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Winter thermal structure across the Laurentian Great Lakes

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ABSTRACT

The formation of winter stratification and thermal structure in general across the Great Lakes varies in character not just between lakes, but interannually within individual lakes. Three large datasets comprise all of the publicly available Great Lakes water temperature data that span both the winter and the entire water column. Multiple sites and multiple years of data are available for Lake Superior, as well as multiple years in Lake Huron and Lake Michigan, 2 years in Lake Ontario at multiple sites, and a single year at two sites in Lake Erie. The lakes show diverse manifestations of winter stratification, with Lake Superior reliably forming winter stratification, Lake Michigan rarely forming stratification, and Huron forming stratification in about half of the winters for which data are available (there is not enough data to evaluate this for Erie and Ontario). Whether a lake forms stratification or not in a given year is governed by how much heat a lake loses below the temperature of maximum density; a heat content of roughly -1 GJm^{-2} relative to the temperature of maximum density appears to be a threshold for the formation of winter stratification. Minimum heat content in a given year is a strong function of average winter air temperature. When combined with a historical database of basin-wide air temperature, the winter stratification threshold can be used to hindcast stratification formation in Superior, Huron, and Michigan over the last century, showing that Michigan and Huron are currently undergoing a climate-driven shift in stratification status.

1. Introduction

Given that the annual cycle of thermal stratification in lakes plays a fundamental role in lake ecosystem function (Wetzel, 2024), it is remarkable how little is documented regarding winter stratification in the Laurentian Great Lakes (hereafter "the Great Lakes"), and in fact large lakes in general. Over the past several years, the limnology community has turned its attention to winter conditions in lakes, which have long been regarded as an observational blind spot (Hampton et al., 2017; Ozersky et al., 2021). An important part of this effort must include developing a better understanding of how lakes transition between seasons, and the nature of winter stratification. Potential shifts in winter thermal structure may occur, or are already occurring, as lakes respond to climate (Woolway et al., 2021; Woolway et al., 2022), and it is important to develop a better understanding of the character of these lakes with data that are currently available.

Previous work on winter whole water column thermal structure is sparse; moored time series temperature data are even more rare. During the winter of 1966–1967, a mooring with temperature measurements at two depths in Lake Superior (Smith, 1973) showed the development of winter stratification, consistent with the work presented here. Moorings with temperature also at two depths in Lake Huron (Miller and Saylor, 1981) in 1974 and 1975 showed stratification in one year but not the other, also consistent with this work. Shipboard surveys of Lake Superior demonstrated the formation of winter stratification (Assel, 1986) and spatial variability in thermal structure (Bennett, 1978). Early works addressed the heat budget of Lake Superior (Schertzer, 1978) and Lake Erie (Schertzer, 1987; Schertzer et al., 1987), with heat content differences between summer and winter consistent with this work. In these shipboard-based works, data from winter months is either sparse or missing, with speculation regarding winter conditions to fill in the gap. It is worth noting that data from these studies are not available in the

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Table 1
Large Lakes Observatory (LLO) winter moorings.

Lake	Mooring name (see map)	Years	# of winters	Location Lat N, Long W	Station depth (m)	Comments
Superior	FWM	2008–2012	5	47° 2.9′, 91° 14.9′	170	Fig. S1
Superior	WM	2006–2023	17	47° 19.3′, 89° 48.1′	185	Near NDBC 45006; Fig. S2
Superior	GM1	2014–2020	6	47° 40.0′, 90° 26.0′	155	Nearshore; Fig. S3
Superior	GM2	2014–2020	6	47° 33.4′, 90° 20.7′	165	Fig. S4
Superior	CM	2008–2013	6	48° 1.3′, 87° 46.1′	257	Near NDBC 45001; Fig. S5
Superior	NM	2009–2012	3	48° 30.0′, 87° 3.0′	200	Fig. S6
Superior	EM	2008–2015	6	47° 32.2′, 86° 34.3′	212	Near NDBC 45004; Fig. S7
Superior	SM	2009–2012	3	47° 2.0′, 86° 40.0′	384	Fig. S8
Superior	FEM	2009–2012	2	47° 28.5′, 85° 14.9′	247	Fig. S9
Superior	45027	2009–2011	3	46° 51.5′, 91° 55.8′	52	nearshore
Superior	45028	2014–2023	8	46° 48.9′, 91° 49.7′	52	

Table 2
Great Lakes Environmental Research Laboratory (GLERL) winter moorings.

Lake	Mooring name (see map)	Years	# of winters	Location Lat N, Long W	Station depth (m)	Comments
Superior	GLERL-SU	2018–2023	5	47° 7.6′, 86° 52.3′	198	Fig. S10
Michigan	GLERL-MI	1990–2021*	24	42° 41.4′, 87° 2.6′	150	Near NDBC 45007 Fig. S11
Michigan	GLERL-23	1982–1983	1	42° 42.6′, 67° 03.6′	153	Near NDBC 45007 Fig. S12A
Michigan	GLERL-33	1982–1983	1	45° 18′, 66° 18′	156	Near NDBC 45002 Fig. S12B
Huron	GLERL-HU	2012–2021	10	45° 9.5′, 82° 35.0′	220	Near NDBC 45003; Fig. S13
Erie	GLERL-T07C	2004–2005	1	41° 55.7′, 81° 38.9′	25	IFYLE; Fig. S14A
Erie	GLERL-T12C	2004–2005	1	42° 34.9′ 79° 54.8′	54	IFYLE; Fig. S14B

*Data prior to 1996 are not used in this paper due to poor vertical coverage.

public domain, and these studies are old enough that it is likely that these data have been lost.

There have only been intermittent efforts to measure winter temperatures in Lake Ontario. An important early paper by Millar (1952) used 10 years of data collected by lake ferries between 1935 and 1945 to generate climatological maps of surface water temperatures across all the Great Lakes; however, while these include winter months, there were no vertical profiles of the water column to give insight into the vertical stratification. The International Field Year for the Great Lakes (IFYGL) on Lake Ontario in 1972–1973 was one of the few studies to systematically measure full water column profiles during winter, the results of which are summarized in Aubert and Richards (1981) and Boyce et al. (1989). Rodgers (1987) used data from winter measurements made between 1965 and 1985 to show how colder winters result in later formation of summer stratification; however, the original data was not archived anywhere.

There has been renewed interest in winter conditions in the Great Lakes. Comprehensive work on Lake Superior using moored assets with significantly greater vertical resolution have explored thermal structure and interannual variability (Titze and Austin, 2014) and provided a descriptive analysis of winter conditions in Lake Superior during the "polar vortex" winter of 2013–2014 (Titze and Austin, 2016). Anderson et al. (2021) demonstrated shifts in the timing of fall overturn in Lake Michigan and a long-term trend toward shorter winter seasons across the Great Lakes (Anderson et al., 2024) using temperature data from moorings in Lakes Michigan, Huron, and Superior (which are also included in this paper). Yang et al., 2021 considered pathways to the formation of winter stratification, attributing differences in stratification formation to the wind environment as well as lake morphometry. They introduced the terms "cryostratified" to describe lakes that had strong inverse winter stratification that varies from near 0 °C at surface to near 4 °C at depth. If the lakes experienced strong wind-driven mixing, the winter water column could be homogenized and hence "cryomictic." The mechanisms that lock in deep temperatures in Superior in the winter were considered by Austin (2024), showing that an extended period of cold, calm conditions are required for the formation of stratification in Lake Superior, and that this condition is slowly relaxed as the water column temperature cools below the temperature of maximum density.

While year-round observations of thermal structure are rare in the Great Lakes, there are a small number of multi-year datasets across the Great Lakes that can be drawn on for insight into fall and winter conditions. Two laboratories are responsible for the bulk of the publicly available, year-round Great Lakes water temperature data: the Great Lakes Environmental Research Laboratory (GLERL) in Ann Arbor, MI,

Table 3
Lake Ontario winter moorings.

Lake	Mooring name (see map)	Years	# of winters	Location Lat N, Long W	Station depth (m)	Comments
Ontario	EAB004	2021–2022	1	44° 00′, 76° 42′	34	Fig. S15A
Ontario	LNR314	2021–2023	2	43° 20′, 79° 5′	77	Fig. S15B
Ontario	LOG036	2021–2023	2	43° 52′.7, 76° 40′	39	Fig. S15C
Ontario	LOH024	2021–2023	2	43° 49′, 77° 44′	85	Fig. S15D
Ontario	LOJ024	2021–2023	2	43° 41′, 77° 44′	137	Fig. S15E
Ontario	LOJ038	2021–2023	2	43° 40′, 76° 26′	114	Fig. S15F
Ontario	LOL024	2021–2023	2	43° 33′, 77° 45′	168	Fig. S15G
Ontario	LON024	2021–2023	2	43° 25′, 77° 45′	114	Fig. S16A
Ontario	LON034	2021–2022	1	43° 25′, 76° 49′	94	Fig. S16B
Ontario	OON003	2021–2023	2	43° 49′, 78° 31′	70	Fig. S16C
Ontario	PPW016	2021–2023	2	43° 47′, 77° 10′	58	Fig. S16D
Ontario	PPW028	2021–2023	2	43° 42′, 77° 12′	101	Fig. S16E
Ontario	WLO003	2021–2022	1	43° 31′, 79° 27′	63	Fig. S16F

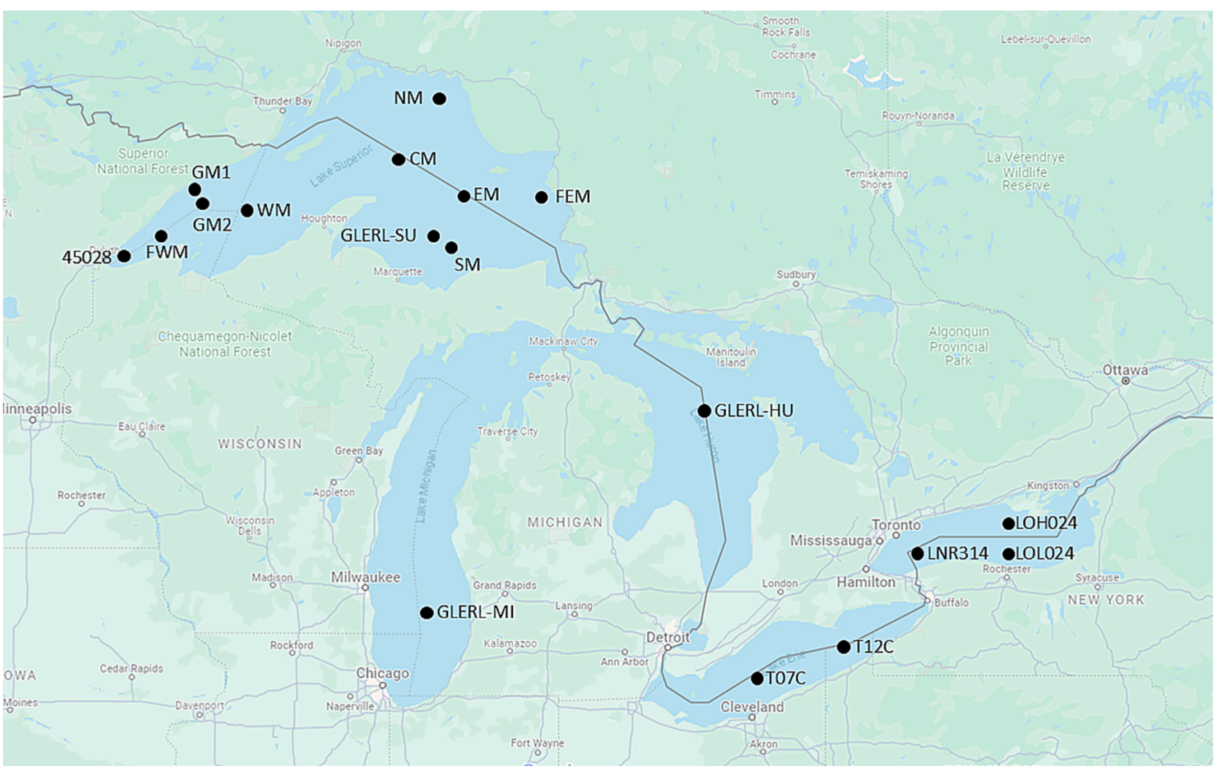

Fig. 1. Location of the moorings used in this study.

and the Large Lakes Observatory (LLO) at the University of Minnesota, Duluth. More recently, starting in the Fall of 2021, researchers have placed temperature moorings at multiple sites in Lake Ontario (Mathew Wells et al., unpublished data). There are several other moored datasets collected in the Great Lakes, but they are either not publicly available or do not have sufficient temporal coverage (i.e., winter coverage) or spatial coverage (i.e., whole water column) to be of use here.

In this manuscript, we explore winter thermal structure across the Great Lakes using publicly available data. There are significant limitations given what data are available, both spatially and temporally. A single year in Erie is available, and only in the last two years have there been systematic data available for Ontario. While Lakes Michigan and Huron have multi-year time series, only a single location is available for either lake. The primary Michigan site is in the relatively shallow southern basin, and no winter data are available for the deeper northern basin, which experiences colder air temperatures, which are a primary

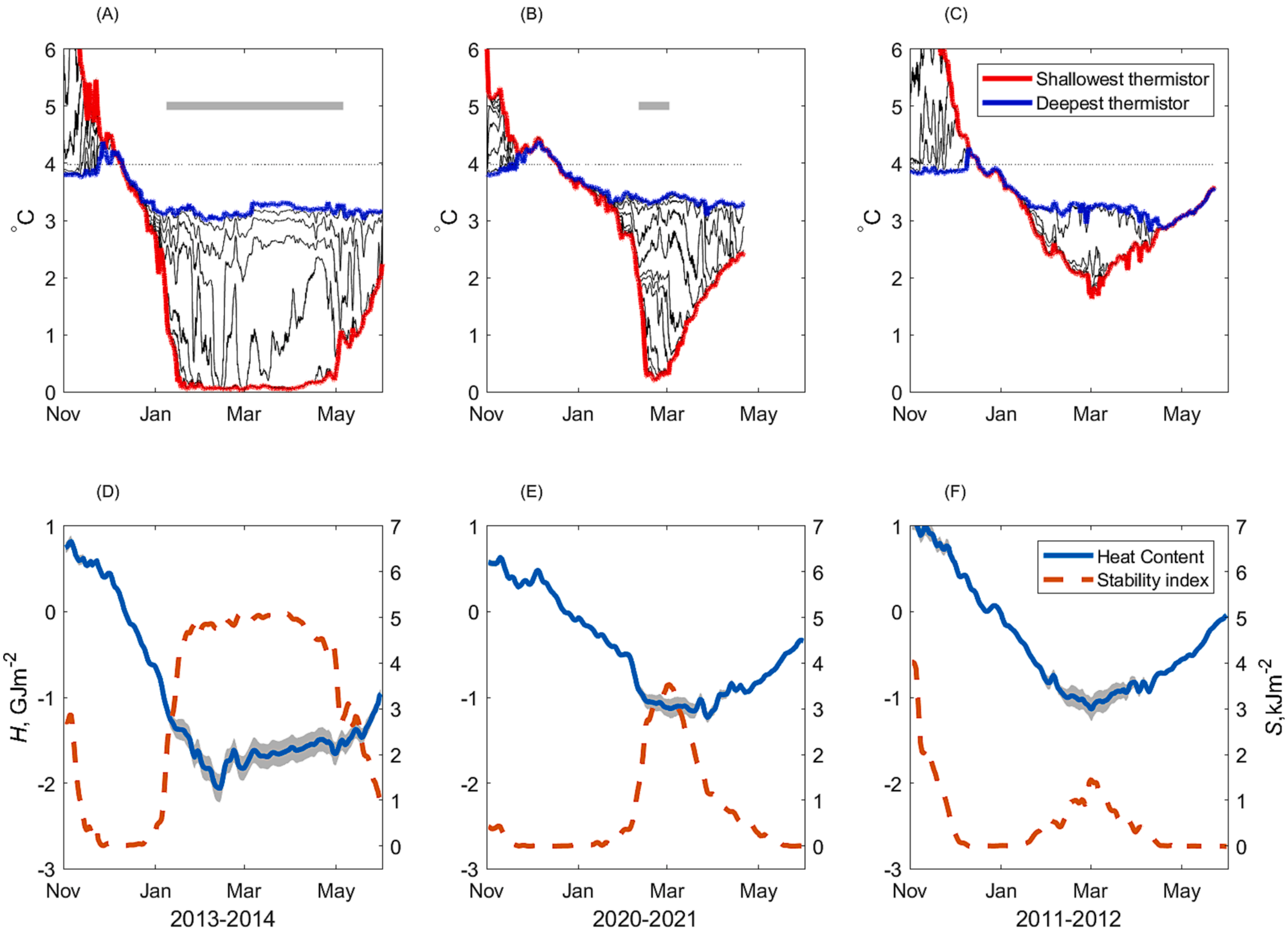

Fig. 2. Lake Superior (WM site) temperatures (A, B, C) and heat content and stability index (D, E, F) in the cold winter of 2013–2014 (A, D), an average winter (B, E), and the warm winter of 2011–2012 (C, F). On the temperature plots, the shallowest thermistor is plotted in red, and the deepest in blue. Gray bar on temperature plots represent period of ice present. Gray shaded area on the heat content estimates represents the uncertainty due to the choice of vertical bin size. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

driver of surface heat fluxes (a mooring was deployed in the northern basin of Lake Michigan in Fall 2024). Therefore, making a blanket statement that, for instance, Lake Michigan does not form winter stratification may be premature. We show here that not only can the existence of winter stratification vary in a given year between shallow and deep sites in a given lake, but that the character of stratification at a given location may vary from year to year. This variability suggests that traditional labels that limnologists have historically applied to lakes to describe annual cycles of stratification need either to be qualified or not used to describe these lakes.

2. Methods

The data used in this paper are summarized in Tables 1–3 and presented in Electronic Supplementary Material (ESM) Fig. S1–S16; we believe this to be a comprehensive list of publicly available winter mooring data in the Great Lakes. In the case of data collected by LLO (Table 1, Fig. 1), multiple locations have been occupied in Lake Superior for several years. The LLO site in western Superior (WM; ESM Fig. S2) is the second longest occupied site in the Great Lakes, spanning 2006–present, but it is missing 2010 due to a mooring failure. A thorough description of the LLO-associated Lake Superior data can be found in Austin and Elmer (2022), and all data are available in an online archive (Austin and Elmer, 2021; Elmer and Austin, 2022). These moorings consist of multiple thermistors spanning the water column, typically with higher vertical resolution in the upper water column where stratification tends to be stronger. The number and model of thermistors on each mooring varies, with typical moorings carrying 12–15 thermistors. Deployments since 2008 have primarily used RBR TR-SOLO thermistors with a stated accuracy of 5 mK. In 2021 and 2022, the WM mooring was deployed with 91 thermistors, providing unprecedented vertical resolution. Many of the moorings also carried Acoustic Doppler Current Profilers (ADCPs) among other sensors, the data from which are not discussed here.

GLERL provides data from four lakes: Superior, Michigan, Huron, and Erie (Table 2; Fig. 1). The Lake Michigan site (ESM Fig. S11), located in the southern basin of the lake, has the distinction as the longest whole water column, year-round time series in the Great Lakes; however, years before 1996 do not adequately span the water column and are not used. In addition, data are available only below 110 m in 2014 and 2015 due to a mooring failure, and hence they are not useful for determining stratification status. In addition, temperature data from the winter of 1982–1983 are available at two sites in Lake Michigan (Gottlieb et al., 1989; ESM Fig. S11). A single mooring in Lake Huron has been deployed since 2012 (ESM Fig. S13), providing 10 years of winter data. Data from two moorings in Lake Erie in the winter of 2004–2005 are available (ESM Fig. S14), collected as part of the International Field Year for Lake Erie. All of these data are available at GLERL's website, and the Superior, Michigan, and Huron data are also available at the National Center for Environmental Information.

Starting in 2021, moorings deployed at 13 locations as part of the Great Lakes Acoustic Telemetry Observation System (GLATOS)

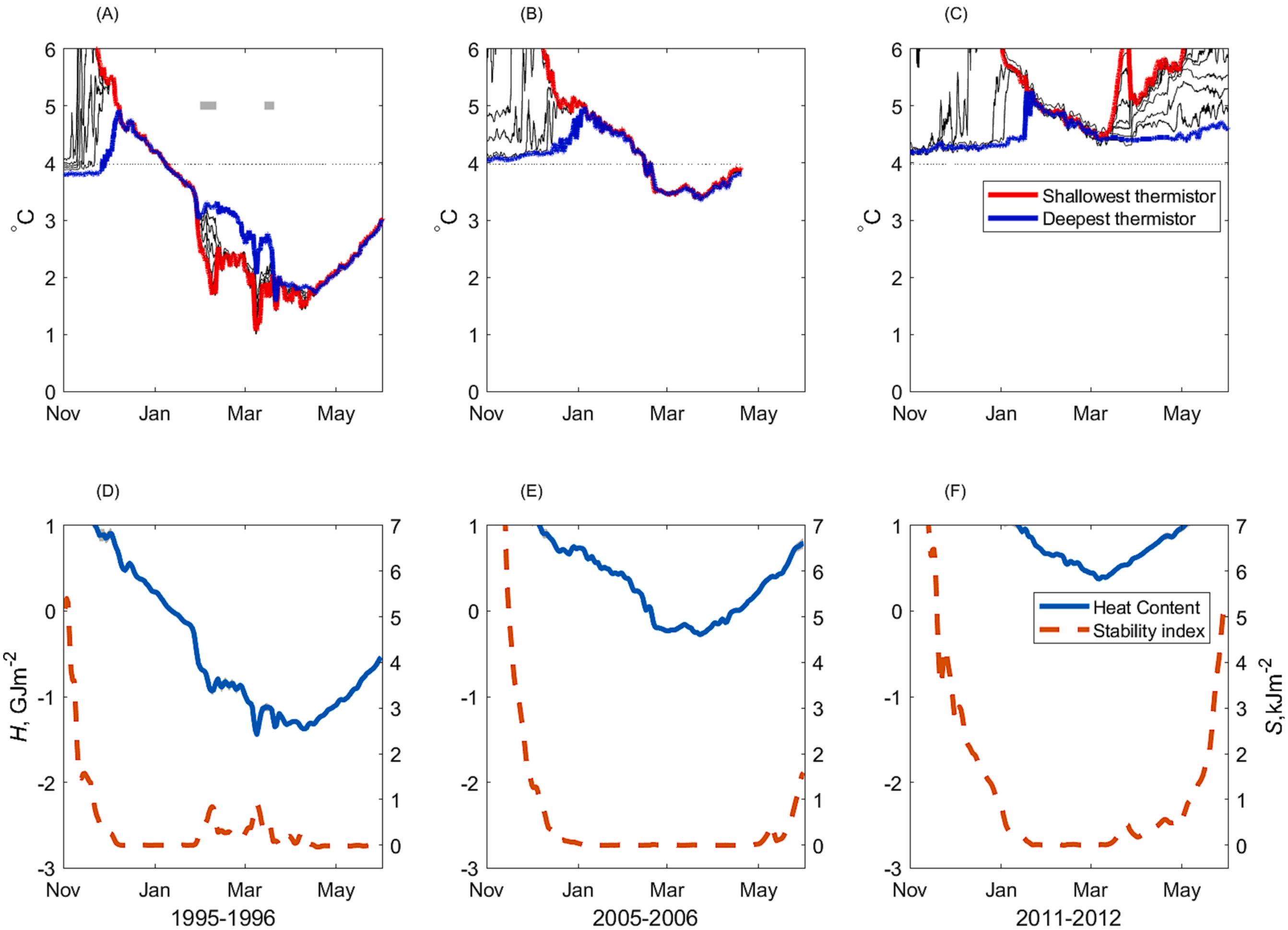

Fig. 3. Lake Michigan temperatures (A, B, C) and heat content and stability index (D, E, F) in the cold winter of 1995–1996 (A, D), an average winter (B, E), and the warm winter of 2011–2012. On the temperature plots, the shallowest thermistor is plotted in red, and the deepest in blue. Gray bar on temperature plots represent period of ice present. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

hydroacoustics array in Lake Ontario were supplemented with thermistors, providing year-round and whole water column temperature data (Table 3; Fig. 1; ESM Fig. S14, S15). These moorings generally had 10–12 thermistors in the vertical, consisting of a near-surface HOBO water level data logger (accuracy ± 0.44 °C) and then deeper Onset HOBO UTBI-001 TidbiT v2 loggers (accuracy ± 0.2 °C). The thermistors added to these platforms were concentrated in the upper portion of the water column near the summer thermocline depth, and the only deep temperature measurements were made by the hydroacoustics sensors at the bottom of each mooring. These Innovasea VR2AR and VR2Tx 69 kHz acoustic receivers are primarily used for monitoring fish acoustic tags in Lake Ontario as part of GLATOS (Krueger et al. 2018). These receivers record ambient temperature primarily to estimate sound speed; the stated accuracy of the thermistors used in the Innovasea receivers is ± 0.5 °C, and the sampling frequency was 1 h. Unfortunately, these instruments used for the deep temperature measurements were not calibrated to the standard of the other instruments and showed constant offsets from the next deepest measurement made by the more accurate HOBO temperature loggers. Since it is reasonable to expect that the water column spends at least part of the winter well mixed, these deep temperatures were manually adjusted by adding a constant value, typically on the order of 0.5–1 °C. The relatively coarse vertical resolution of these measurements results in larger uncertainty when estimating parameters such as heat content and stability. As there are only 2 years of data available, the data are not useful for comparisons to the other lakes. On the other hand, having multiple sites allows for useful spatial comparisons in the 2 years.

To determine the nature of local thermal structure, two primary metrics are computed: the one-dimensional heat content and the Schmidt Stability Index. Each was calculated for each mooring site as a function of time. Hypsometric corrections are not applied (and may not be appropriate for lakes where horizontal temperature structure may be significant) but would not change the primary results of this work. The local heat content of the water column relative to the depth-dependent temperature of maximum density (T_{MD}; Chen and Millero, 1986) is determined using:

$$H(t) = \int_{-D}^{0} \rho c_p (T(t,z) - T_{MD}(z)) dz$$

where z is the vertical coordinate (m), defined with z = 0 m at the surface and positive upward, D is the water depth (m), T is water temperature (°C), ρ the water density (kgm^{-3}), c_p the specific heat (Jkg^{-1}K^{-1}), and H the heat content (Jm^{-2}). Estimating this value relative to T_{MD} results in positive values for temperature profiles above T_{MD} and negative below. This can be discretized for discrete data (such as temperature data from a mooring) using:

$$H(t) = \sum_{i=1}^{N} \rho c_p (T_i(t) - T_{MD}) \Delta z_i$$

where temperature T_i is measured at N different depths, and the Δz_i represent the amount of the water column each measurement is

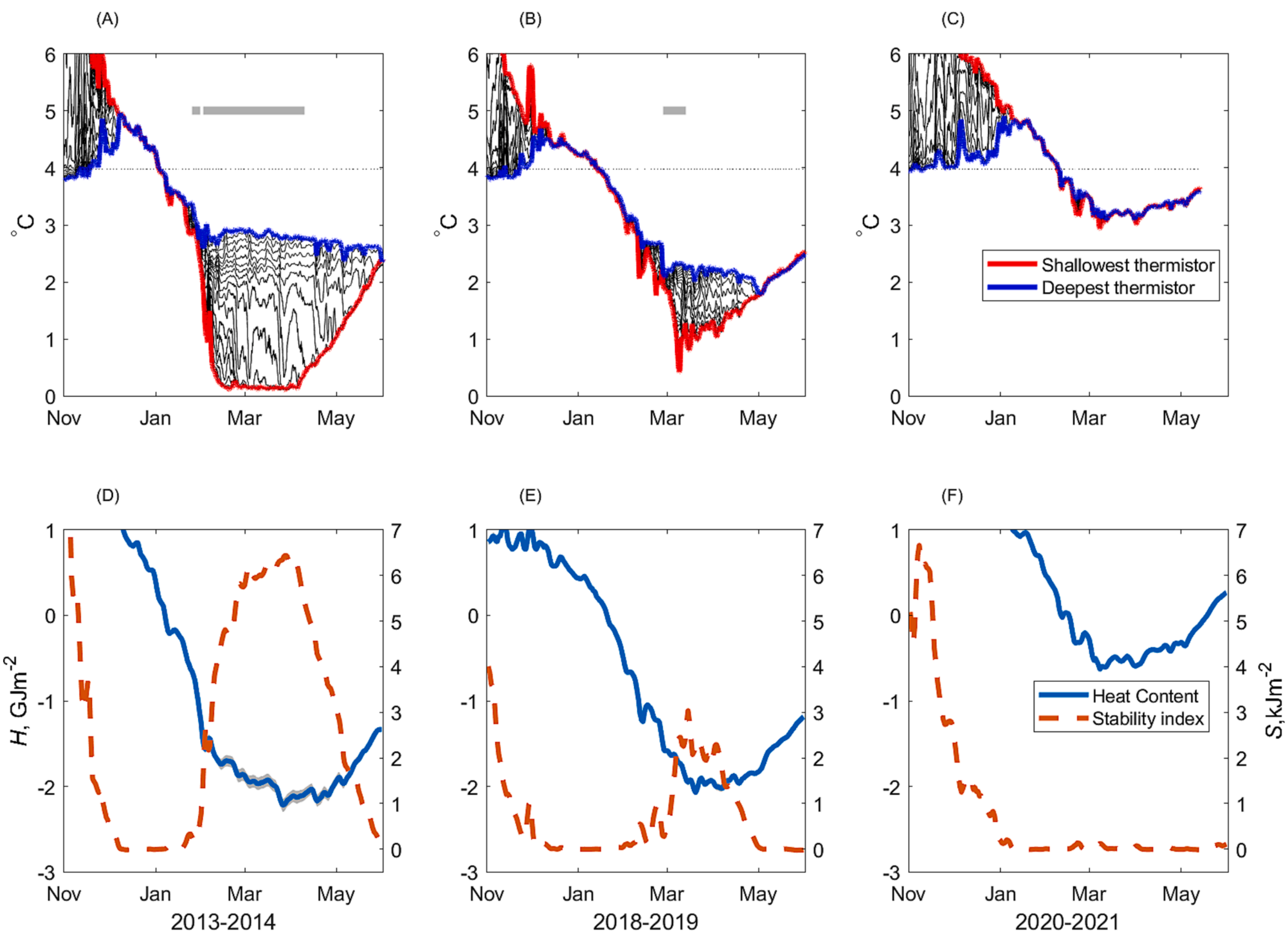

Fig. 4. Lake Huron temperatures (A, B, C) and heat content and stability index (D, E, F) in the cold winter of 2013–2014 (A, D), an average winter (B, E), and the warm winter of 2021–2022. On the temperature plots, the shallowest thermistor is plotted in red, and the deepest in blue. Gray bar on temperature plots represent period of ice present. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

estimated to be representative of, and:

$$D = \sum_{i=1}^{N} \Delta z_i$$

Temperature is extrapolated to the surface and bottom using temperature measured at the shallowest and deepest thermistor, respectively. The determination of the Δz_i introduces uncertainty in the estimation of the heat content, although stability requirements significantly constrain the potential range of heat content for a given distribution of temperature. The uncertainty in the determination of H is small compared to, for example, annual and interannual variability in H. When the water column is well mixed, the determination of the Δz_i introduces no uncertainty. While the formation of ice also plays a role in the heat budget, the amount of heat that needs to be removed to form ice is relatively small compared to the heat budget of the liquid water column. While there are few estimates of open lake ice thickness (Hawley et al., 2018; Titze and Austin, 2016), we can compute the amount of heat per unit area that would need to be lost to form, for example, 0.1 m of ice:

$$Q = L_F \rho_{ICE} \tau = (3.3 \times 10^5 \mathrm{Jkg}^{-1})(910 \mathrm{kg\ m}^{-3})(0.1\mathrm{m}) = 3 \times 10^7 \mathrm{Jm}^{-2}$$

where L_F is the latent heat of fusion of water (Jkg^{-1}), ρ_{ICE} is the density of ice (kgm^{-3}), and τ is thickness (m). This amount is relatively small compared to a typical minimum heat content on the order of -1×10^9 Jm^{-2}. The fact that heat loss associated with ice formation is small is fortuitous given that ice thickness data are not available. The exception to this may be the shallower parts of Lake Erie, which form significant ice cover in most years. In western Lake Erie, where the mean depth is roughly 10 m, the minimum possible heat content for the water column relative to T_{MD} is on the order of -1.6×10^8 Jm^{-2}, equivalent to about 0.5 m of ice, suggesting that the freezing of water into ice may be a significant part of the winter heat budget in this case.

The Schmidt Stability Index (S, Jm^{-2}) is defined (Idso, 1973; Read, 2011) as:

$$S(t) = g \int_{-D}^{0} (z - z_{CV}) \rho(z,t) dz$$

where $g = 9.80$ ms^{-2} is acceleration due to gravity, z_{cv} the center of volume of the water column, and ρ the water density as a function of space and time. For depth-discrete data, this can be rewritten as:

$$S(t) = g \sum_{i=1}^{N} (z_i - z_{CV}) \rho_i(t) \Delta z_i$$

This value can be interpreted as the amount of mechanical energy required to mix the water column to isothermy. It is always positive; the larger this value is, the more stably stratified the water column is, and hence more difficult to mix. If this value is zero, the water column is unstratified.

To determine representative meteorological conditions for each lake, data from a recent compilation of daily, subbasin-averaged coastal air temperature measurements from 1897 to 2023 (Fujisaki-Manome et al., 2024) were used. Coastal meteorological data may not be entirely

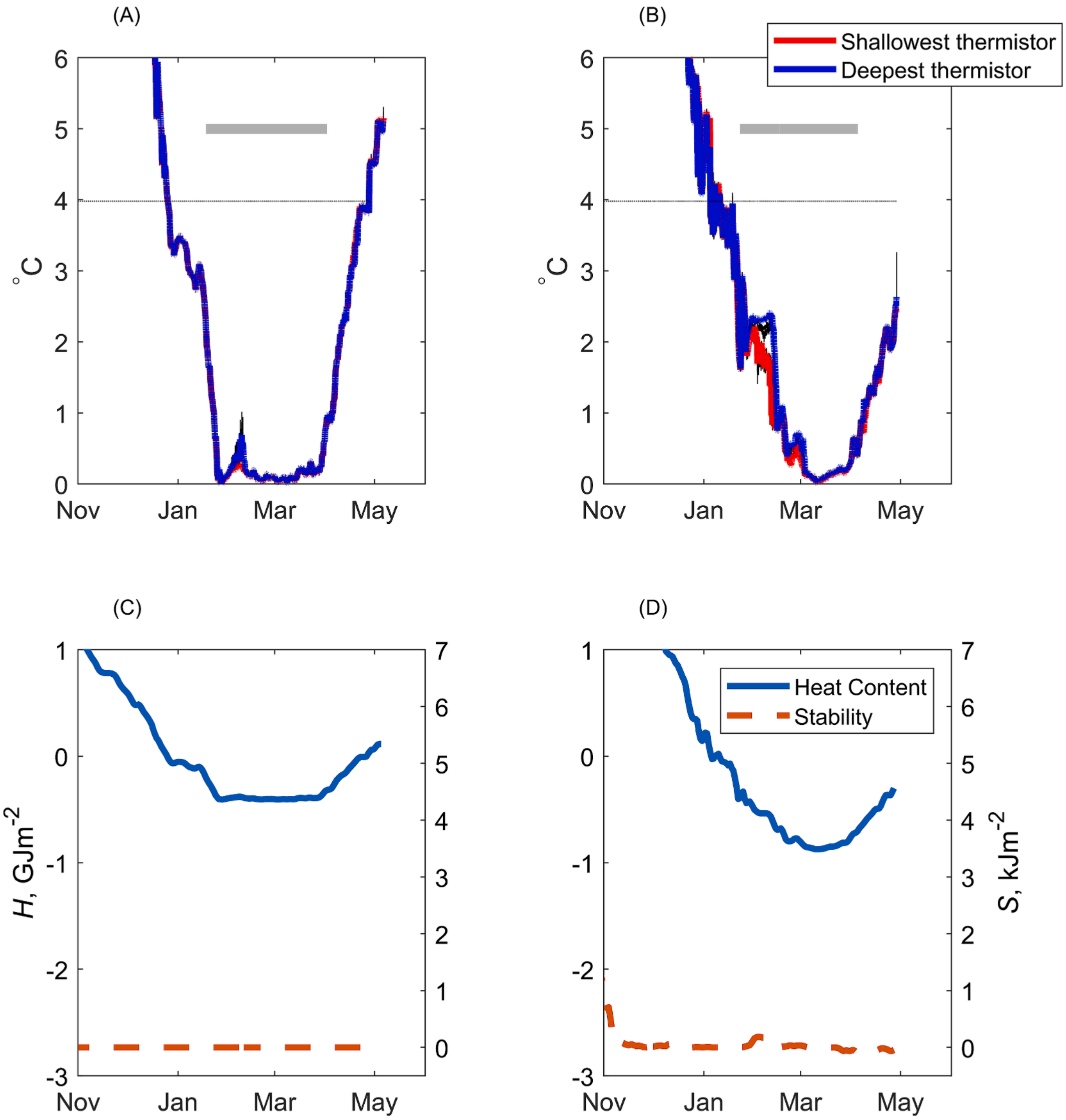

Fig. 5. Lake Erie temperatures (A, B) at GLERL-T07 and GLERL-T12 and heat content and stability index (C, D) in the winter of 2004–2005. Gray bar on temperature plots represent period of ice present.

representative of the meteorological conditions over the lake (Schwab and Morton, 1984), which makes direct comparisons of conditions between lakes difficult. However, coastal air temperatures do appear to be a useful indicator of interannual variability at a fixed site, as will be explored.

Ice data were taken from GLERL's site (https://www.glerl.noaa.gov/data/ice/#historical), which gets data from the National Ice Center and the Canadian Ice Service (collectively, the North American Ice Service; NAIS). Daily ice data are available with a spatial resolution of 1.8 km. Ice cover at a specific location was determined by averaging daily fractional ice coverage at all grid cells within 10 km of the site in question. Ice is considered present when this value exceeds 0.1.

3. Results

The five lakes exhibit very different winter behavior (Figs. 2–6), and in some cases individual lakes exhibit distinct behavior interannually. For Superior, Huron, and Michigan, for which there are multiple years available, we display 3 years from each lake, choosing a year with a low minimum heat content (for that lake), a year with a "typical" minimum heat content, and one with a high minimum heat content. In the discussion section, we will show that these correspond to winters with below average, average, and above average winter air temperature. These differences in heat content can lead to differences in stratification, with winter stratification more likely to occur in the "cold" years. In addition, we consider the presence or absence of ice at each location and show that ice formation typically occurs only once the upper portion of the water column reaches the freezing point of water, T_F (taken here to be 0 °C). For Ontario and Erie, multiple sites from a single year will be considered.

Examples of winter stratification at the WM site in Lake Superior for a low minimum heat content (2013–2014), typical (2020–2021), and high minimum heat content year (2011–2012) (Fig. 2) suggest that Lake Superior reliably forms winter stratification. Winter stratification forms at all other sites (ESM Fig. S2–S8) and other years at WM, with the exception of the shallow 45027 and 45028 sites in the western arm of Superior, which do not form persistent winter stratification, although occasional intrusions of warmer water at the bottom do occur. At those two sites, the water column cools uniformly, reaching T_F in some years. In the case of 2013–2014 at WM, the cold upper layer cools to nearly T_F, at which point ice forms (the grey bars represent the period of ice coverage in the vicinity of WM). The heat content for all years at WM (Fig. 7A) displays significant interannual variability, with a minimum winter heat content ranging from −1 GJm^{-2} to nearly −2 GJm^{-2}. The

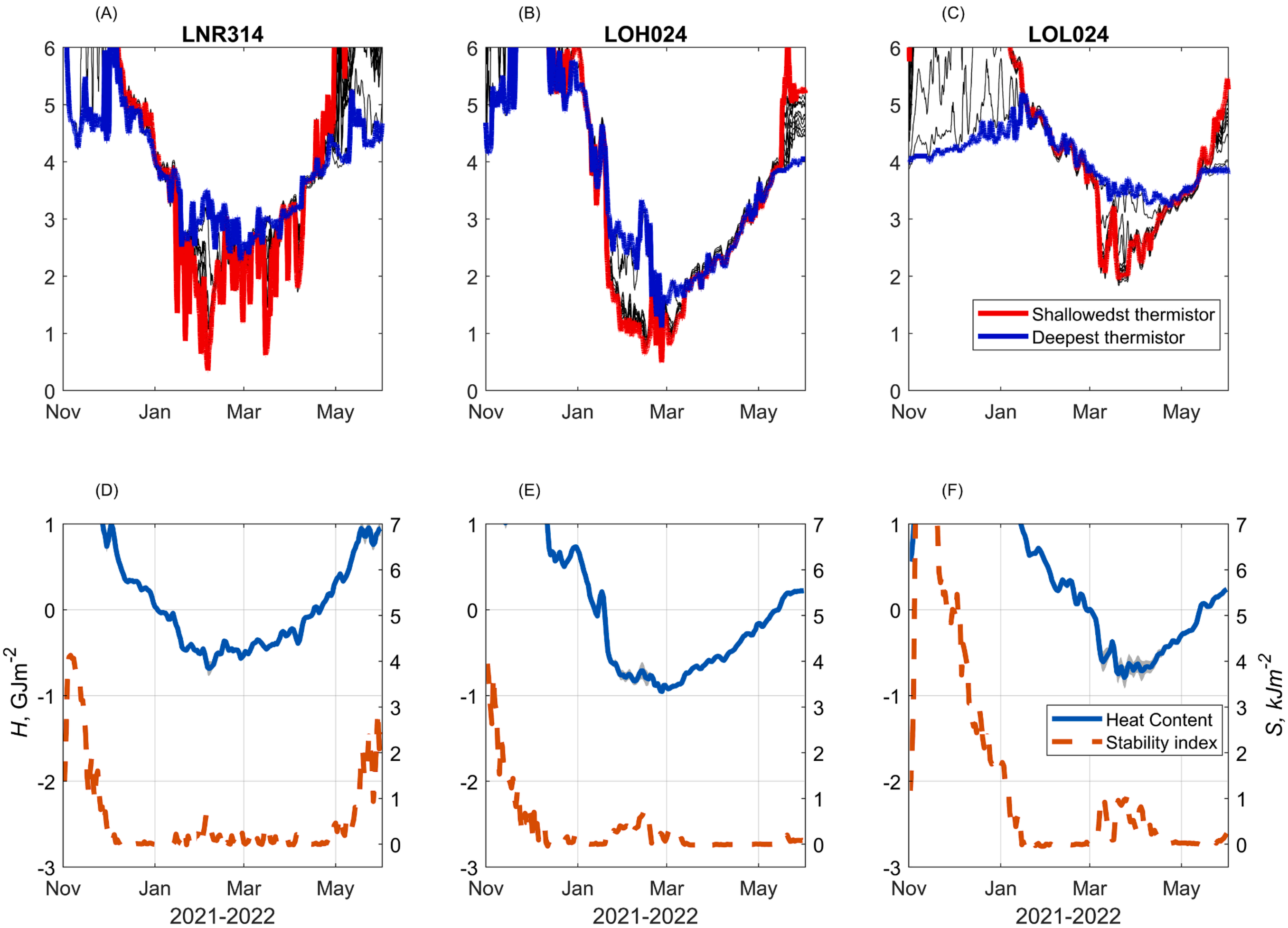

Fig. 6. Lake Ontario temperatures (A, B, C) at LNR314, LOH024, and LOL024 and heat content and stability index (D, E, F) in the winter of 2021–2022.

amount of heat lost below T_{MD} in winter typically exceeds the amount of heat gained above T_{MD} in the summer. The difference between maximum and minimum heat content are consistent with previous estimates (Bennett, 1978; Schertzer, 1978). The stability displayed for all years at WM (Fig. 7D) shows that $S > 0$ Jm^{-2} in late winter in all years, peaking in early March. Similar plots for all other sites in Superior except for the two shallow sites (45027 and 45028) display similar properties. Stability is much greater in the summer due to the much larger temperature (and hence density) differences possible during positive stratification.

In contrast, given the available data, Lake Michigan forms persistent winter stratification only in the winter of 1995–1996 (Fig. 3A; ESM Fig. S10), during which a small amount of stratification formed for about a month (with the caveat that data are not available for winter 2013–2014 and 2014–2015, two anomalously cold years). In 2005-–2006 (Fig. 3B), the temperature drops below T_{MD} but does not form stratification, which is typical at this site. In the warm winter 2011–2012 (Fig. 3C), temperature at this site fails to cool to T_{MD}, although the water column is well mixed for a period of about 2 months, cooling to about 4.3 °C before starting to form the next year's positive summer stratification. The heat content from the Michigan site (Fig. 7B) shows multiple years in which the heat content relative to T_{MD} does not reach zero; very cold years tend to achieve roughly -1GJm^{-2} at the seasonal minimum. Unlike Superior, significantly more heat is gained above T_{MD} in the summer than is lost below T_{MD} in the winter. The stability index shows that significant stratification rarely occurs, with the caveat that the 2013–2015 data are not included here. The significantly warmer annual cycle of heat content here is a consequence of the site (Fig. 1) being roughly 5° of latitude (500 km) further south than the Superior site. The average December–February (DJF) air temperature in the Lake Michigan sub-basin is roughly 5 °C warmer than for Superior (Fujisaki-Manome et al., 2024). It may be that the mooring site is not entirely representative of Lake Michigan; given its great meridional extent and the much deeper northern basin, the northern portion of the lake may stratify more reliably in the winter, but data are not currently available to address this. In the winter of 1982–1983 (Gottlieb et al., 1989), data from moorings in both the north and south of the lake showed a lack of winter stratification (ESM Fig. S11), suggesting that the lack of stratification in Michigan may not be a new phenomenon, although air temperature in the winter of 1982–1983 was above normal (Fujisaki-Manome et al., 2024).

Lake Huron, intriguingly, sits between these two behaviors, displaying robust stratification in some years and none in others. In the "polar vortex" winter of 2013–2014, the lake forms strong winter stratification and cools off sufficiently to form ice (Fig. 4A). The minimum heat content is actually lower than that for Superior in the same year. In a typical year in Huron, some persistent winter stratification will form (Fig. 4B), but in seven years of the 11 winters of data available, stratification does not form (ESM Fig. S12). At nearly 2 GJm^{-2}, the range of minimum heat content in Huron and Michigan (Fig. 7C) is significantly greater than that of Superior, which is roughly 1 GJm^{-2} (this remains unexplained). The stability index (Fig. 7F) shows some years where $S = 0$ GJm^{-2} for the entire winter season and others when $S > 0$ GJm^{-2}, indicating the formation of stratification. Maximum values of S in cold years are similar to those in Superior.

In 2004–2005, two sites were monitored in Lake Erie (Fig. 5). Both

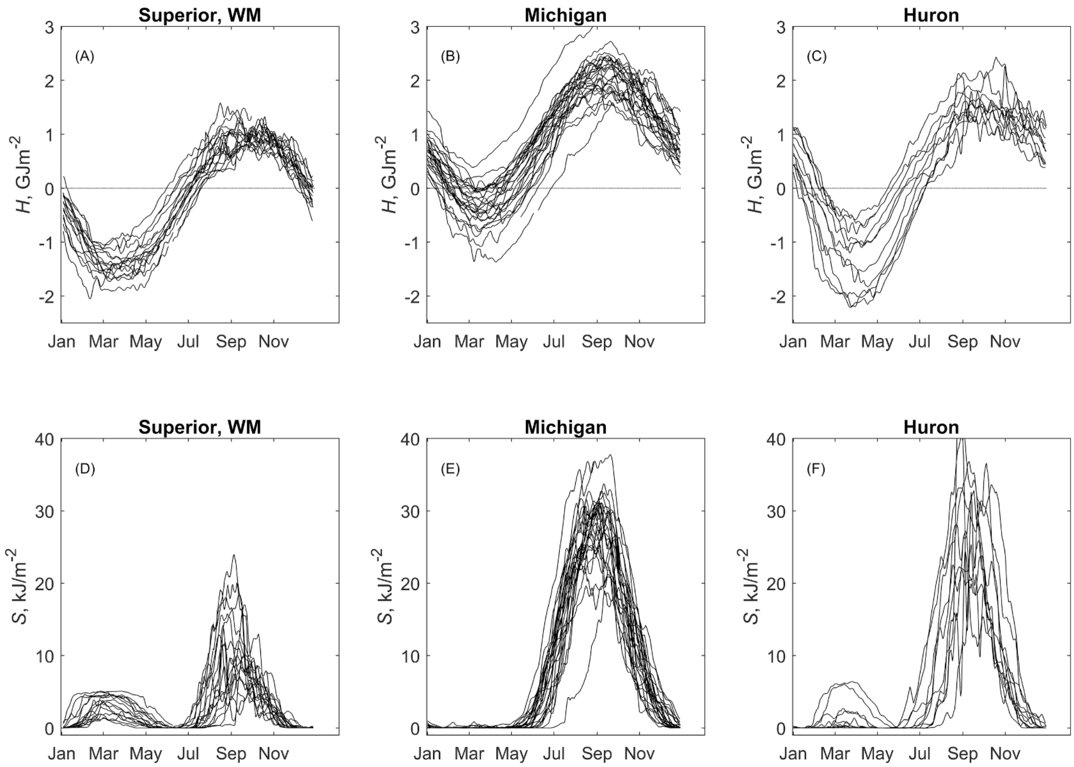

Fig. 7. Heat content (A, B, C) and stability (D, E, F) at Superior WM (A, D), GLERL-MM (B, E), and GLERL-HU (C, F).

sites cool off uniformly with the shallower site reaching T_F more quickly than the deeper site, resulting in the formation of ice. Sporadic stratification occurs at the deeper site, but it quickly destratifies and cools to T_F. This is similar to other observations of Erie winter behavior (Hawley et al., 2018) in which bottom water temperature drops to T_F prior to ice formation. For reasons that will be discussed, this is likely typical behavior for Erie (and other shallow sites) in the winter. At GLERL-T12, ice is present prior to the water column reaching T_F, suggesting that advective processes may be bringing colder water to the location, rather than local cooling occurring at the site.

In Lake Ontario, no sites form winter stratification in 2022–2023 (ESM Fig. S15, S16). In 2021–2022, a few sites form modest stratification (Fig. 6). Shallow sites tended to not form any stratification, similar to the response observed in Lake Erie. A coastal site (LNR314) near the outlet of the Niagara River (Fig. 6A) repeatedly forms inverse stratification that fails to persist. This is likely some manifestation of the cold Niagara plume that floats over the warmer water of Lake Ontario, rather than local formation of stratification. Two other relatively deep sites (LOH024, 85 m, and LON024, 114 m) (Fig. 6B, 6C) form modest but persistent winter stratification. Oddly, the timing of stratification at the two sites is different, with the shallower and more northerly LOH024 site stratifying first. By the time stratification forms at LOL024, most of the stratification at LOH024 has been mixed away. Minimum heat content at LOH024 occurs measurably earlier than at LOL024.

4. Discussion

4.1. Intra-lake comparisons

Multiple sites were occupied in Lake Superior and Ontario. A comparison of heat content during a 2-year period (2011–2012) (Fig. 8A) during which seven sites were occupied in Superior nearly continuously show distinct grouping of winter heat content behavior. In both years, five of the sites (FWM, WM, CM, EM, NM) are virtually indistinguishable from each other. Two more sites, SM and FEM, both deep sites in the far southeast portion of the lake are similar to each other in both years and display a significantly lower winter heat content. Finally, the shallow site 45027 has a much higher minimum heat content, largely because in shallow water, only so much heat can be lost from the water column before the entire water column is at T_F; at this point, ice will form in response to any additional lost heat, limiting how low the water column heat content can become. A comparison of H_{MIN} and WM and GLERL-SU (Fig. 9A), two Lake Superior stations with multiple years of data and a separation distance of roughly 350 km, shows strong interannual coherence within Superior. In Lake Ontario (Fig. 8B), heat contents are lower in the 2021–2022 winter, and there is remarkably little variability in heat content between the 13 sites (not all sites were occupied in both years), given the range of depths occupied (33–168 m).

4.2. Inter-lake comparisons

Correlation of interannual minimum heat content among lakes is weaker, as might be expected given the greater spatial separation. Annual minimum heat contents in Michigan are higher than in Superior as expected (Fig. 9B), and there is a much greater range of minimum heat content than in Superior. While the relationship between the two is weak, 2012 appears to have been anomalously warm in both lakes. The relationship between Superior and Huron (Fig. 9C) is similarly weak, though both anomalously warm and cold years do appear to be related. In many cases, the minimum heat content in Huron is lower than those in Superior, which is remarkable considering that the Huron site is significantly further south than the Superior site; the average winter (DJF) air temperature in the Huron sub-basin is, on average, about 4 °C warmer (Fujisaki-Manome et al., 2024). As with Michigan, the range of minimum heat contents in Huron is significantly greater than in Superior. Bennett (1978) compares the “heat incomes” of the five lakes, though it is not made clear what data are used for this analysis. He defines the spring heat income to be the amount of heat necessary to bring the lake from its minimum winter heat content to T_{MD}, the summer heat income to be the amount of heat to bring the lake from T_{MD} to the

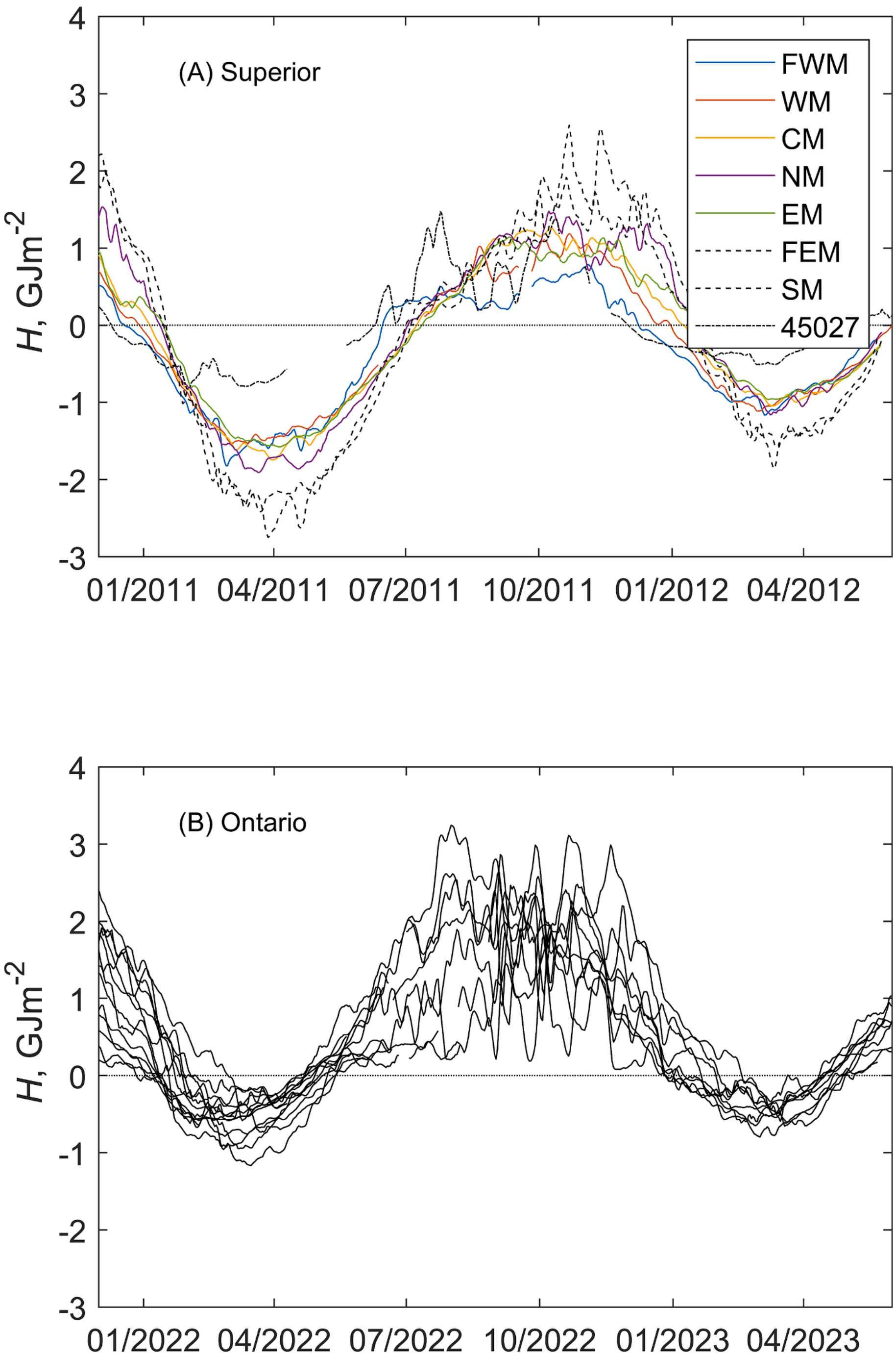

Fig. 8. Heat content at seven sites in Lake Superior, 2011–2012. (B) Heat content at multiple sites, Ontario.

maximum summer heat content, and the annual income the sum of these two (the difference between minimum and maximum annual heat content in a given year). He observed that while the summer heat incomes appear similar across all five lakes, the spring incomes tend to be a function of depth, with deeper lakes having greater spring incomes. While the estimated incomes are roughly the same order of magnitude in Bennett (1978) and this work, the results here are contrary to this, with summer incomes differing significantly between Superior, Huron, and Michigan (Fig. 7). The smallest summer incomes occur in Superior and the greatest in Michigan. In general, this is because Superior water temperatures reach T_{MD} later than the other lakes, and Michigan earlier. Relating spring incomes to depth between lakes is difficult because the Huron site, for instance, is deeper than the WM site in Superior, although Superior is on average deeper than Huron. A comparison of simultaneous minimum heat contents within Superior (Fig. 8) suggests that spring heat incomes at five sites ranging in depth from 170 m to 257 m are very similar, so that there does not appear to be a strong dependence of summer income on depth, at least within an individual lake.

4.3. Threshold for winter stratification

There is a strong relationship between minimum heat content and maximum stability in Lake Superior (Fig. 10A), which suggests that there is a threshold amount of heat that needs to be lost before winter stratification can form. This threshold is on the order of -1 GJm^{-2}, and this value appears similar in all lakes (Fig. 10A, B). Note that these three

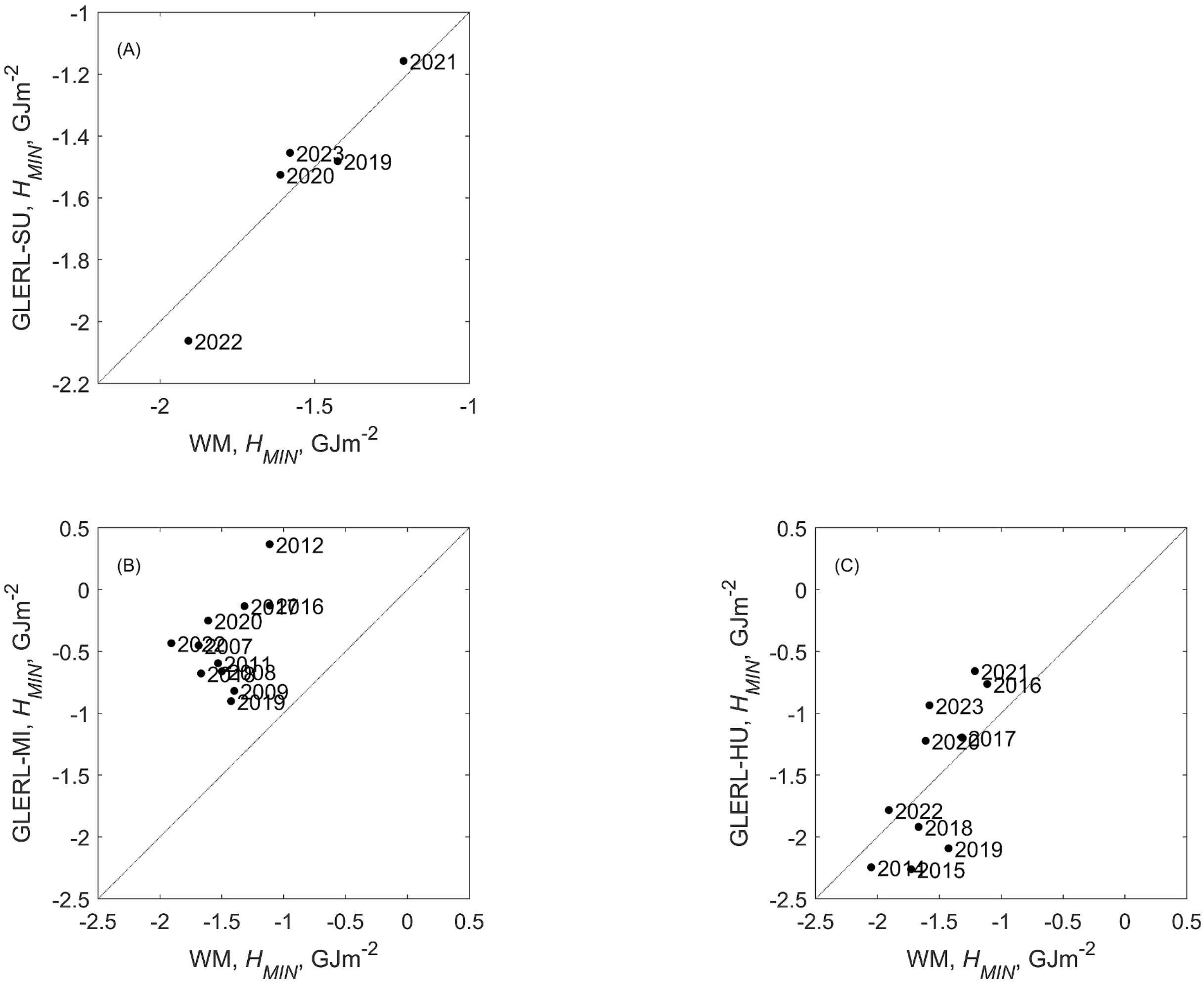

Fig. 9. (A) Interannual variability in minimum heat content between two sites in Lake Superior. (B) Interannual variability in minimum heat content between Superior site WM and the Lake Michigan site. (C) Interannual variability in minimum heat content between Superior site WM and the Lake Huron site.

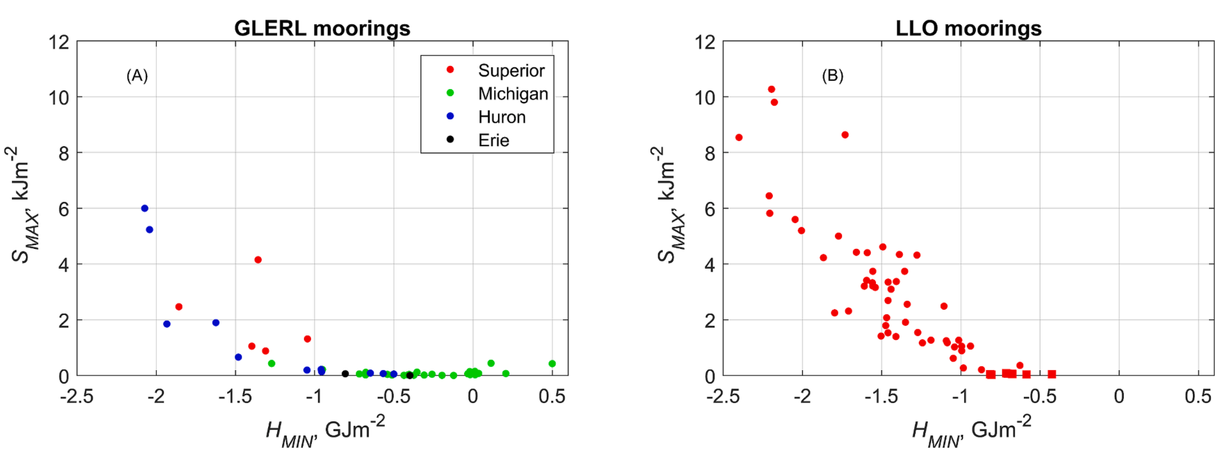

Fig. 10. (A) Maximum stability as a function of minimum heat content at GLERL sites, all years. (B) Maximum stability as a function of minimum heat content at all LLO sites, all years.

sites have similar depths (Superior: 185 m; Huron: 200 m; Michigan: 150 m). The threshold value should depend on the character of the wind field; a less windy environment should result in an earlier onset of stratification (i.e., at a less negative threshold heat content) (Austin, 2024) and delayed formation of stratification in the case of stronger winds. The fact that all three lakes appear to have roughly the same heat content threshold suggests that they have similar wind environments.

4.4. Atmospheric drivers

The minimum heat content in each lake is a strong function of winter (DJF) air temperature (Fig. 11), as expected (e.g., Piccolroaz et al.,

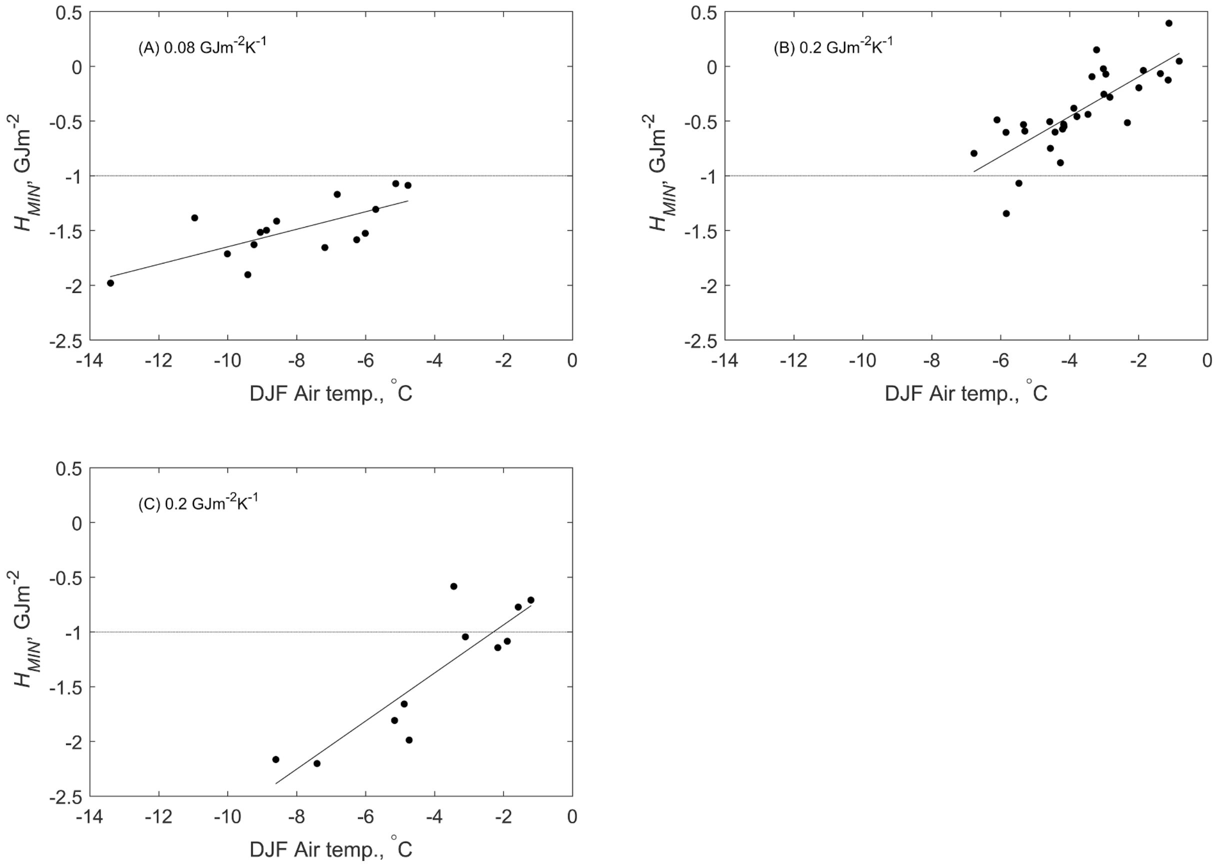

Fig. 11. Minimum annual heat content in (A) Lake Superior, (B) Lake Michigan, and (C) Lake Huron as a function of December–February (DJF) air temperature. Number on plot represents the slope of the best linear fit of minimum heat content as a function of air temperature. Horizontal dashed lines represent the empirical threshold of −1 GJm^{-2} for the formation of winter stratification.

2013), with colder winters resulting in lower minimum heat contents. Understanding what drives differences in stratification regimes between lakes is difficult to do systematically, since the relationship between the basin-averaged air temperature and a given mooring site is going to be site-specific. However, it does appear that the sub-basinwide averages capture interannual variability within a lake. The relatively small range of heat content observed at WM compared to other lakes is apparent; in addition, while winter air temperature is clearly a driver of minimum heat content, the Superior WM site is significantly less sensitive to interannual differences in air temperature than the sites in Michigan and Huron, both of which show a similar sensitivity to interannual variability in average winter air temperature. Superior tends to form stratification at warmer water temperatures than Michigan and Huron, which may lead to earlier ice formation and a shut down of the latent and sensible fluxes, which dominate the surface heat flux in the winter, resulting in lessened sensitivity to air temperature. The earlier onset of stratification in Superior is an outstanding question; Austin (2024) suggests that periods of extremely cold, calm air are necessary for the onset of stratification; it may be that Superior, given its more northerly location, is more likely to get periods of cold calm conditions than Michigan or Huron.

4.5. Vertical structure

Vertical profiles from WM in Superior (17 winters), Michigan (24 winters), and Huron (10 winters) on 15 March, which tends to be around the time of minimum heat content in all lakes (Fig. 12), clearly illustrate differences in stratification. The dashed line in each panel is T_{MD}, which decreases with depth from 3.98 °C at the surface at a rate of about 0.2 °C/100 m (Chen and Millero, 1986). There are multiple years in Michigan when the water remains warmer than T_{MD}, and in most cases, little if any stratification forms. In Superior and Huron, years with ice cover are characterized by a deep surface mixed layer on the order of 50–100 m thick with water cooled to about 0.1 °C, just above T_F. Deep temperatures are warmest in Lake Superior, which are typically above 3 °C, whereas there are multiple years in both Michigan and Huron where deep temperatures fall significantly below 3 °C.

4.6. Implications of the heat content threshold

The existence of a stratification formation threshold (Fig. 10) places a potential lower limit on how deep water needs to be for stratification to form. At a given location, the lake must be able to lose at least 1 GJm^{-2} through the cooling of water before forming stratification. Therefore, a simple scaling can be used to determine the minimum depth required to form stratification given a particular threshold heat content:

$$D_{MIN} = \frac{H_{CRIT}}{\rho c_p (T_{MD} - T_F)} = \frac{(1 GJm^{-2})}{(1000 kgm^{-3})(4.2 \times 10^3 Jkg^{-1}K^{-1})(4^\circ C - 0^\circ C)} \approx 60m$$

where H_{CRIT} is the critical heat content threshold. This criterion implies that, in the winter wind environment of the Great Lakes, it is unlikely that winter stratification will form in water shallower than 60 m; the water column will reach T_F and start forming ice before the threshold heat content value for forming stratification is reached. This is broadly consistent with our limited observations. The two Superior sites and the two Erie moorings that are shallower than 60 m do not form stratification in the years for which we have data; instead, they cool off uniformly, and if they reach T_F, they start forming ice before the onset of

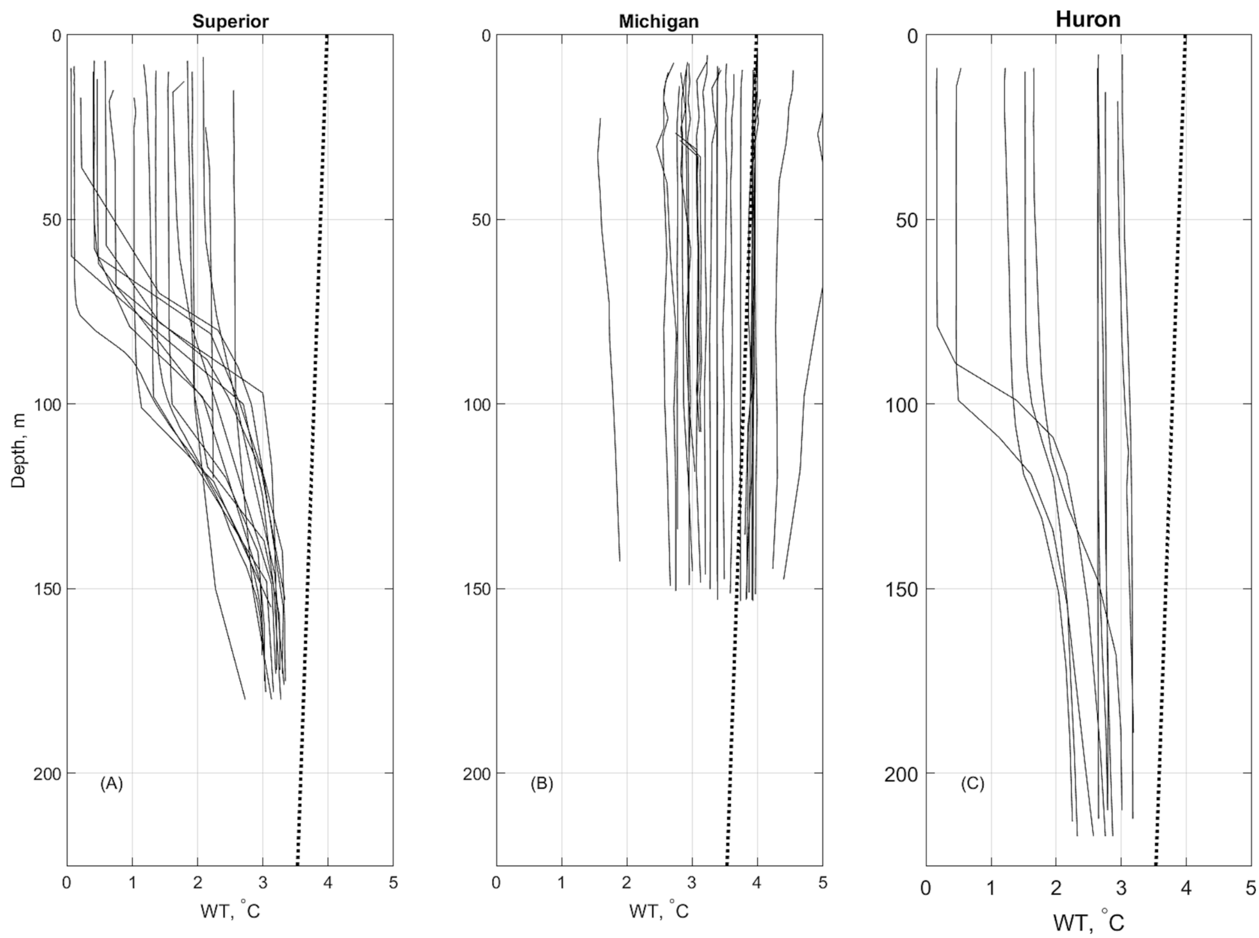

Fig. 12. Vertical structure of temperature on 15 March in (A) Superior WM (17 winters), (B) Michigan (GLERL-MI) (24 winters), and (C) Huron (GLERL-HU) (10 winters). Heavy dashed line on all plots is T_{MD}.

stratification. Conversely, all other sites for which the heat content falls below H_{CRIT} form stratification.

4.7. Hindcasting stratification

The existence of a database of air temperatures spanning over a century, the strong relationship between heat content (for Lakes Superior, Michigan, and Huron; Fig. 11), and the empirical threshold for the formation of winter stratification (Fig. 10) provides an opportunity to speculate about the long-term stratification behavior of these lakes. Extracting DJF air temperatures from the historical database (Fujisaki-Manome et al., 2024) and applying the relationships between DJF-averaged air temperature and heat content (Fig. 11) results in estimates of minimum heat content in each winter from 1897 to 2023 (Fig. 13). Two critical thresholds are displayed as dotted lines: $H = 0$ GJm^{-2}, which distinguished between years in which the water column either cools below T_{MD} ($H_{MIN} < 0$ GJm^{-2}) or does not ($H_{MIN} > 0$ GJm^{-2}); and $H = -1$ GJm^{-2}, distinguishing between years in which winter stratification is formed ($H_{MIN} < -1$ GJm^{-2}) and years in which a lake cools below T_{MD} but does not stratify (-1 GJm^{-2} $< H_{MIN} < 0$ GJm^{-2}). Years for which data are available and are used to derive the model are colored red (Fig. 13).

Lake Superior WM reliably meets the criterion for forming winter stratification ($H_{MIN} < -1$ GJm^{-2}) in all years from 1897 to 2023. The character of winter stratification in Michigan varies, in some years likely forming stratification, in other years cooling below T_{MD} but not forming stratification, and in recent years more frequently not cooling to T_{MD}. Prior to 1980, the formation of stratification in Michigan may have occurred regularly, whereas since then, this model suggests that, with the exception of the 2014 “polar vortex” winter, winter stratification no longer forms. Huron typically stratifies, but years when it does not cool sufficiently to form winter stratification are becoming more frequent. The slow transition from one stratification to another in Michigan and Huron have only occurred in the last 2–3 decades. The records available for these two lakes (1996–present for Michigan; 2013–present for Huron) both fall within this window. Drawing conclusions about the stratification status of either of these two lakes using the directly observed temperature data covered in this paper could be misleading; very warm years in Michigan (not cooling to T_{MD}) and Huron (not stratifying) are a relatively recent phenomenon, and in both cases are the result of a long-term trend towards warmer winters.

5. Conclusions

The Great Lakes display distinct winter thermal structure, and each individual lake displays considerable interannual variability in both stability and heat content (excluding Erie and Ontario, for which only one or two years of data are available). Superior, the deepest and furthest north, reliably forms winter stratification (except at shallow sites) and forms ice in cold years. There is coherence in interannual variability between spatially disparate sites within Superior in metrics such as minimum heat content. The single site in southern Lake Michigan rarely forms winter stratification, although data are missing from two of the coldest years during the period of record; in some years, temperatures at this site remain above T_{MD}. Lake Huron forms stratification in some years, stays well-mixed in others, and forms ice in cold

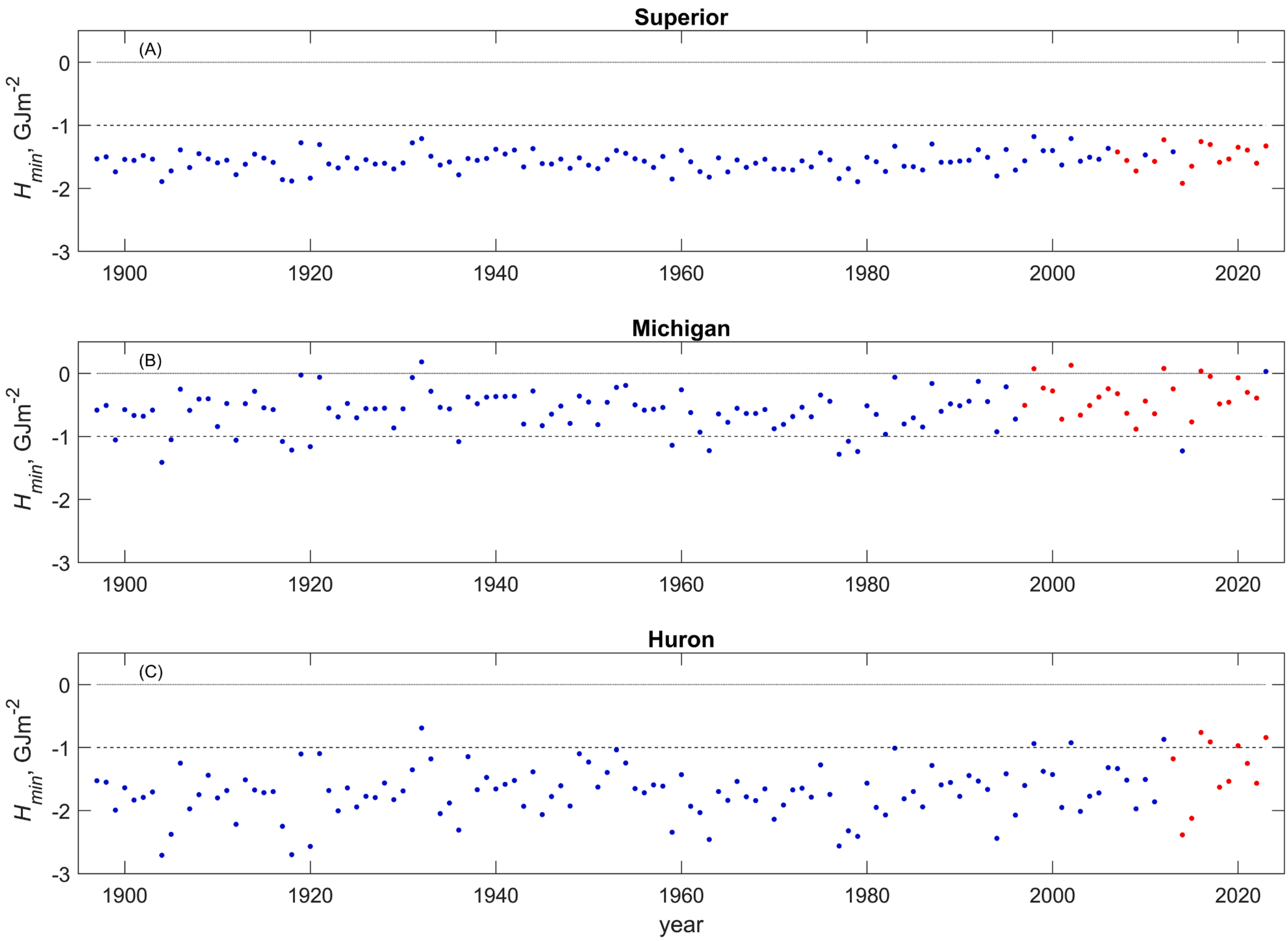

Fig. 13. Hindcast of minimum heat content for (A) Lake Superior WM, (B) Lake Michigan GLERL-MI, and (C) Lake Huron GLERL-HU. Red dots represent years for which data are available and were used to create the model. Upper dashed line indicates $H = 0$ Jm^{-2}; lower dashed line indicates the empirical threshold of $H = -1$ GJm^{-2} necessary for the formation of winter stratification. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

years. While the available data are very limited, in the one year available, the entire water column in Lake Erie cools off to nearly T_F at two sites. Empirically, it appears that all lakes need a threshold amount of heat removed below T_{MD} before winter stratification can form. This threshold precludes the formation of stratification in water shallower than approximately 60 m, which is consistent with the observations presented here. The existence of a threshold heat content for the formation of winter stratification allows us to hindcast likely stratification status, showing that both Michigan and Huron are undergoing a transition in stratification status. The variability of stratification both within an individual lake in a given year and the variability from year to year suggests that traditional stratification categories such as dimictic and monomictic (e.g., Hutchinson and Loffler (1955); Lewis, 1983) cannot be unambiguously applied to these lakes.

CRediT authorship contribution statement

Jay A. Austin: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Eric J. Anderson:** Writing – review & editing, Data curation, Conceptualization. **Andrew D. Gronewold:** Writing – review & editing, Conceptualization. **Steven A. Ruberg:** Writing – review & editing, Data curation, Conceptualization. **Craig A. Stow:** Writing – review & editing, Data curation, Conceptualization. **Mathew G. Wells:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization.

Data availability

All LLO Lake Superior data through 2021 is available at the Data Repository for the University of Minnesota (DRUM), as described and linked to in Austin and Elmer (2022). We are currently compiling a submission of more recent data. All GLERL data are available at GLERL's website and through NCEI. Lake Ontario data are publicly available through the GLOS Seagull platform (https://seagull.glos.org/data-console-datasets/3290c009a7ba4595b6ebef2df6ae4a07).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jglr.2025.102550.

References

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., Hawley, N., 2021. Seasonal overturn and stratification changes drive deep-water warming in one of Earth's largest lakes. Nat. Comm. 12, 1688. https://doi.org/10.1038/s41467-021-21971-1.

Anderson, E.J., Tillotson, B., Stow, C.A., 2024. Indications of a changing winter through the lens of lake mixing in Earth's largest freshwater system, Environ. Res. Lett. 19, 124060. https://doi.org/10.1088/1748-9326/ad8ee0.

Assel, R.A., 1986. Fall and winter thermal structure of Lake Superior. J. Great Lakes Res. 12 (4), 251–262. https://doi.org/10.1016/S0380-1330(86)71725-5.

Aubert, E.J., Richards, T.L. (Eds.), 1981. IFYGL - the International Field Year for the Great Lakes. National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory, US Department of Commerce.

Austin, J.A., 2024. What controls the onset of winter stratification in a deep, dimictic lake? Limnol. Oceanogr. 69, 2791–2800. https://doi.org/10.1002/lno.12704.

Austin, J.A., Elmer, C., 2021. Lake Superior moored temperature and currents, Sep 2005-May 2015. University of Minnesota Duluth, Large Lakes Observatory. Retrieved from the Data Repository for the University of Minnesota. https://doi.org/10.13020/zqw9-mk81.

Austin, J., Elmer, C., 2022. An archive of Lake Superior temperature and current measurements, 2005–2020. Limnol. Oceanogr. Lett. 8, 595–602. https://doi.org/10.1002/lol2.10293.

Bennett, E.B., 1978. Characteristics of the thermal regime of Lake Superior. J. Great Lakes Res. 4 (3–4), 310–319. https://doi.org/10.1016/S0380-1330(78)72200-8.

Boyce, F.M., Donelan, M.A., Hamblin, P.F., Murthy, C.R., Simons, T.J., 1989. Thermal structure and circulation in the Great Lakes. Atmos. Ocean 27 (4), 607–642. https://doi.org/10.1080/07055900.1989.9649358.

Chen, C.-T.-A., Millero, F.J., 1986. Precise thermodynamic properties for natural waters covering only the limnological range. Limnol. Oceanogr. 31 (3), 657–662.

Elmer, C., Austin, J., 2022. Lake Superior moored temperature and currents, Spring 2015 to Spring 2021. Retrieved from the Data Repository for the University of Minnesota. https://doi.org/10.13020/nw8b-mk79.

Fujisaki-Manome, A, Cannon, D., King, K., 2024. Daily mean air temperature data for the North American Great Lakes based on coastal weather stations; 1897-2023 (NCEI Accession 0291722). [indicate subset used]. NOAA National Centers for Environmental Information. Dataset. https://doi.org/10.25921/ws45-s314 [Accessed December 2024].

Gottlieb, E.S., Saylor, J.H., Miller, G.S., 1989. Currents and temperatures observed in Lake Michigan. NOAA Technical Memorandum ERL GLERL-71. 47, pp.

Hampton, S.E. and 61 co-authors, 2017. Ecology under lake ice. Ecol. Lett. 20, 98–111. https://doi.org/10.1111/ele.12699.

Hawley, N., Beletsky, D., Wang, J., 2018. Ice thickness measurements in Lake Erie during the winter of 2010–2011. J. Great Lakes Res. 44 (3), 388–397. https://doi.org/10.1016/j.jglr.2018.04.004.

Hutchinson, G.E., Loffler, H., 1955. The thermal classification of lakes. Proc. Natl. Acad. Sci. U.S.A. 42 (2), 84–86. https://doi.org/10.1073/pnas.42.2.84.

Idso, S., 1973. On the concept of lake stability. Limnol. Oceanogr. 18 (4), 681–683.

Krueger, C.C., Holbrook, C.M., Binder, T.R., Vandergoot, C.S., Hayden, T.A., Hondorp, D. W., Nate, N., Paige, K., Riley, S.C., Fisk, A.T., Cooke, S.J., 2018. Acoustic telemetry observation systems: challenges encountered and overcome in the Laurentian Great Lakes. Can. J. Fish. Aquat. Sci. 75 (10), 1755–1763.

Lewis, W.M., 1983. A revised classification of lakes based on mixing. Can. J. Fish Aquat. Sci. 40 (10), 779–1787. https://doi.org/10.1139/f83-207.

Millar, F.G., 1952. Surface temperatures of the Great Lakes. J. Fish. Board Can. 9 (7), 329–394.

Miller, G.S., Saylor, J.H., 1981. Winter temperature structure in Lake Huron. J. Great Lakes Res. 7 (3), 201–206. https://doi.org/10.1016/S0380-1330(81)72046-X.

Ozersky, T. and 23 co-authors, 2021. The changing face of winter: lessons and questions from the Laurentian Great Lakes. J. Geophys. Res. Biogeosci. 126 (6), e2021JG006247. https://doi.org/10.1029/2021JG006247.

Piccolroaz, S., Toffolon, M., Majone, B., 2013. A simple lumped model to convert air temperature into surface water temperature in lakes. Hydrol. Earth Syst. Sci. 17, 3323–3338. https://doi.org/10.5194/hess-17-3323-2013.

Read, J., Hamilton, D.H., Jones, I.D., Murakoa, K., Winslow, L.A., Kroiss, R., Wu, C.H., Gaiser, E., 2011. Derivation of lake mixing and stratification indices from high-resolution lake buoy data Environ. Model. Softw. 26, 1325–1336. https://doi.org/10.1016/j.envsoft.2011.05.006.

Rodgers, G.K., 1987. Time of onset of full thermal stratification in Lake Ontario in relation to lake temperatures in winter. Can. J. Fish. Aquat. Sci. 44 (12), 2225–2229.

Schertzer, W.M., 1978. Energy budget and monthly evaporation estimates for Lake Superior, 1973. J. Great Lakes Res. 4 (3–4), 320–330. https://doi.org/10.1016/S0380-1330(78)72201-X.

Schertzer, W.M., 1987. Heat balance and heat storage estimates for Lake Erie, 1967 to 1982. J. Great Lakes Res. 13 (4), 454–467. https://doi.org/10.1016/S0380-1330(87)71666-9.

Schertzer, W.M., Saylor, J.H., Boyce, F.M., Robertson, D.G., Rosa, F., 1987. Seasonal thermal cycle of Lake Erie. J. Great Lakes Res. 13 (4), 454–467. https://doi.org/10.1016/S0380-1330(87)71666-9.

Schwab, D., Morton, J., 1984. Estimation of overlake wind speed from overland wind speed: a comparison of three methods. J. Great Lakes Res. 10 (1), 68–72. https://doi.org/10.1016/S0380-1330(84)71808-9.

Smith, N.P., 1973. The fall overturn and winter cooling in Lake Superior. Limnol. Oceanogr. 18 (3), 483–487. https://doi.org/10.4319/lo.1973.18.3.0483.

Titze, D., Austin, J., 2014. Winter thermal structure of Lake Superior. Limnol. Oceanogr. 59 (4), 1336–1348. https://doi.org/10.4319/lo.2014.59.4.1336.

Titze, D., Austin, J., 2016. Novel, direct observations of ice on Lake Superior during the high ice coverage of winter 2013-2014. J. Great Lakes Res. 42 (5), 997–1006. https://doi.org/10.1016/j.jglr.2016.07.026.

Woolway, R.I., Denfeld, B., Tan, Z., Jansen, J., Weyhenmeyer, G.A., La Fuente, S., 2021. Winter inverse lake stratification under historic and future climate change. Limnol. Oceanogr. Lett. 7 (4), 302–311. https://doi.org/10.1002/lol2.10231.

Woolway, R.I. and 25 co-authors, 2022. Phenological shifts in lake stratification under climate change. Nat. Comm. 12, 2318. https://doi.org/10.1038/s41467-021-22657-4.

Yang, B. and 19 co-authors, 2021. A new thermal categorization of ice-covered lakes. Geophys. Res. Lett. 48 (3), e2020GL091374. https://doi.org/10.1029/2020GL091374.