Sub-Indicator: Surface Water Temperature

Overall Assessment

Trends:

10-Year Trend: Unassessed

30-Year Trend: Increasing

Long-term Trend (1980-2020): Increasing

Rationale: An overall assessment is challenging to assign given that the lakes' surface water temperature responses to changes in metrological forcing and inflows (i.e., rivers and groundwaters) are geographically different. However, in general, based on the buoy observations (Figures 1-3), it appears that the upper Great Lakes (Superior, Michigan, Huron) show consistent trends towards higher temperatures over the last 30 years and will be classified as "Increasing", with an average trend of ~0.06°C yr^{-1}. In the lower Great Lakes (Erie and Ontario), the rate of temperature increases on average was much slower at ~ 0.03°C yr^{-1}. Lake Erie (Figure 2) positive trend was spatially variable ranging from ~0.02°C yr^{-1} in the west basin to ~0.05°C yr^{-1} in central and eastern basins with fewer data available. Lake Ontario (Figure 3), while displaying positive trends at two eastern sites (0.05°C yr^{-1} and 0.09°C yr^{-1}), has significantly fewer data available, with less than 20 years. Model output is generally consistent with the buoy output (Figure 4) but shows distinct biases at some locations. Due to the magnitude of interannual variability compared to the long-term trend, measures such as the 10-year trend will not be assessed.

The year 1980 is the start of buoy-based surface water temperature observations in the Great Lakes – see Table 1 for more details, and the term long-term was used to reflect the most extended historical observation period to present.

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

Lake-by-Lake Assessment

Lake Superior

10-Year Trend: Unassessed

30-Year Trend: Increasing

Long-term Trend (1980-2020): Increasing

Rationale: All three buoys deployed on Lake Superior show trends towards warmer summer surface water temperature, all on the order of 0.07 ± 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}, maximum density) over the last 10 years is 25 days earlier.

Lake Michigan

10-Year Trend: Unassessed

30-Year Trend: Increasing

Long-term Trend (1980-2020): Increasing

Rationale: Both buoys deployed on Lake Michigan show trends towards higher summer surface water temperatures, on the order of 0.06 ± 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 39 days earlier.

Lake Huron (including St. Marys River)

10-Year Trend: Unassessed

30-Year Trend: Increasing

Long-term Trend (1980-2020): 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 3°C higher than the baseline period average. The average date of the lake reaching T_{MD} over the last 10 years is 18 days earlier. As with Michigan and Superior, 2014 stands out as a particularly cold summer. Model output from LLTM confirms this, with temperatures after 1997 significantly higher than the "baseline" temperature.

Lake Erie (including St. Clair-Detroit River Ecosystem)

10-Year Trend: Unassessed

30-Year Trend: Increasing

Long-term Trend (1980-2020): Increasing

Rationale: Three buoys (one NDBC, two ECCC) show trends towards warmer summer surface water temperatures. The trend at the NDBC buoy (0.02± 0.01°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 20 days earlier.

Lake Ontario (including Niagara River and International section of the St. Lawrence River)

10-Year Trend: Unassessed

30-Year Trend: Increasing

Long-term Trend (1980-2020): Increasing

Rationale: Of the three buoys on Lake Ontario, two displayed weak positive trends in summer surface water temperature; at a third buoy, 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 a long-term trend cannot be assessed, and the 30-year trend carries less weight than it does on other lakes. A very low average temperature reported in 1992 at 45135 appears to be due to a large wind-driven upwelling event, rather than being reflective of seasonally cool surface waters. 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 13 days earlier than during the baseline period.

Trend Assessment Definitions

Increasing: A site was classified as "Increasing" if the best estimate of the trend of temperature as a function of time as determined by linear regression is positive and exceeds the standard error of the trend estimate.

Undetermined: A site was classified as "Undetermined" if the best estimate of the trend of temperature as a function of time as determined by linear regression did not exceed the standard error of the trend estimate.

Decreasing: A site was classified as "Decreasing" if the best estimate of the trend of temperature as a function of time as determined by linear regression is negative and exceeds the standard error of the trend estimate.

Sub-Indicator Purpose

The purpose of this sub-indicator is to assess trends in surface water temperature for each of the five Great Lakes by measuring changes in water temperature using long-term data and to infer the impact of climate change on the Great Lakes Region. This sub-indicator measures the thermal properties of the Great Lakes that affect the ecosystems' function and influence water evaporation from the lakes that affect the lake's water level (if higher surface water temperatures persists, this may potentially lead to reduced winter ice cover and increased water evaporation from the lakes resulting in lower water levels).

Ecosystem Objective

There should be no change in temperature that would adversely affect any local or general use of the waters.

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

The purpose of the surface water temperature sub-indicator is to assess the long-term thermal response of the Great Lakes to changes in climate. Three sources will be 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, data collected from a set of four buoys operated by Environment and Climate Change Canad 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. 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, if more than 90% of the expected data points are present, a mean of summer water temperature (July, August, September; JAS) inclusive is taken 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 the coastal 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.

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).

Ecological Condition

Overall, the Great Lakes surface water temperature seems to be increasing between 1980 and 2020, at rates that are geographically different. For example, as shown in Table 1 and Figures 1-7, the warming rates for Lake Superior is ~0.06 °C yr^{-1}, which is ~2 times more than Lake Erie with an average rate of ~0.03 °C yr^{-1}; suggesting that Lake Superior's mean surface water temperature on average is getting warmer ~2 times faster than Lake Erie. Meanwhile, lakes are experiencing earlier onset of stratification (T_{MD} = 3.98°C) over the last 10 years ranging from 39 days for Lake Michigan to 13 days 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 and hence regional climate. 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 one of the characteristics of the emerging climate change trend is for winter air temperatures to increase faster than the annual average. Due to the connectivity noted, this suggests that winter climate trends 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 has increased from roughly 145 days to 170 days, an increase of about 20%. This is going to have significant 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	Data can be found here: www.ndbc.noaa.gov www.meds-sdmm.dfo-mpo.gc.ca		

Data Limitations

Due to the relatively short time frame in which data on surface water temperatures exist, it is difficult to attribute climatic patterns to either natural cycles or anthropogenic activity. The numerical model output used in this report is a one-dimensional model and does not fully take into account the three-dimensional nature of the lakes. The numerical model is limited by the availability and quality of meteorological forcing data. A comparison of the modeled and observed average summer surface water temperatures (Figure 6) shows that while the model captures the gross structure of interannual variability at most sites, there can be, in some instances, significant bias between the two. This may be because the model is attempting to provide a lake-wide average temperature, whereas the buoy observations are made at distinct points within these large, spatially heterogeneous systems.

The field season was considerably foreshortened in 2020 due to COVID-related restrictions on the use of research vessels, so that reliable buoy-based data was limited.

Additional Information

Subsurface temperature data is not available on a long-term basis necessary for determining lake heat content or trends therein. However, due to an unusual thermodynamic property of freshwater, the heat content can be determined using just a surface temperature in one specific circumstance. Specifically, when the surface water temperature reaches its temperature of maximum density (3.98°C) in the spring (or early summer), the entire water column must also be at the same temperature. Subsequent to this, lakes tend to form stratification in which a layer of warm water sits on top of cooler water below; hence, this date is often referred to as the onset of spring stratification. While this only gives us a glimpse of the heat content, the date can be used at which this event happens as a stable proxy for inter-annual variability in heat content. In warm years, this event will occur early, and in cold years it will be delayed. All lakes are experiencing earlier onset of stratification relative to the baseline period of 1960-1990. The associated lengthening of stratification periods that accompany the warming of water temperatures may result in an increased period of oxygen depletion in the deep waters of some of the Great Lakes, such as Lake Erie.

While there are some groups that periodically deploy equipment over the winter, there are no structures in place to guarantee funding for systematic, year-round measurements of temperature in the Great Lakes during the winter months. The dearth of data, and in fact knowledge of these systems in the winter has been the focus of recent work (Ozersky et al. 2021). As these systems have strong seasonal connectivity, developing a long-term program for year-round measurements should be a priority. Likewise, there are very few long-term measurements of thermal structure (temperature throughout the water column) so little if anything is known about trends in features like thermocline depth.

Acknowledgments

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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 operational	Source
45006	W. Superior	0.05 ± 0.03	0.30	1981	37	NDBC
45001	C. Superior	0.07 ± 0.04	0.28	1979	37	NDBC
45004	E. Superior	0.07 ± 0.04	0.25	1980	34	NDBC
45002	N. Michigan	0.06 ± 0.02	0.41	1980	37	NDBC
45007	S. Michigan	0.05 ± 0.02	0.39	1981	35	NDBC
45003	N. Huron	0.06 ± 0.02	0.41	1980	37	NDBC
45008	S. Huron	0.06 ± 0.02	0.45	1982	35	NDBC
45005	W. Erie	0.02 ± 0.01	0.25	1980	36	NDBC
45132	C. Erie	0.05 ± 0.02	0.43	1994	22	ECCC
45142	E. Erie	0.04 ± 0.02	0.38	1994	22	ECCC
45159	W. Ontario	(-0.04 ± 0.10)	-0.14	2002	9	ECCC
45012	E. Ontario	0.05 ± 0.04	0.28	2002	18	NDBC
45135	E. Ontario	0.09 ± 0.03	0.64	1990	19	ECCC

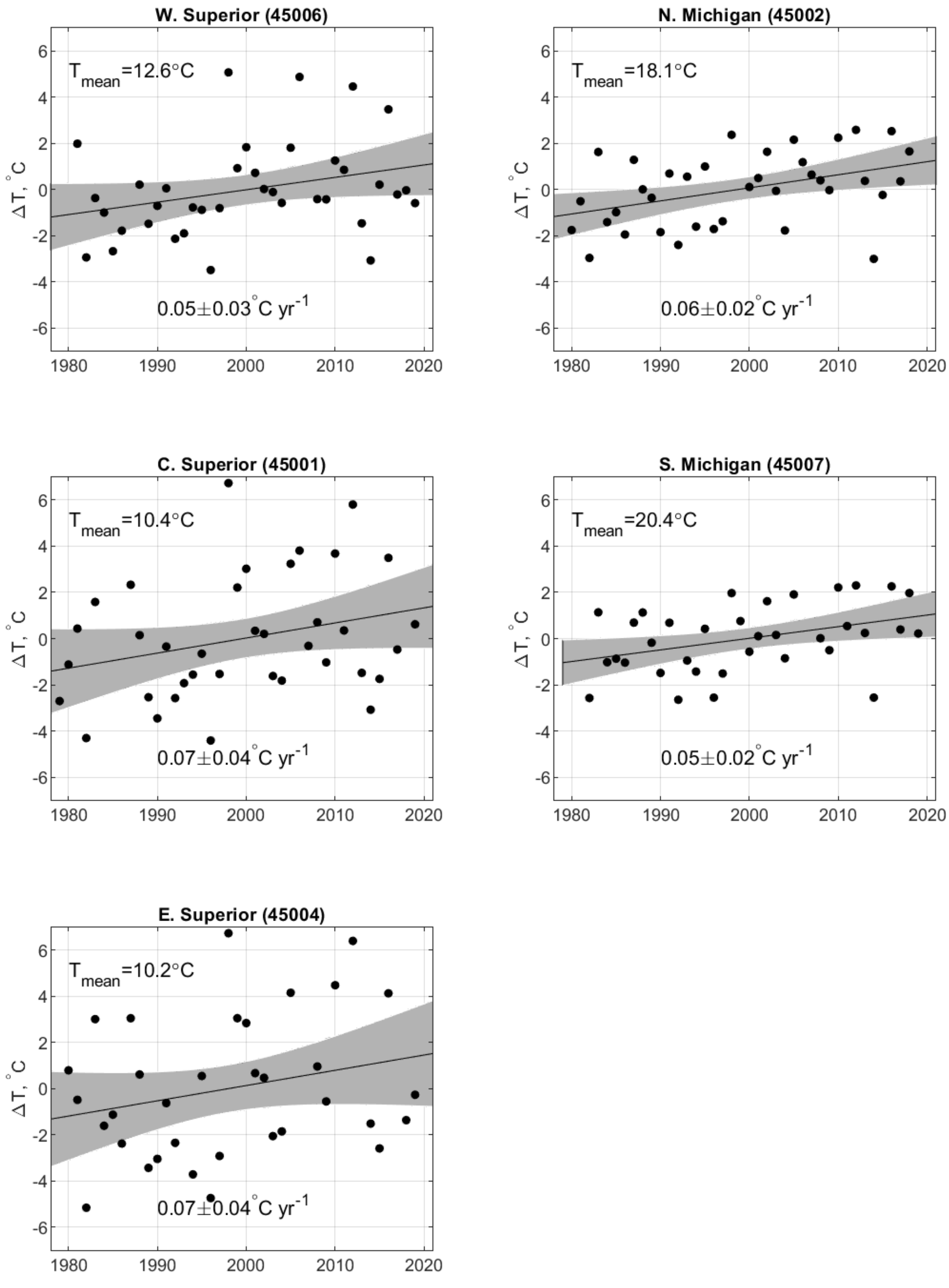

Figure 1. Summer surface water temperature anomalies at buoys in Lake Superior (first column) and Lake Michigan (second column). Solid line is the best estimate of linear trend; shaded area is region of one standard error for fit. Data from NOAA NDBC.

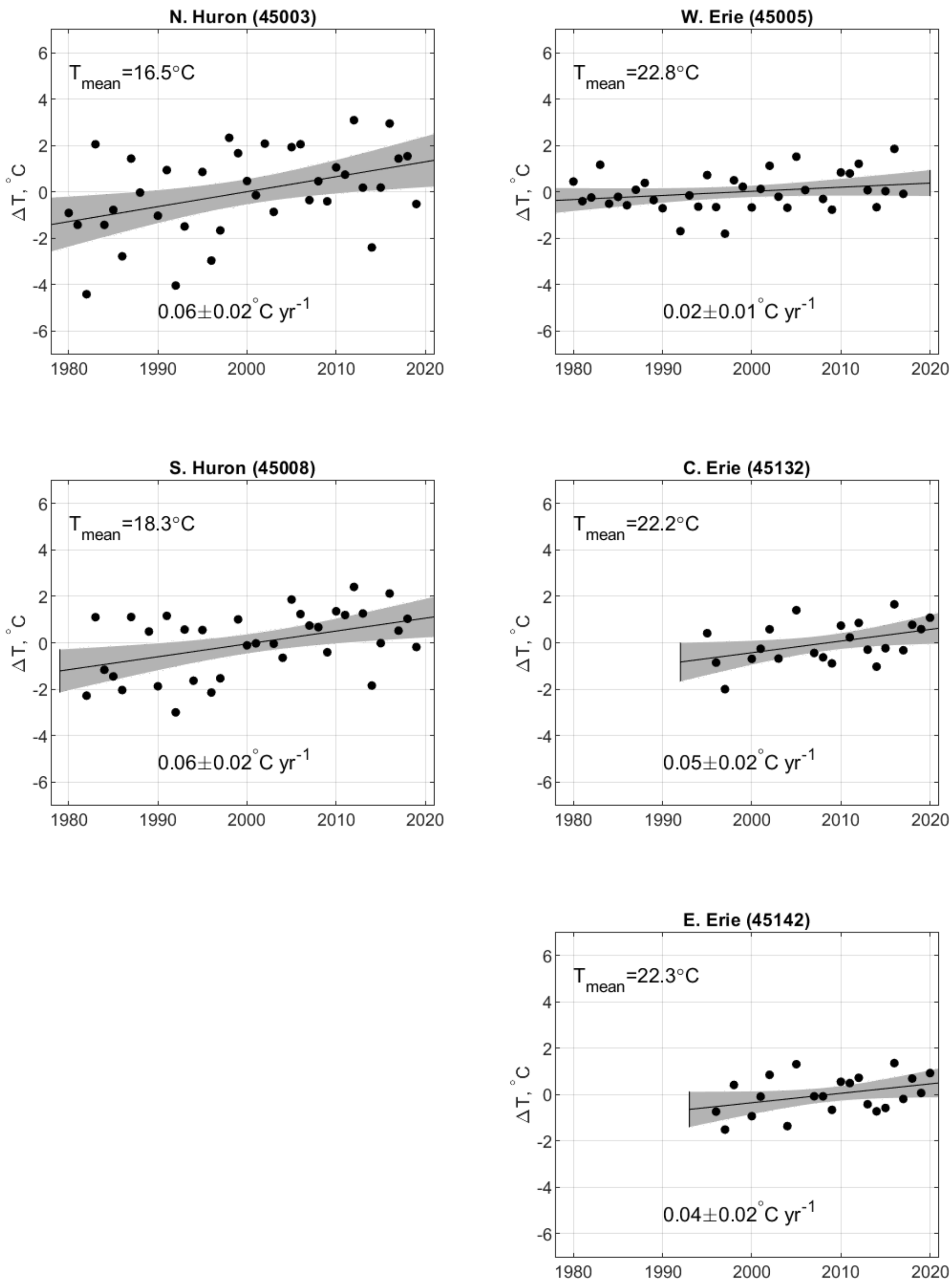

Figure 2. Summer surface water temperature anomalies at buoys in Lake Huron (first column) and Lake Erie (second column). Solid line is the best estimate of linear trend; shaded area is region of one standard error for fit. Data from NDBC and ECCC.

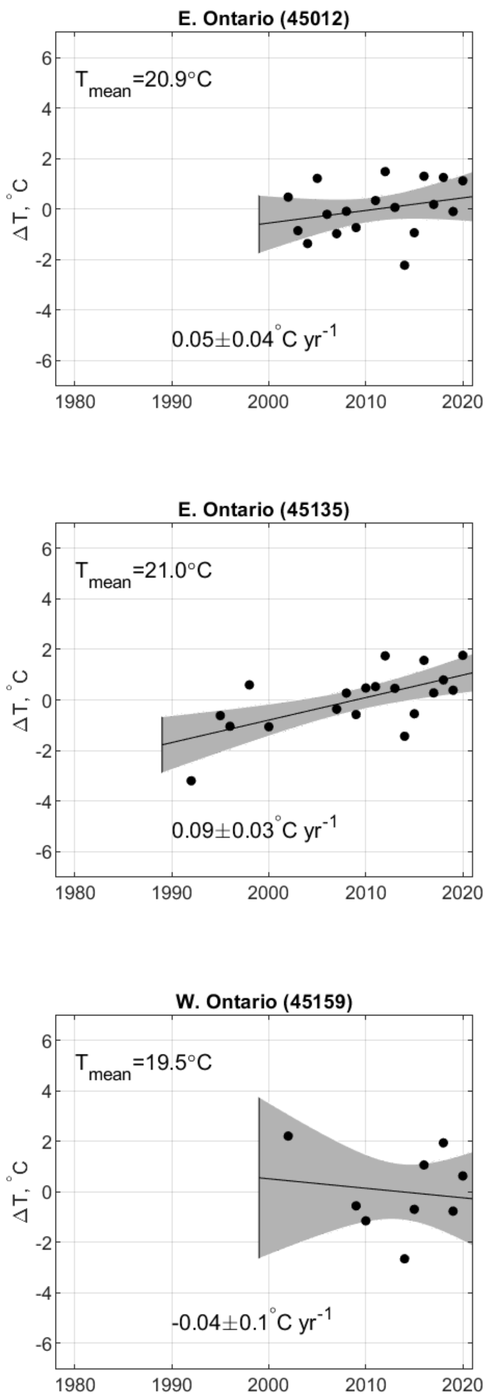

Figure 3. Summer surface water temperature anomalies at buoys in Lake Ontario. Solid line is the best estimate of linear trend; shaded area is region of one standard error for fit. Data from NDBC and ECCC.

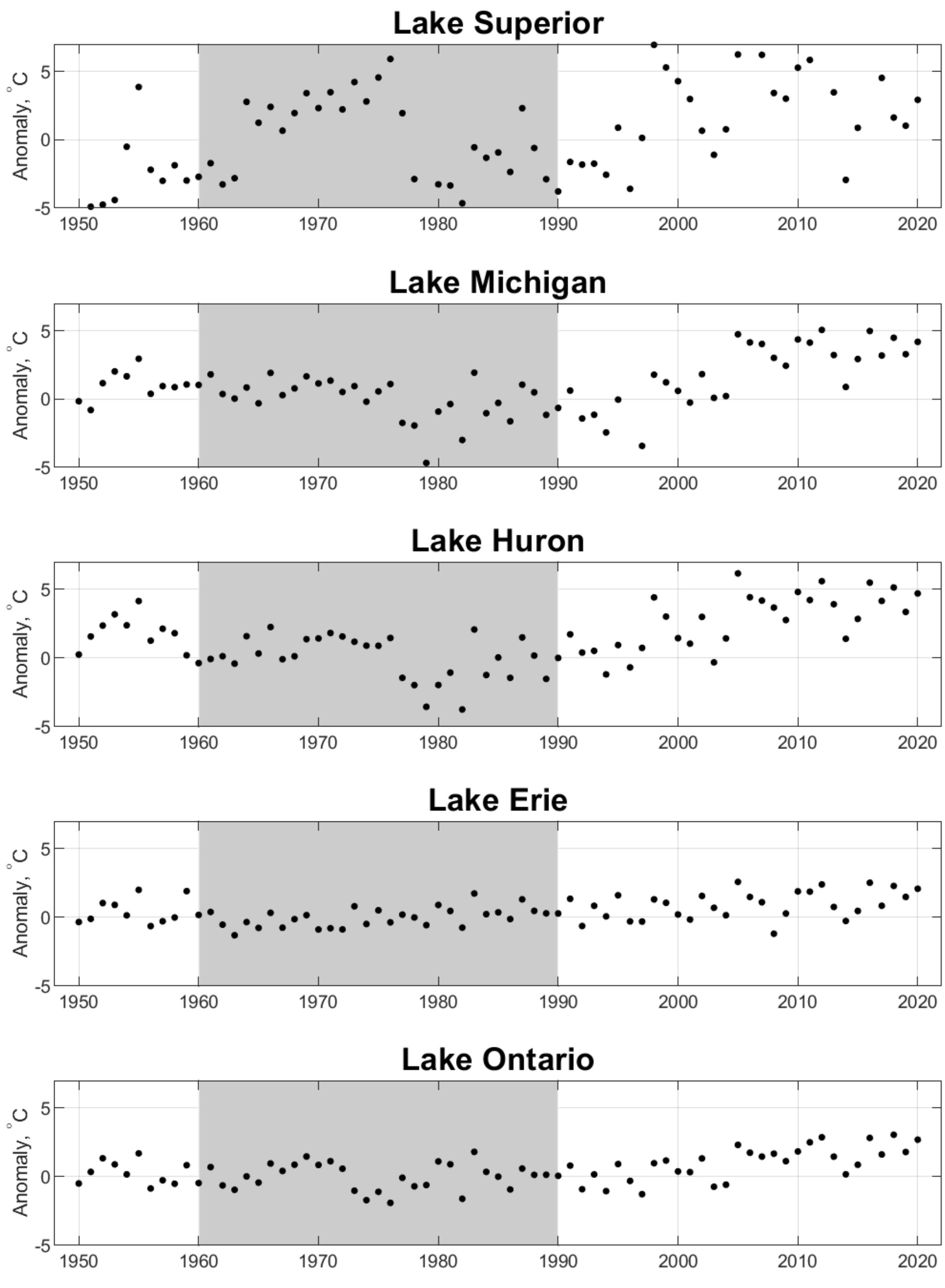

Figure 4. Mean summer (JAS) surface water temperature anomalies from LLTM output, 1950 to 2020. Shaded region represents baseline period. Source: Large Lake Thermodynamic Model.

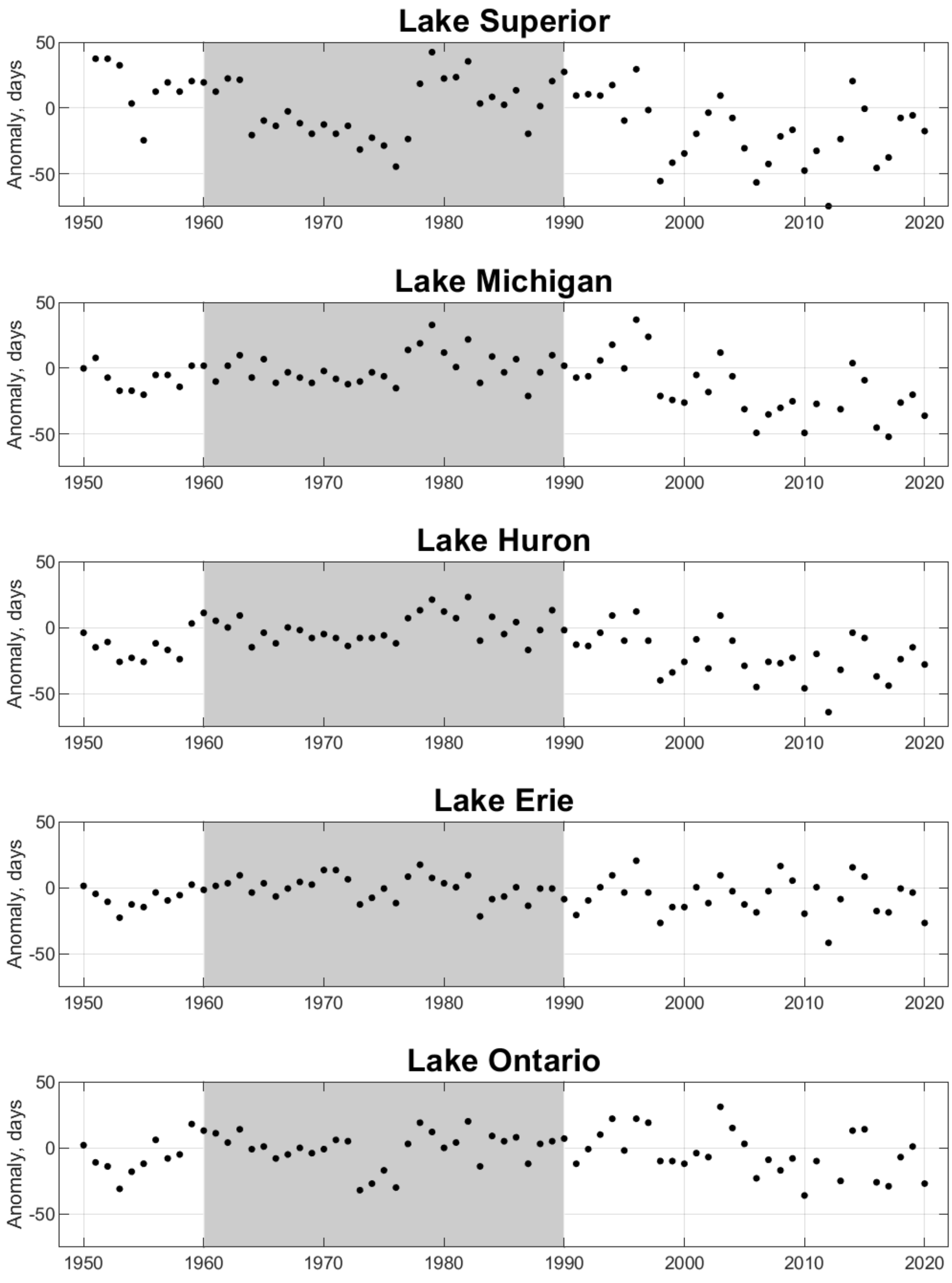

Figure 5. Date of reaching the temperature of maximum density (4C) from LLTM model output, 1950 to 2020. Shaded region represents baseline period. Source: Large Lake Thermodynamic Model.

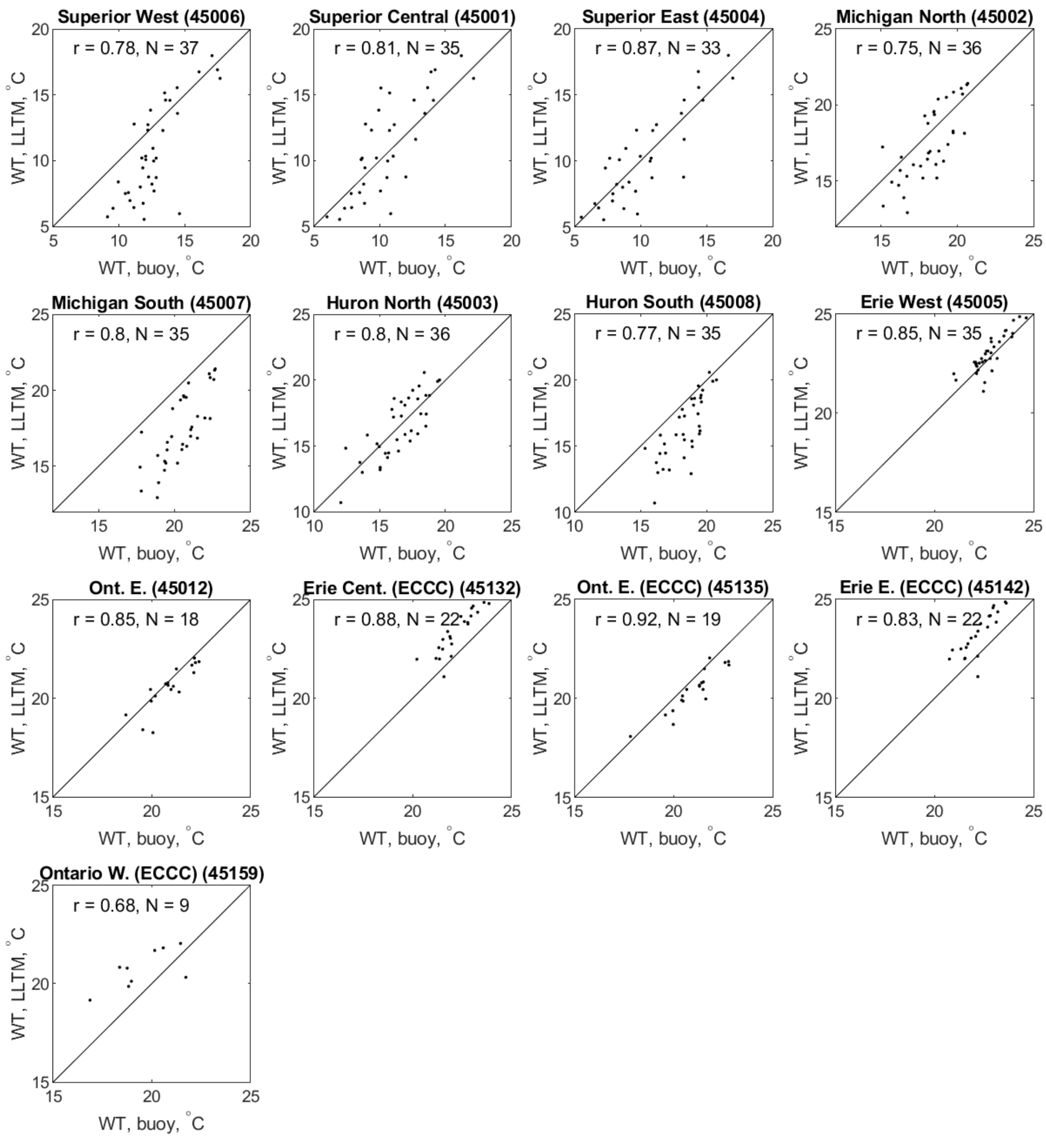

Figure 6. Model output- buoy data comparison, 1981-2020. WT = Water Temperature. Source: data: NDBC and ECCC. Model: LLTM.

Figure 7. Location of surface buoys used in this report. Source: National Data Buoy Center (NDBC) and Environment and Climate Change Canada (ECCC)