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Indications of a changing winter through the lens of lake mixing in Earth's largest freshwater system

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Abstract

Global surface freshwater primarily resides in lakes, with the overwhelming majority found in Earth's largest lakes, thus understanding potential climate change effects in these large lakes is critical. In dimictic lakes, climate change has extended the duration of summer thermal stratification and reduced the length of the ice season. These changes are relatively straightforward to evaluate in smaller, inland lakes. However, in large lakes, such as the North American Great Lakes, temporally intermittent and spatially heterogeneous ice cover, and spatial thermal heterogeneity limit the utility of simple ice on–off or mixing classifications; therefore, assessing how climate change is impacting winter conditions in large lakes is challenging. Here, we use *in-situ* and satellite-derived surface water temperature observations from the North American Great Lakes to overcome these limitations and show that warming air temperatures are driving reductions in the number of winter days, collectively those with either ice cover or inverse thermal stratification, in favor of increases in isothermal conditions for the period 1995–2023. We find that on average the Great Lakes are experiencing a loss of 14 winter days per decade. Our results demonstrate how climate change has yielded disproportionate changes in the annual thermal cycle and mixing conditions of Earth's largest freshwater system and signals the potential for fundamental ecosystem shifts due to a loss of winter.

1. Introduction

Holding the majority of Earth's surface freshwater, lakes play a significant role in the hydrosphere and provide vital drinking water and other ecosystem services to communities worldwide. Existing at nearly every latitude, altitude, climate, and on every continent, lakes are considered ideal 'sentinels' of global climate change (Williamson *et al* 2009a, 2009b, Messager *et al* 2016). Thus, lake warming trends are reported alongside changes in air, land, and ocean conditions in routine climate reports (Blunden *et al* 2023). Most studies of observed climate-induced changes in lakes have focused on lake surface water temperatures (LSWT) due to the global availability of satellite-derived measurements and the lack of *in-situ* observations at depth (Austin and Colman 2007, Zhang *et al* 2014, O'Reilly *et al* 2015, Mason *et al* 2016, Wan *et al* 2018, Kraemer *et al* 2021, Woolway *et al* 2021a, Woolway 2023). Studies that have investigated winter trends have largely focused on ice phenology, reporting ice on/off dates and the impact of ice-off date on summer stratification (Sharma *et al* 2021, 2022, Pilla and Williamson 2022, Woolway *et al* 2022). Generally, it has been found that summer LSWTs are increasing, leading to longer summer stratification periods (figure 1; Woolway *et al* 2021a), and that lake ice duration is decreasing (Sharma *et al* 2021), including in large lakes such as the North American Great Lakes (hereafter, the Great Lakes) (Ozersky *et al* 2021). Furthermore, studies of lake response to climate change projections have shown that many lakes are likely to experience a shift in the frequency and duration of vertical mixing phases by the end of the century (e.g. dimictic to monomictic; Woolway 2019). In particular, dimictic lakes such as

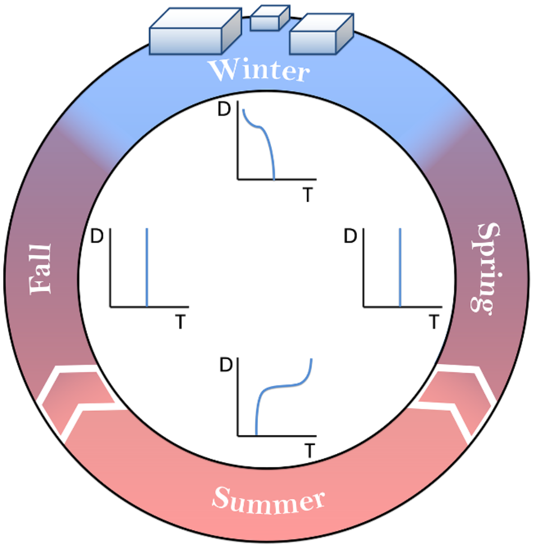

Figure 1. Seasonal cycle in a dimictic lake. Climate change is driving earlier onset and later breakup of summer stratification. An increase in summer duration will lead to a reduction in duration among the fall and spring isothermal (mixed) periods and the winter inverse stratification (or ice covered) period. The change in duration of these isothermal and winter periods has not been explored in Earth's largest lakes. Representative plots of an idealized vertical temperature profile are shown corresponding to each season for the dimictic cycle. The vertical axis represents the lake depth (D) from surface (higher values) to lake bottom (horizontal axis intercept), and the horizontal axis represents temperature (T) (values increasing monotonically from left to right).

the Laurentian Great Lakes (figure 1)—those with two distinct overturn periods per year—which currently experience intermittent winter ice, may become monomictic, a state with one annual vertical mixing phase, by the year 2100. The impacts resulting from changes in mixing conditions on lake ecosystems have already been observed in different species leading to phenological shifts and reduction in productivity (Thackeray *et al* 2010, Kuczynski *et al* 2017, Asch *et al* 2019).

In smaller lakes or those with relatively simple shorelines, ice cover generally expands or contracts rapidly between 0 and 100%, and thus phenology metrics alone can provide reasonable depictions of long-term trends in lake conditions. However, in large lakes, particularly those with more complex shoreline topography and bathymetry, there can be high spatial and temporal variability throughout the winter season (Wang *et al* 2012). For instance, in shallow or enclosed bays, ice concentrations can remain high for extended periods even if offshore or deeper regions remain ice free. Additionally, large mid-latitude lakes can experience high temporal variability in ice concentration over the winter season, leading to intermittent ice coverage. While ice on/off dates can still be an important metric in analyzing long-term trends in Earth's largest lakes (e.g. $>15\,000$ km^2), they may not fully capture other physical indicators of a changing winter.

LSWT in large or deep lakes may not reflect how subsurface physical conditions are changing over time. Subsurface waters, beyond the reach of satellite observations, can and do respond differently than surface waters to atmospheric conditions (Titze and Austin 2014, Pilla *et al* 2020, Anderson *et al* 2021). Even though more than 84% of Earth's surface freshwater is found in the ten largest lakes, relatively few studies of subsurface changes due to climate change have been carried out as compared to those concerning LSWT in smaller lakes (Austin and Colman 2007, 2008, Hampton *et al* 2008, Anderson *et al* 2021). Additionally, when winter temperature trends are considered, they are often reported on monthly time scales. While these metrics are important to characterizing seasonal conditions and trends, they are hard to connect to critical indices of lake functioning like overturn and stratification dates. As such, how winter periods in Earth's largest lakes are responding to climate change remain understudied, particularly regarding changes in duration of winter stratification and isothermal periods (Ozersky *et al* 2021).

Lake mixing characterization requires knowledge of vertical thermal structure at temporal resolution fine enough to differentiate stratification or isothermal (mixed) conditions. In large lakes, vertical thermal structure can differ considerably with location, and therefore a single characterization for the entire lake may be unrepresentative. Instead, a spatially varying characterization of thermal structure is required. While assessment of lake mixing inherently relies on known vertical temperature profiles, sustained instrument deployments to acquire continuous subsurface water temperature data suitable for long-term trend analysis are limited to a few sites for the entire planet. For example, at present in the Great Lakes, only Lake Michigan has a single thermistor chain that has been deployed for a climate-trend relevant period (Anderson *et al* 2021). Yet even for sites with shorter periods of record, spatial coverage of subsurface temperature data is sparse; only a few locations per lake are monitored at any given time. In contrast, satellite-derived LSWT provides high spatial (e.g. ~1 km) and temporal (e.g. daily) coverage, thus a relationship between LSWT and subsurface structure could be used to approximate the extent of lake stratification or mixing at any given time.

Here, we combine *in-situ* subsurface temperature measurements and satellite-derived LSWT data to assess changing winter for Earth's largest freshwater system, the Great Lakes, and consider the dimictic annual cycle as a point of reference, in which the lakes have a fall and spring overturn separated by summer and winter stratification periods (figure 1). Many of

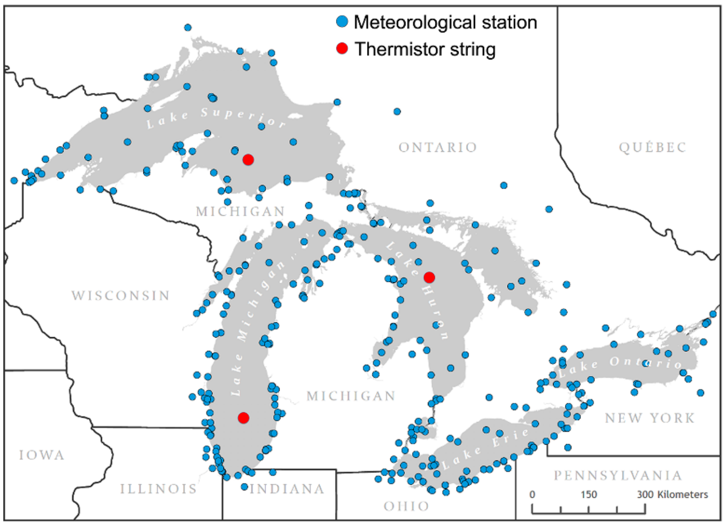

Figure 2. Map of the North American Great Lakes depicting locations of meteorological stations (blue circles) and subsurface thermistor string moorings (red circles).

Earth's large lakes are found at the mid-latitudes of the Northern Hemisphere and undergo a similar dimictic annual cycle with intermittent ice coverage (O'Reilly *et al* 2015, Woolway and Merchant 2018). As such, the Great Lakes make ideal representatives from which to study how winter conditions in Earth's large lakes are responding to climate change. As studies of global lakes have shown that the duration of the summer stratified period is increasing, a key question is how are the other parts of the annual cycle responding for Earth's large lakes? Using observed water temperature data, we identify these periods and investigate changes in their duration over recent decades. Specifically, we document spatio-temporal trends in ice cover, inverse (winter) stratification, and isothermal periods as indicators of the loss of winter for the Great Lakes.

2. Methods

2.1. Study site

The Great Lakes contain 21% of Earth's liquid surface freshwater, and by area, make up the world's largest freshwater system (figure 2). This international basin contains five of the world's largest lakes, including Superior, Michigan, Huron, Erie, and Ontario. The basin supplies drinking water for more than 48 million people and supports a seven-billion-dollar fishery that is vital to the regional economy (Allan *et al* 2013). Over the past 50 years, several efforts have been made to improve or manage water quality with varying levels of success (De Pinto *et al* 1986). However, threats to water quality and ecosystem function remain; for example, the hypoxic extent and intensity of harmful algal blooms have grown in recent decades (Michalak *et al* 2013). In part, these effects on ecosystem health and water quality may be tied to documented climate change driven increases in water temperatures and lake heatwaves (Anderson *et al* 2021, Woolway *et al* 2021b). While the lakes vary in depth and surface area, they experience summer stratification and some degree of inverse stratification and ice cover in the winter.

2.2. Water temperature data

We obtained LSWT 1995–2023 from the Great Lakes Surface Environmental Analysis (GLSEA; Schwab *et al* 1999), which provides spatially-varying serial-complete daily LSWT and ice concentrations at a resolution of approximately 1.8 km across the entire surface of the lakes. The GLSEA is a satellite-derived product from the National Oceanic and Atmospheric Administration (NOAA) CoastWatch program, which uses the NOAA advanced very high-resolution radiometer, spatio-temporal interpolationto handle gap filling, and is calibrated using buoy-based water temperatures from the NOAA National Data Buoy Center (NDBC). The GLSEA has been employed for numerous studies of lake hydrodynamics and climate trends (Mason *et al* 2016, Anderson *et al* 2018, Zhong *et al* 2019, Anderson *et al* 2021, Woolway *et al* 2021b, Woolway 2023) and generally has a high level of accuracy (RMSE ~0.5 °C; Schneider and Hook 2010).

To relate LSWT to isothermal conditions, we used subsurface water temperature data from thermistor strings deployed by the NOAA Great Lakes Environmental Research Laboratory in Lakes Michigan, Huron, and Superior (figure 2; Anderson *et al* 2021). The thermistor moorings have been deployed continuously to record sub-daily subsurface water temperatures at multiple depths throughout the water column (table 1). For subsurface analysis, we choose a period of 5 years with overlapping data (2018–2022) to develop an understanding of how

Table 1. Subsurface temperature station information including thermistor string mooring location, depth, and duration in the great lakes. For the period 2018–2022, the number of sensors and approximate sensor vertical spacing are provided.

Lake	Location	Period	Depth (m)	# Sensors	Sensor spacing
Michigan	42° 41.4′ N, 87° 2.6′ W	1990–2022	154	18	5 m (0–50 m depth), 10 m (50–154 m depth)
Huron	45° 9.5′ N, 82° 35.0′ W	2012–2022	220	21	5 m (0–50 m depth), 10 m (50–120 m depth), 20 m (136–220 m depth)
Superior	47° 7.6′ N, 86° 52.3′ W	2018–2022	198	20	5 m (0–58 m depth), 10 m (58–78 m depth), 20 m (78–184 m depth)

subsurface thermal structure relates to surface temperatures. Hourly water temperatures were recorded at each site using Sea-Bird Scientific SBE56 sensors (0.002 °C accuracy) for this period.

2.3. Atmospheric data

Atmospheric data were obtained from 161 meteorological stations around the Great Lakes for the period 1995–2023 (figure 2). The stations include NDBC buoys, NOAA Coastal-Marine Automated Network, United States Coast Guard Stations, and airports from the Automated Surface Observing System. These data are collected and organized as part of the Great Lakes Coastal Forecast System (GLCFS; Schwab and Bedford 1994). Hourly, spatially-varying, overlake meteorological fields provided by the NOAA GLCFS are created by filtering for outliers,using atmospheric-stability based adjustments to a common reference height, correcting for the overlake/overland effect, and using a natural neighbor interpolation. The resultant fields have been validated against *in-situ* buoys and overwater field campaigns, and the details of the underlying methodology behind the NOAA product are given in Resio and Vincent (1977), Phillips and Irbe (1978), Schwab and Morton (1984), Liu and Schwab (1987) and Croley (1989).

2.4. Mixing characterization

Determining whether a region in the lake is isothermal (mixed) or stratified requires knowledge of the vertical thermal structure. Here, we focus on fall isothermal, winter inverse stratification, and spring isothermal periods (figure 1). When LSWT is close to 4.0 °C, the approximate temperature of maximum density for freshwater, as is the case during fall, spring, and winter periods, differentiation between isothermal and stratified periods can be difficult. Therefore, to use LSWT from the GLSEA to identify isothermal periods, we use the subsurface temperature data from the thermistor strings described previously. First, subsurface data were filtered to isothermal periods, specifically when the difference between the maximum and minimum column temperatures was less than 0.1 °C. This value was chosen as a conservative estimate of a mixed column; variations of this threshold (0.1 °C–0.5 °C) yielded negligible impact on the overall results. We compared this subset of water column data to the corresponding GLSEA LSWT data at the thermistor chain locations for the period 2018–2022 (figure 3(a)). The filtered subsurface data revealed water temperatures of an isothermal column that ranged from approximately 1.8 °C–5.2 °C. For the corresponding days, the GLSEA yielded LSWT ranging from approximately 2 °C–5.5 °C. We differentiated fall and spring isothermal periods based on the day of minimum water temperature at the thermistor location, in which fall and spring isothermal days were taken to be those before and after this date, respectively (figures 3(b) and (c)). The resulting histograms showed similar agreement between the subsurface and surface isothermal column temperatures, where the GLSEA ranged from roughly 3 °C–5.5 °C in the fall and 2 °C–5 °C in the spring. The difference in ranges between the two demonstrate the effect of wind mixing, where fall months in the Great Lakes generally experience higher wind speeds and thus the lake can mix under a greater range of water temperatures.

Using the GLSEA for each day for winters 1996–2023, all pixels in the lakes were classified based on LSWT and ice condition into categories of (*i*) ice covered, (*ii*) open water less than 2 °C, (*iii*) fall days between 3 °C–5.5 °C, and (*iv*) spring days between 2 °C–5 °C. In lieu of subsurface thermal structure information in other areas of the lakes, these categories are used as proxies for winter conditions (combination of ice covered or open water less than 2 °C), fall isothermal period, and spring isothermal period (figure 1). For the analysis, we also discuss the total number of isothermal days per winter season, which is the summation of the fall and spring isothermal periods. While these temperature ranges are considered here as reasonable

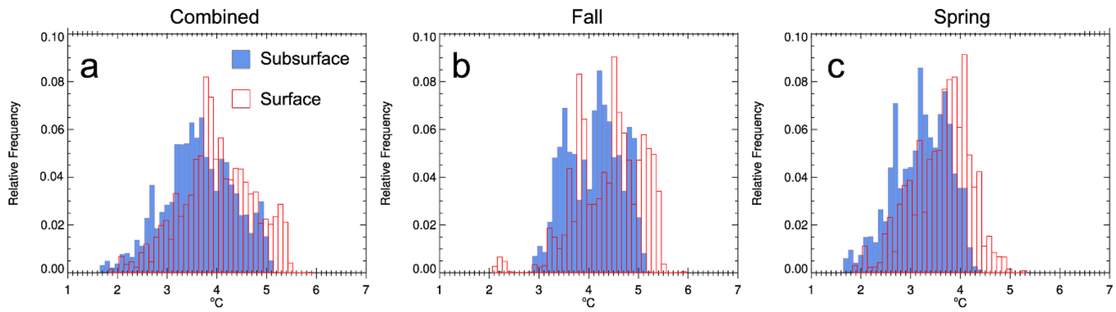

Figure 3. Water column temperatures during isothermal periods for the years 2018–2022. Histograms of subsurface (thermistor string) and surface (GLSEA) water temperatures during periods when the water column was unstratified. Shown for (a) total (combined) isothermal periods, (b) fall isothermal days, and (c) spring isothermal days.

proxies for isothermal or mixing conditions in offshore regions, they are likely too conservative in the nearshore, where the water column is more easily mixed.However, in nearshore or shallow water regions, we expect the temperature categories noted above to still prove useful in gaining insight into lake response to climate change. For all locations in the lakes, the number of days per year in each category was summed.

2.5. Trend analysis

Trends in lake conditions were analyzed using three approaches. First, the trend for each lake pixel was calculated using Sen's slope for each category, resulting in spatial maps of changes in the number of days of ice cover, inverse stratification, and isothermal conditions (Sen 1968). Confidence intervals of one standard deviation that contained zero were considered to have no detectable trend. Second, we follow an approach used in lake and marine heatwave analysis (Woolway *et al* 2021b) to determine how areal extent of winter conditions (combined categories of ice cover and open water less than 2 °C) and isothermal conditions (combined fall and spring isothermal periods) are changing over time. The distribution over all years was used to determine the 90th percentile of the number of days in each category (e.g. 90th percentile for the number of isothermal/mixing days per year). For each year, the number of pixels in the Great Lakes above the 90th percentile were determined and then summed into a total areal extent (% coverage). Finally, daily trends in areal extent of each category (e.g. % of the total area with ice cover) were calculated using Sen's slopes, and a moving average (30 d) was computed to reveal the times of year with the greatest change in areal extent. To complement these efforts and quantify the effect of meteorological drivers on changes in winter conditions, we used a similar approach to analyze changes in overlake air temperature. Average daily values were used to calculate a Sen's slope and then a 30 day moving average was computed to show the times of year with the greatest change in air temperature(°C per decade).

3. Results

3.1. Loss of winter days

Decreasing trends in the total number of winter days, collectively taken as days with ice cover or open water less than 2 °C, are found throughout the lakes for the period 1996–2023 (figure 4). Only 0.02% of water pixels have increasing winter days. In Superior, Huron, and Erie, a loss of winter days is found over nearly their entire area, in both shallow regions or bays as well as offshore areas. In Michigan and Ontario, decreasing winter trends are constrained primarily to coastlines and bays. A spatial average across the entire surface of the Great Lakes yields a loss of winter days at a rate of 1.43 d per year.

A decrease in the number of ice-covered days is found primarily along coastal regions and bays in Lake Huron, western Lake Superior, and northern Lake Michigan (figure 5(a)). However, Lake Erie, which is the shallowest of the Great Lakes and experiences the most seasonal ice cover each year (Wang *et al* 2012), shows a decrease in the number of ice-covered days across nearly the entirety of its surface. Conversely, Lake Ontario, which is both deep and experiences very little ice cover in most years (Wang *et al* 2012), has a decreasing trend only near its outlet, a topographically complex region that is more prone to ice formation than the rest of the lake. As a whole, the Great Lakes are experiencing a mean loss of ice-covered days by 1.53 d per year (figure 5(a)). For many locations with ice cover loss, we see a slight increasing trend in open water days between 0 °C and 2 °C (figure 5(b)), suggesting the water temperatures are not sufficient to freeze but may still be inversely stratified. However, in offshore areas of Superior and Huron, as well as the nearshore in Lake Ontario and southern Lake Michigan, we find a loss of these open water inversely stratified days. Without a corresponding increase in ice days in these regions,

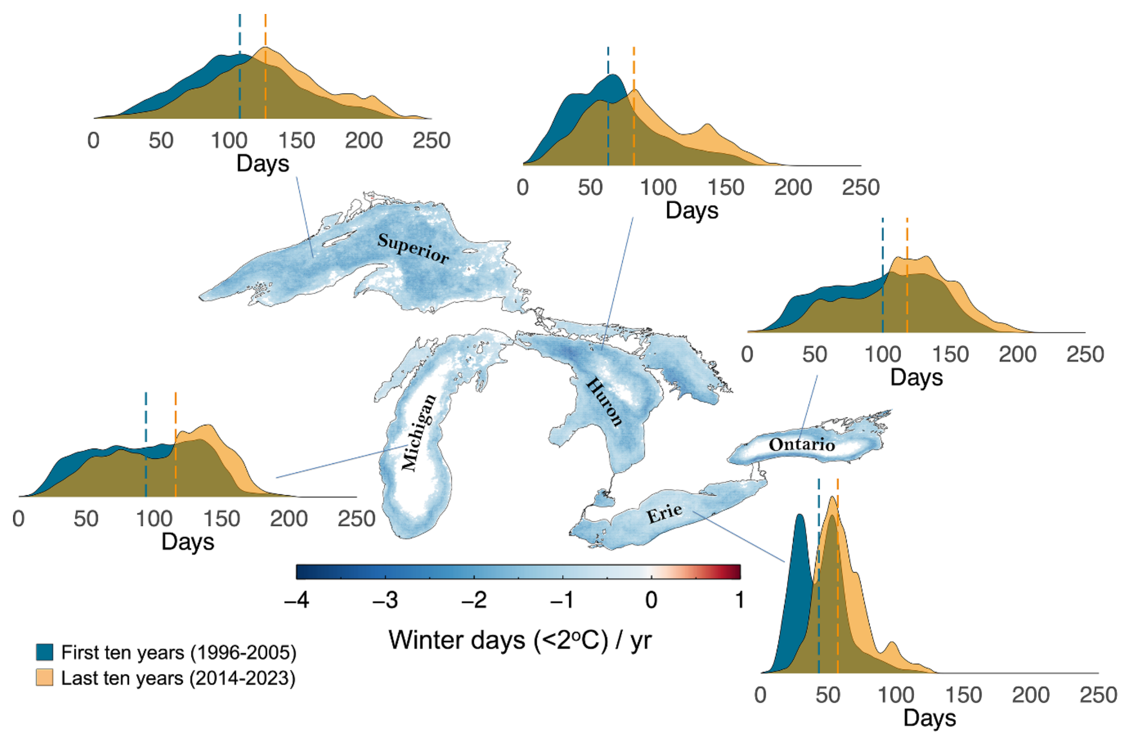

Figure 4. Depiction of the loss of winter days in the Great Lakes and shift toward longer isothermal periods. Map of the Great Lakes representing the trend in number of winter days (temperatures less than 2 °C including ice cover) for winters 1996–2023. For each lake, the histograms depict the total number of mixing days for the first (1996–2005) and last (2014–2023) ten years of the data period. Vertical dashed lines represent the medians of each distribution.

this suggests these waters are experiencing a loss of winter days.

The loss of winter days, whether from decreasing ice or warming above 2 °C, is paired with increases in the total number of isothermal days (temperatures between 2 °C–5.5 °C), where increasing trends in both fall isothermal proxy days (temperatures between 3 °C–5.5 °C) and spring isothermal proxy days (temperatures between 2 °C–5 °C) are found throughout the lakes (figures 5(c) and (d)). Comparing the first and last ten years, the shift in median number of total isothermal days for each lake ranges from 14 to 22 d (figure 4). Notably, the bimodal distribution of isothermal days in Lake Erie in the first 10 years stems from differences between the western part of the lake (and other shallow shoreline areas) and the deeper waters of the central and eastern basins. In the first 10 years, the western and shallow areas have fewer isothermal days and more winter stratification days, however in the last 10 years these areas experience many more isothermal days by comparison, and thus the collapse of this bimodal distribution in the last 10 years. A strong negative correlation exists between the loss of winter days and an increase in the total isothermal days, where the Great Lakes as a whole yield a correlation coefficient of −0.86 (figure 6(a), table S1). Coincident with the decrease in winter days and increase in isothermal periods, the number of days with temperatures above 5.5 °C (i.e. summer proxy) is also increasing (figure S1). An analysis of the spatial characterization shows that the extent of the lakes under winter condition is decreasing with time, though there is a large amount of interannual variability (figure 7(a)). Consistent with this loss, the proportion of the Great Lakes with an isothermal water column is growing with time (figure 7(b)).

3.2. Atmospheric drivers

Lake temperature in the winter is generally the result of reduced solar radiation and decreased air temperatures over the water. If overwater air temperature during December–February (DJF) is considered a reasonable indicator of the winter intensity, we can see that air temperature in milder winters is correlated with increased total isothermal days and inversely correlated with the number of ice-covered days (figures 6(b) and (c)). DJF air temperatures also have a strong correlation with the CV of ice days, suggesting that ice concentration is highly sensitive and possibly less predictable in response to small changes in air temperature (figure 6(d)), although there are notable differences in the air temperature thresholds between deeper and shallower lakes (e.g. Superior versus Erie). While overwater wind speed is strongly

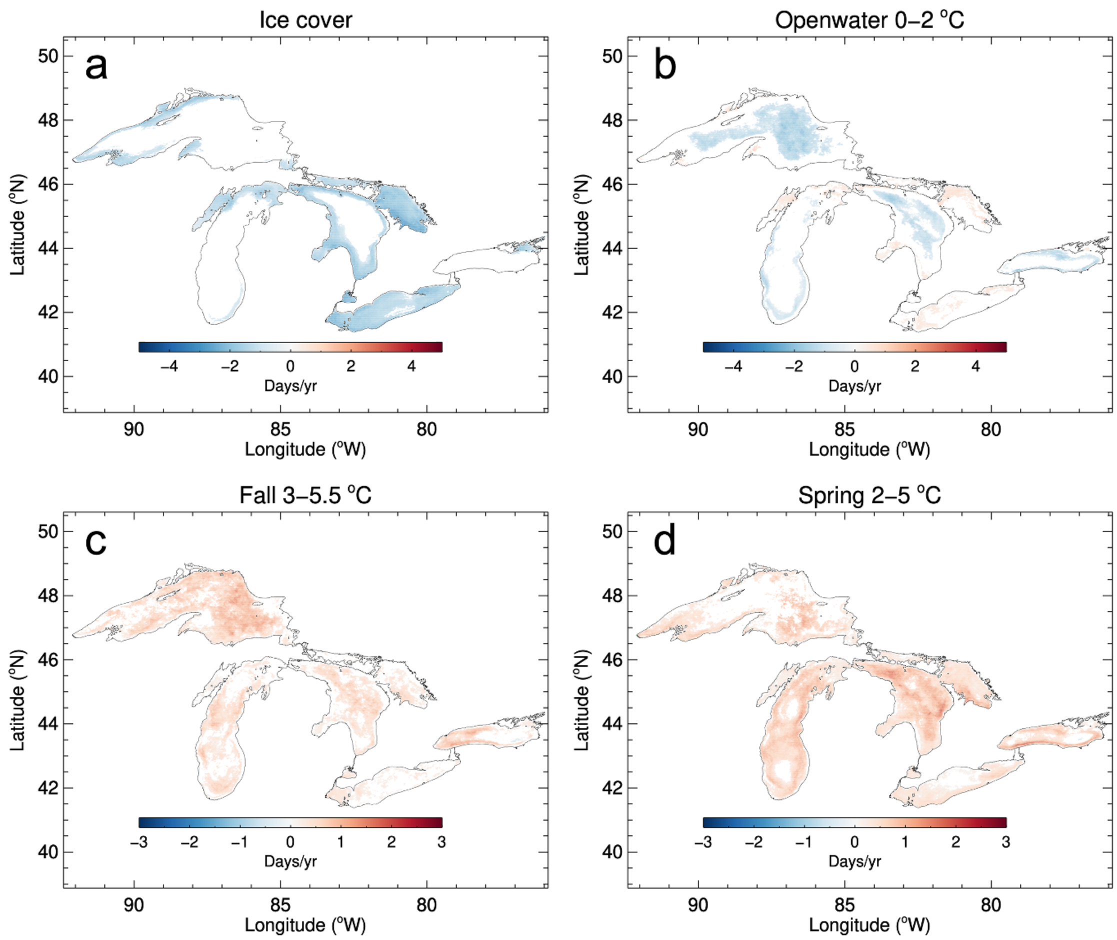

Figure 5. Spatial changes in winter and isothermal days: spatial trends (days/year) in (a) number of ice days, (b) number of open water days between 0 °C–2 °C (ice-free inverse stratification proxy), (c) fall isothermal days between 3 °C–5.5 °C (fall mixing proxy), and (d) spring isothermal days between 2 °C–5 °C (spring mixing proxy) for winters 1996–2023.

related to the timing of fall overturn, correlations between wind speed and total isothermal days (fall and spring) and ice-covered days were weak (figure S2 and S3). Slopes and standard errors for figures 6 and S2 are provided in table S1.

As the overall lake heat content is dependent upon time-integrated meteorology, primarily air temperature, and not just the conditions for a single day or even month, a time-series of how atmospheric conditions are changing throughout the annual cycle can reveal how and why winter conditions are being eroded. In the Great Lakes, air temperatures are warming throughout most of the year (figure 8(a)). The greatest warming trends in overlake air temperature occur in between late December and early January, and during the summer months of May through July. From mid-December to early May, the lakes see a decrease in the extent of the lake experiencing winter conditions (either ice days or inverse stratification; figure 8(b)) and an increase in lake extent where the water column is isothermal (figure 8(c)). Overall, an increase in regional air temperature is a driving mechanism behind the reduction in extent of ice cover and cold-water temperatures (0 °C–2 °C) in favor of an increase in water temperatures (2 °C–5.5 °C) and potentially increased water column mixing during the winter months.

4. Discussion

We undertook a novel investigation into changing winter conditions through the lens of lake mixing characterization in Earth's largest freshwater system. Our results show that from 1996 to 2023, winter days, or those with either ice cover or temperatures below 2 °C, are decreasing and giving way to an increase in the number of isothermal or mixed days across the Great Lakes. This change is in part due to the loss of ice days in nearshore and shallow areas, which tend to experience the highest annual ice concentrations. Other studies have reported long-term decreases in annual maximum ice concentration and changes in ice phenology that corroborate these findings (Ozersky *et al* 2021). However, this work also demonstrates changes in the number of open water

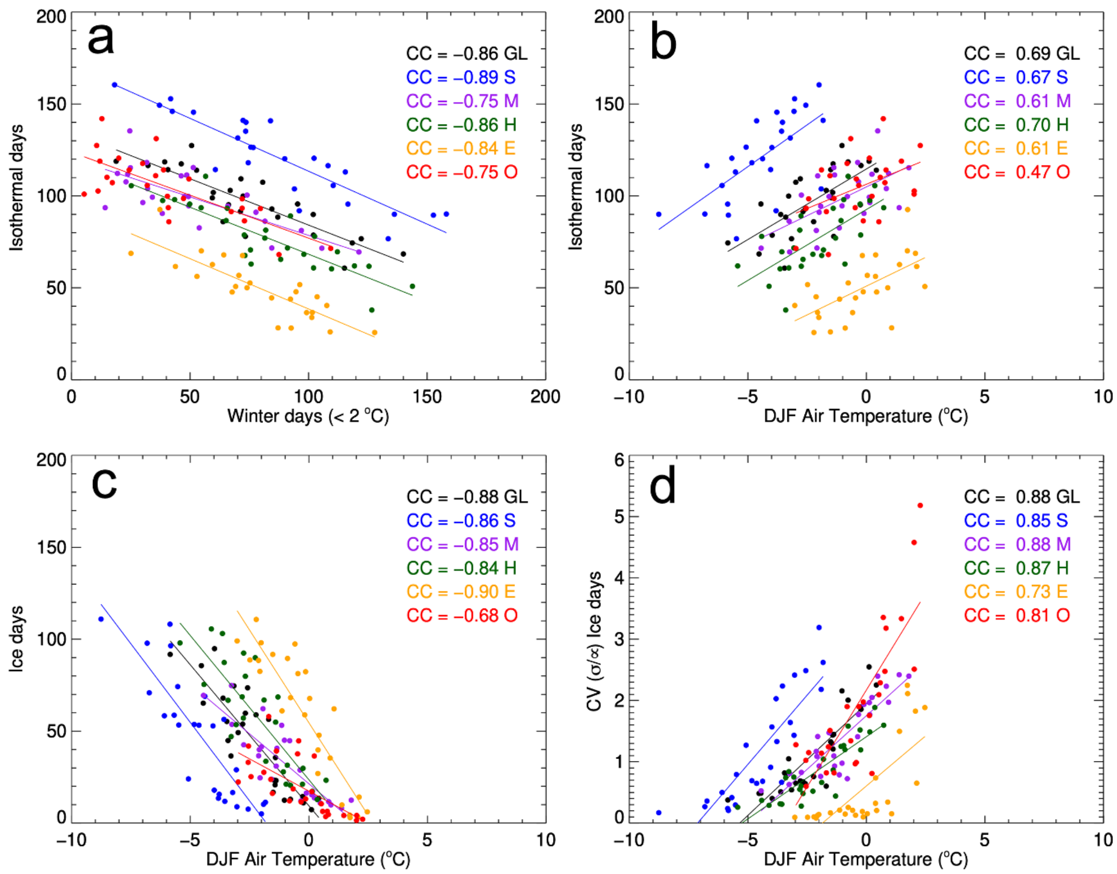

Figure 6. Relationships between (a) number of mixing days and number of days below 2 °C, (b) number of mixing days and December–January–February (DJF) overlake air temperature, (c) number of ice days and DJF air temperature, and (d) coefficient of variance (CV) of ice days and DJF air temperature. Each dot represents a single year (mean number of days; mean air temperature). Correlation coefficients (CC) are calculated between each paired data set, and ordinary least-squares (linear) fits are provided for visual purposes (slopes and standard errors in table S1). Data are plotted for the Great Lakes as a whole (GL) and for each individual lake: Superior (S), Michigan (M), Huron (H), Erie (E), and Ontario (O).

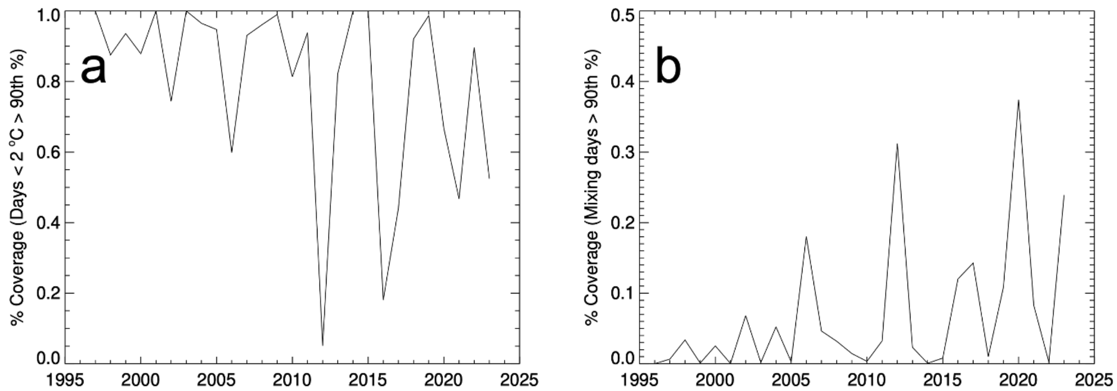

Figure 7. Observed change in spatial extent of winter and isothermal days from 1996 to 2022. Time-series plots of the areal extent given in % coverage of the Great Lakes where the number of days is greater than the 90th percentile for (a) days with temperatures less than 2 °C and (b) total mixing days.

inversely stratified days. Lakes Superior, Michigan, Huron, and Ontario all experience some degree of loss of these inversely stratified (open water) days. The exception is Lake Erie, where either no trend is found or some areas are seeing increases in these cold open water days. This effect is essentially due to the conversion from ice covered days to cold open water days, and it is found in shallow, semi-enclosed areas of the other lakes where ice loss has been reported. Overall, the conversion from winter days to isothermal days is primarily driven by nearly year-round increasing trends in overlake air temperature, though other meteorological conditions play pivotal roles in lake heat content and timing of mixing events. For instance,

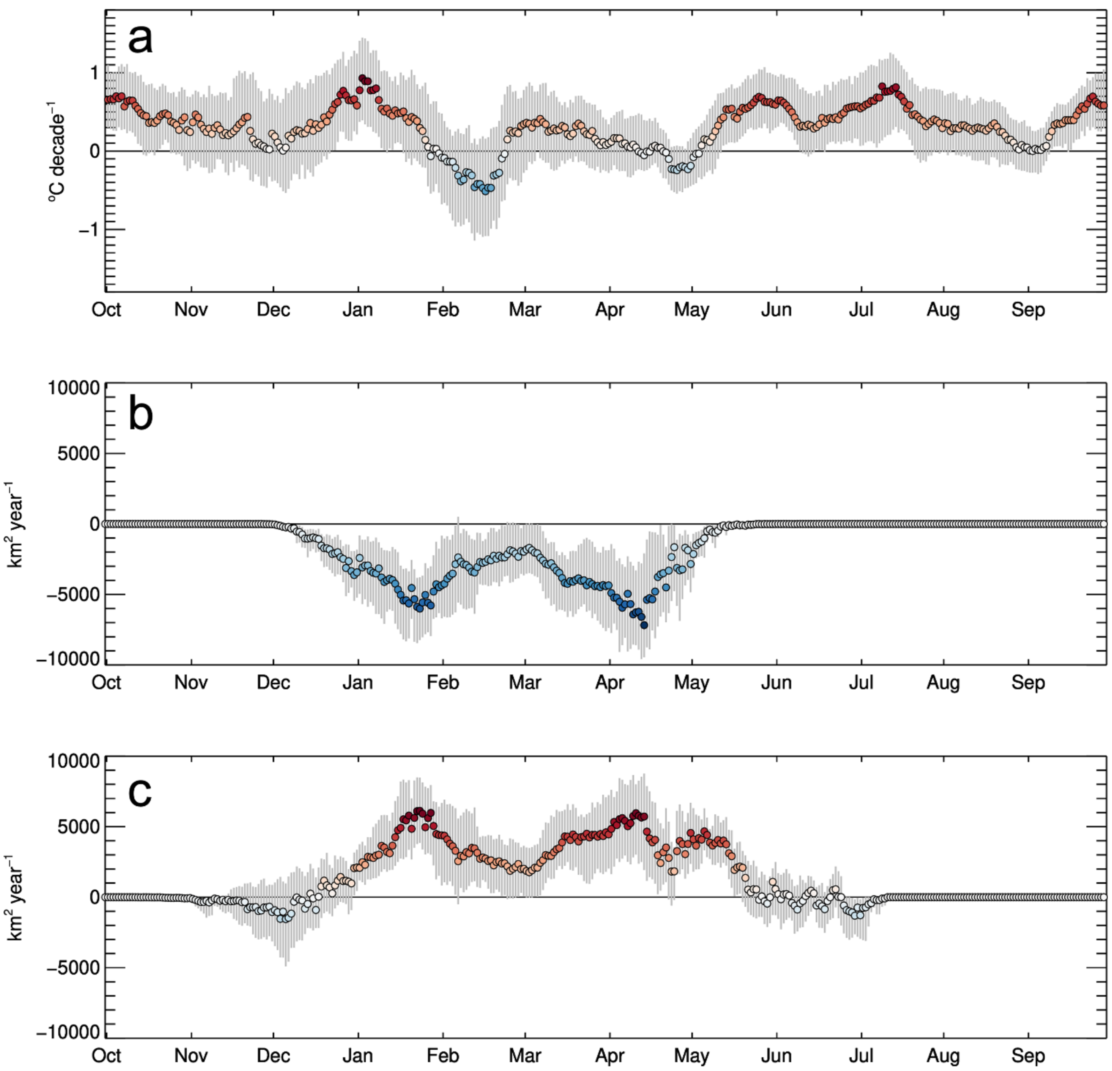

Figure 8. Changes in air temperature, winter spatial extent, and isothermal spatial extent as a function of time of year. Daily trends for the period 1995–2023 for (a) air temperature, (b) areal extent where temperatures are less than 2 °C, including ice (winter proxy), and (c) areal extent where water temperature is between 2 °C–5.5 °C (isothermal proxy). Each dot represents the 30-day moving average of the Sen's slope calculated across the time period (1995–2023), where colors are scaled with the value of the y-axis. Gray vertical bars are shown for one standard deviation of the given trend.

decreasing wind speeds throughout most of the year, with exceptions at the beginning and end of winter (figure S3), would result in an overall reduction in mixing. However, weak correlations between winter winds and the loss of winter kes forecasting system: days suggest that the increase in winter isothermal days are instead driven by other factors (figure S2). In addition, increased solar radiation, through the decrease of overlake cloud cover, can lead to warmer water temperatures (Anderson *et al* 2021), however limited amount of downward solar radiation in the winter months means this is likely not a dominant factor.

Considering the dimictic annual cycle, which has periods of winter inverse stratification and ice formation, spring mixing, summer stratification, and fall mixing, previous studies have shown that receding ice off dates have led to earlier summer stratification (Pilla and Williamson 2022), increases and shifts in monthly water temperatures (Woolway 2023), and the delay in fall overturn (Anderson *et al* 2021). Each of these efforts point to a summer stratified period taking up a greater proportion of the annual cycle (figure 1). This work extends these efforts by revealing how the remainder of the dimictic cycle is changing in response to climate change, and more specifically, how increases in air temperature affect isothermal periods and winter stratification. While surface water temperatures can provide reasonable indicators for offshore or deep water mixing conditions, nearshore waters can undergo water column mixing under a wider range of temperatures due to nearshore processes like wave breaking. However, the analysis here is underpinned by categories relating to water temperature and ice cover. Therefore, the results reported here still reveal fundamental changes in nearshore areas and in sum support the overall finding that we see signs of collapse in the winter period and a tendency toward a more monomictic state.

The consequences of a temporal shift in lake mixing and a shorter winter season may cascade through the food web and modify the provision of valued ecosystem services. Aquatic ectotherms such as fish have shown phenological shifts due to warming trends (Thackeray *et al* 2010). Fish are able to adjust migration phenology on an annual basis due to warming trends which could lead to phenological mismatches with historic prey (Kuczynski *et al* 2017). For example, under an extreme emissions scenario (e.g. RCP8.5), extreme mismatches (>30 d) between phytoplankton blooms and fish spawning are expected to become more frequent. This could result in less phytoplankton for consumption by fish larvae, overall reducing fisheries productivity (Asch *et al* 2019). Beyond direct ecological impacts, changes in lake mixing periods also effect cultural ecosystem services. Ceremonial, artistic, and recreational activities often occur on and around nearshore ice. Ice fishing tournaments are already seeing a higher frequency of cancellations due to warmer winters (Knoll *et al* 2019). Given significant participation in recreational fishing, over 14 million people in the Great Lakes region, and the economic importance highlighted by Michigan's lake whitefish industry, which generated $4.18 million in dockside value in 2020, the economic implications of a changing winter need to be considered.

5. Conclusion

We analyzed satellite-derived lake surface temperature and ice cover to investigate how winter conditions in the Great Lakes are responding to climate change. Our study finds observational evidence that some of Earth's largest lakes are experiencing a loss of winter days, on the order of 14 d per decade, or specifically a transition from ice covered and open water inverse stratification days to those of isothermal water column mixing. This suggests that as the duration of the summer stratified period is increasing in response to rising air temperatures, the remainder of the annual cycle is trending toward a monomictic state. As most of Earth's liquid surface freshwater resides in a small number of its largest lakes, a shift of this magnitude signals a potentially fundamental change to a significant portion of Earth's surface freshwater.

Data availability statement

The data sets used in this study are available from NOAA. GLSEA data is available from the NOAA Coastwatch Program: https://apps.glerl.noaa.gov/thredds/catalog/catalog.html. Subsurface temperature data is available at: www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:0190726, www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:0203568, www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:0240825,www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:0281714, www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:0281714, www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:0220860, www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:0239472,andwww.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:0281724. Meteorological data is available from NOAA at: https://apps.glerl.noaa.gov/marobs/.

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

E J A is responsible for conception of the study and design. E J A, B T, and C A S are responsible for analysis of the results and manuscript preparation.

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