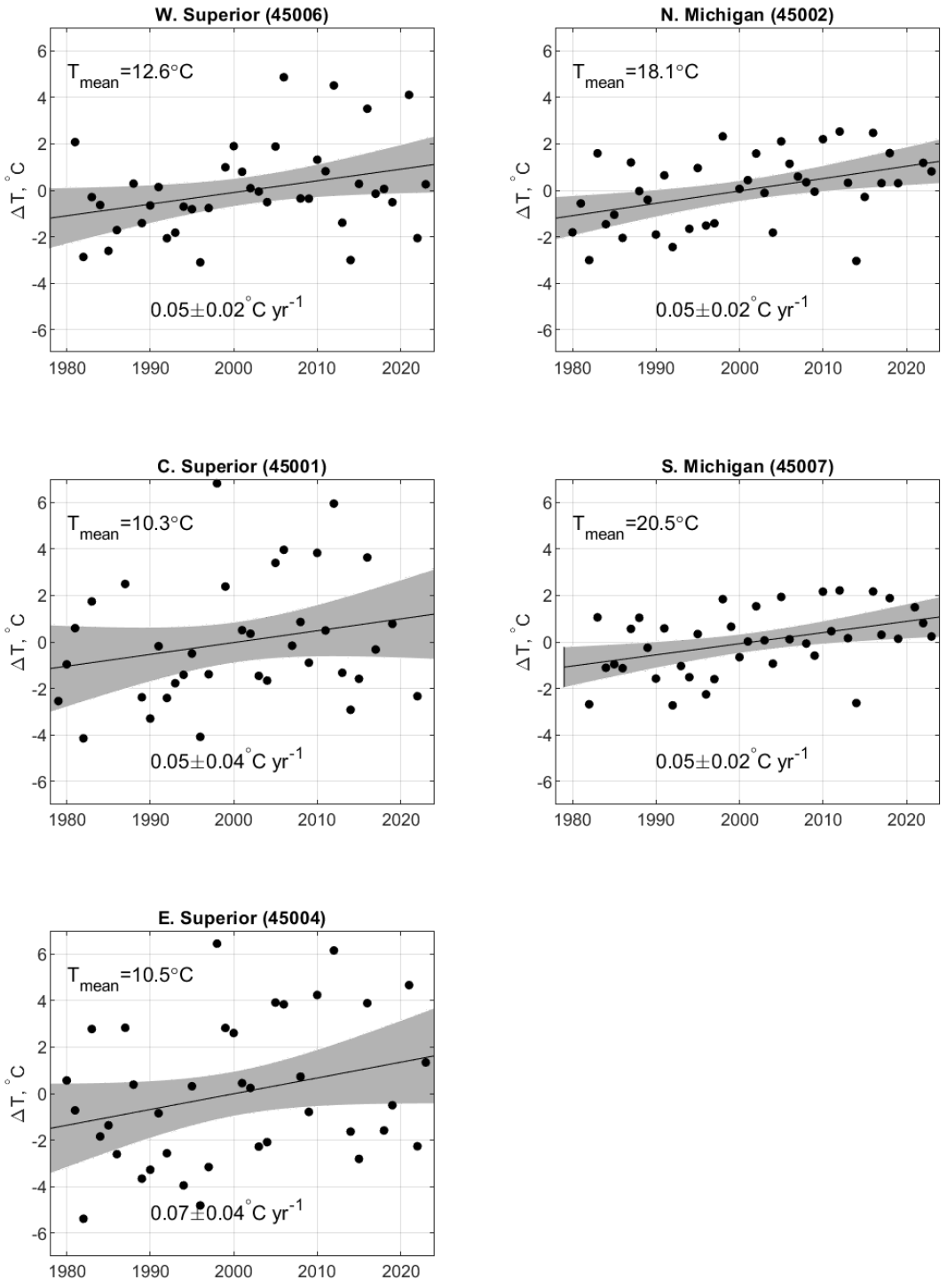



**Figure 1.** Summer surface water temperature anomalies at buoys in Lake Superior (first column) and Lake Michigan (second column). Solid line is the best estimate of linear trend; shaded area is region of one standard error for fit. Fits are over all available data.

Source: NOAA NDBC.

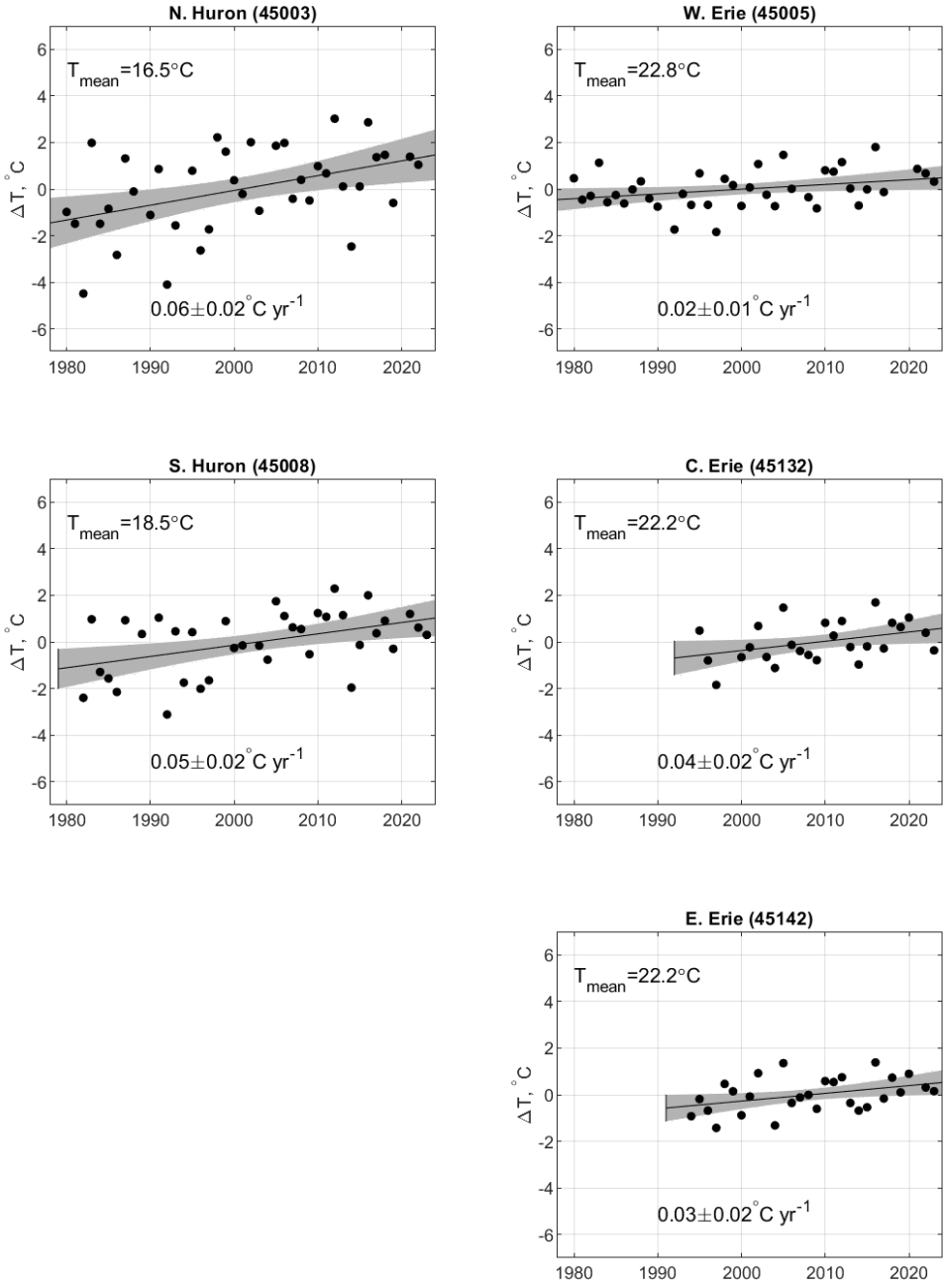



**Figure 2**. Summer surface water temperature anomalies at buoys in Lake Huron (first column) and Lake Erie (second column). Solid line is the best estimate of linear trend; shaded area is region of one standard error for fit.

Source: NDBC and ECCC.

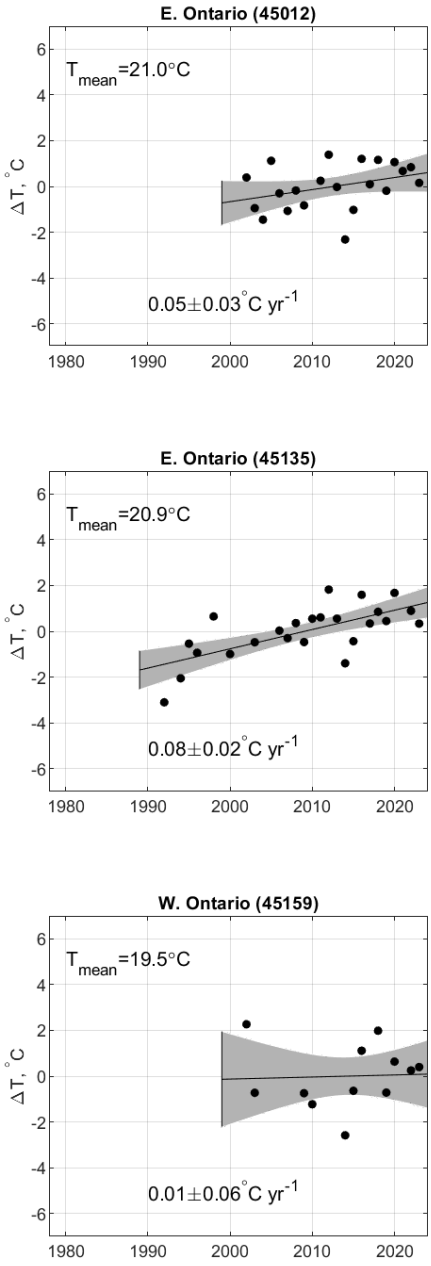



**Figure 3.** Summer surface water temperature anomalies at buoys in Lake Ontario. Solid line is the best estimate of linear trend; shaded area is region of one standard error for fit.

Source: NDBC and ECCC.

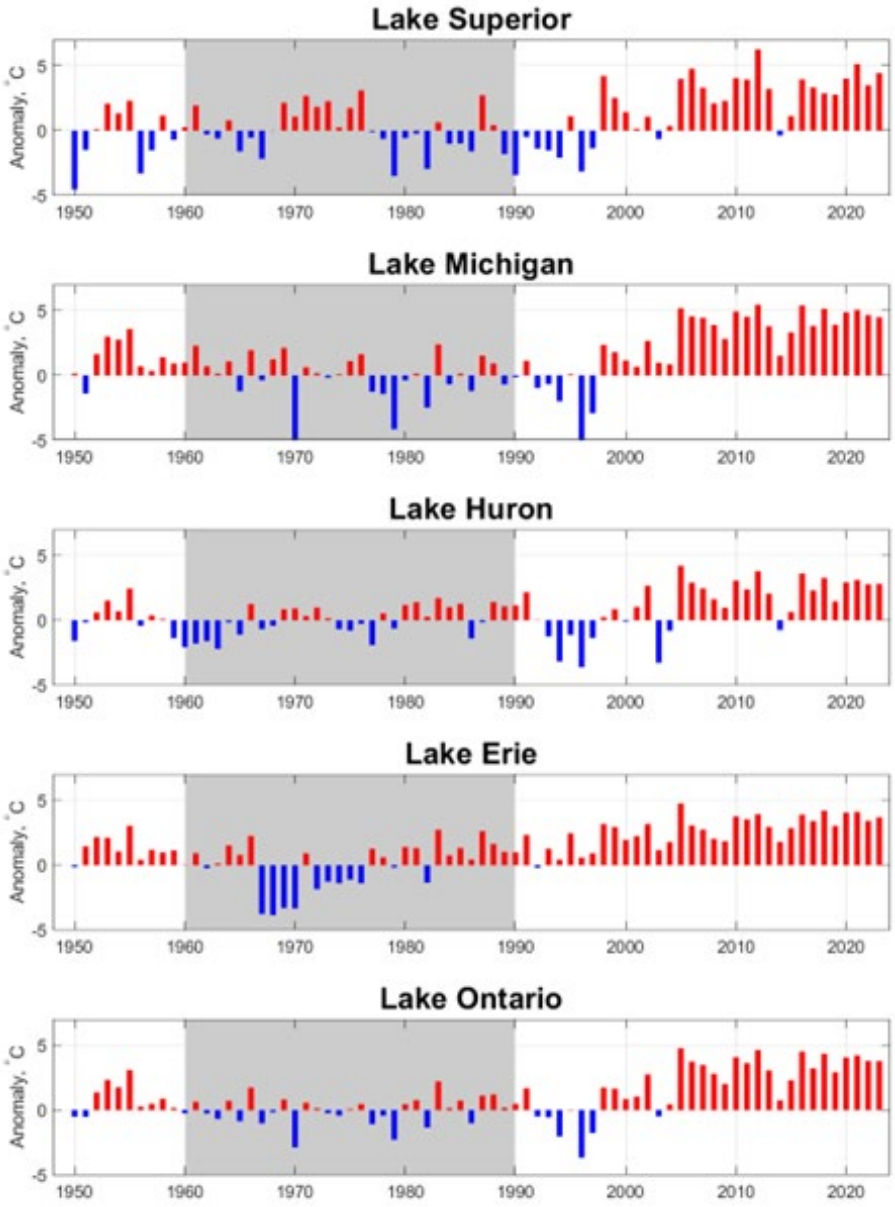



**Figure 4.** Mean summer (JAS) surface water temperature anomalies from LLTM output, 1950 to 2020. Shaded region represents baseline period.

Source: Large Lake Thermodynamic Model.

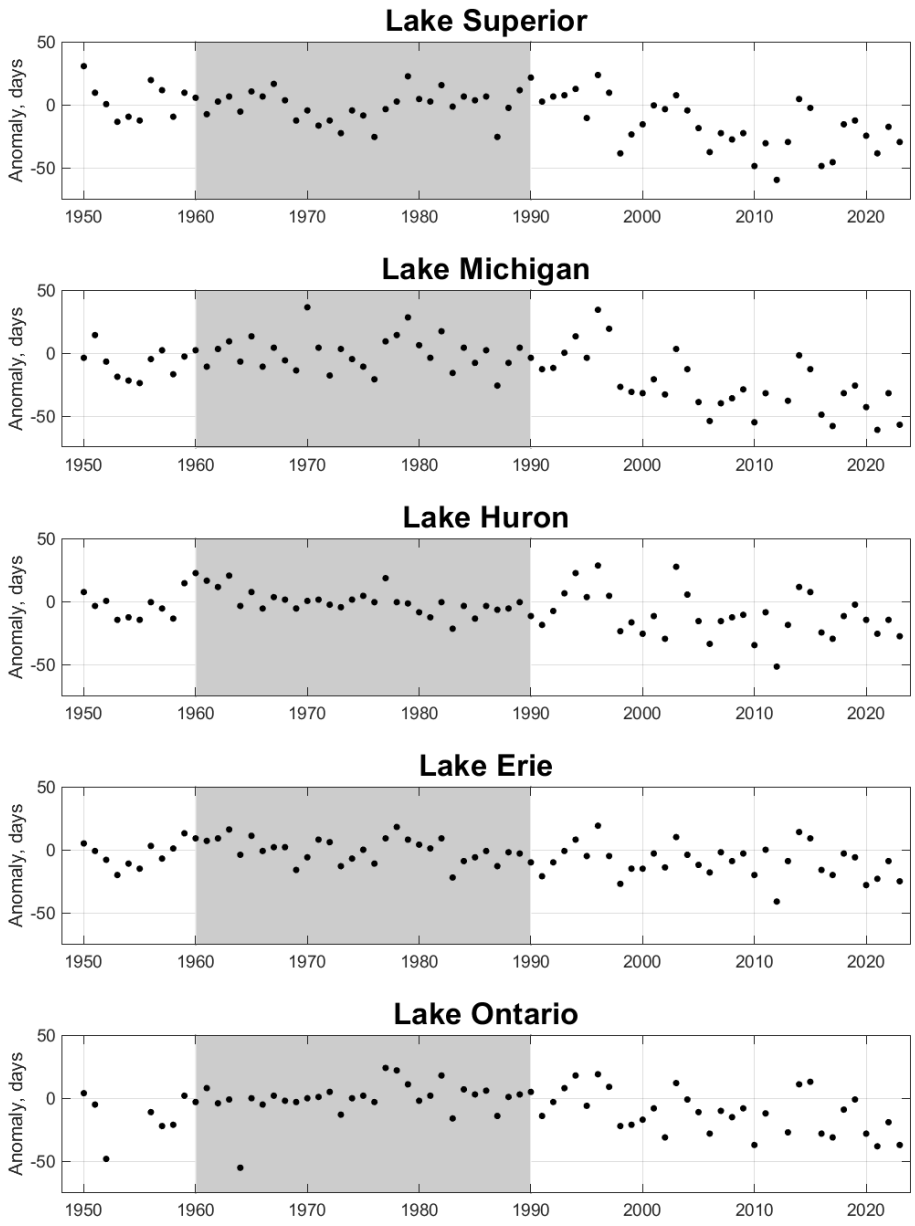
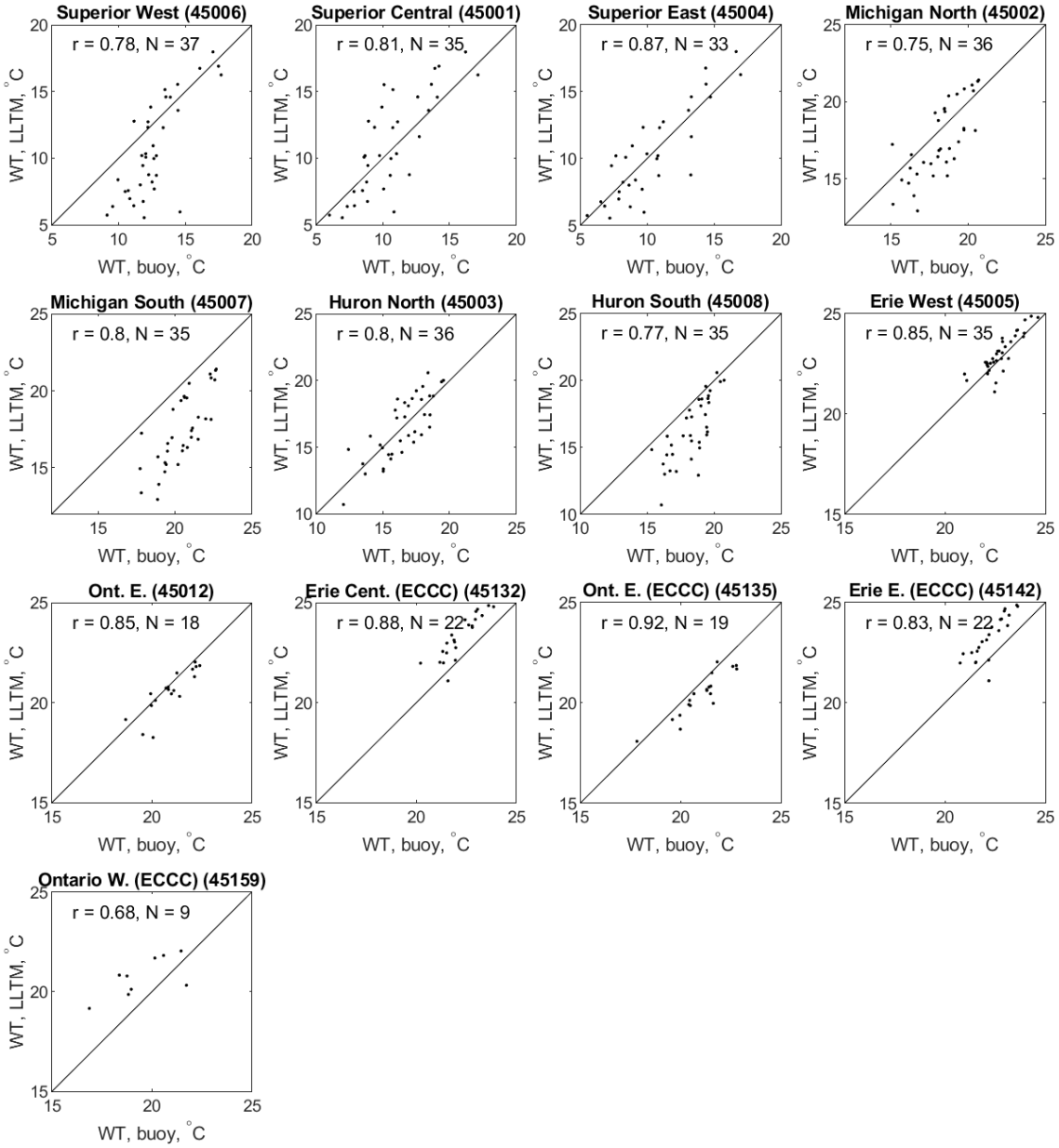



**Figure 5**. Date of reaching the temperature of maximum density (4°C) from LLTM model output, 1950 to 2020. Shaded region represents baseline period.

Source: Large Lake Thermodynamic Model.

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