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The spatiotemporal dynamics of heatwaves and cold-spells in Earth's largest freshwater systems

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Key Points:

- Heatwaves and cold-spells have become longer over the last 82 years, while their temperature anomalies have remained largely unchanged.
- Several interannual and multidecadal teleconnection patterns impact the timing of heatwaves and cold-spells in the Great Lakes.
- Local air temperature and ice cover anomalies have a significant impact on the spatial variability of heatwaves and cold-spells.

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This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1029/2025GL116548.

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Abstract

Extreme water temperatures impact the ecological and economic value of freshwater systems. They disrupt fisheries habitat, trigger harmful algal blooms, and stress coastal infrastructure. This study examines the spatiotemporal patterns of heatwaves and cold-spells in the Great Lakes using 82 years of simulated surface temperature data. Significant increasing trends in heatwave duration were observed in Lake Superior and Lake Michigan-Huron, while cold-spell duration increased on all lakes except Ontario. Temperature anomalies during these events varied from the climatological mean by as much as +/- 10°C, but did not change significantly over time. Analysis revealed substantial spatial variability in heatwaves and cold-spells, both within and across lakes, with differences driven by air temperature and ice cover anomalies as well as associated climate teleconnections (i.e. the East Pacific/North Pacific and Atlantic Multidecadal Oscillation). These findings highlight the importance of both climatic and lake processes in shaping extreme temperature events.

Plain Language Summary

This study investigates long-term changes in extreme surface water temperatures in the Great Lakes, which have important ecological and economic implications. By analyzing 82 years of water temperature simulations, we identified patterns of unusually warm and cold water events, known as heatwaves and cold-spells. We found that heatwaves are lasting longer in parts of the lakes, particularly in Lake Superior and the northern areas of Lake Michigan-Huron. Cold-spells are also becoming longer across most of the Great Lakes, except in Lake Ontario. However, the intensity of temperature changes during these events has remained relatively stable. To better understand these trends, we used a method to identify the most common patterns of heatwaves and cold-spells across the region and the times of year they typically occur. Our analysis showed that changes in air temperature and ice cover are major factors shaping these patterns. Additionally, global atmospheric circulation patterns influence when and where these extremes occur. These findings highlight the complex interactions between large-scale climate drivers and lake-specific conditions that affect extreme temperature variability in the Great Lakes.

1 Introduction

Extreme temperature events in lakes, such as heatwaves and cold-spells, can have profound effects on both aquatic and terrestrial ecosystems (Till et al., 2019; Holbrook et al., 2020; Woolway et al., 2021). Unlike the steady, long-term rise in global mean temperature, these abrupt thermal anomalies develop rapidly, providing minimal time for ecological and human systems to adjust (Till et al., 2019; Smale et al., 2019). Their consequences range from large-scale species mortality and shifts in species distributions to reduced aquaculture yields and geopolitical disputes over transboundary water resources (Till et al., 2019; Holbrook et al., 2020; Smale et al., 2019; Woodward et al., 2010; Gronewold et al., 2024). These events can also impact critical infrastructure, such as drinking water intakes and industrial cooling systems for power generation, which are sensitive to sudden changes in lake temperature. Observational records reveal an increasing frequency, duration, and intensity of these events in recent decades (Till et al., 2019; Woolway et al., 2021), and climate projections suggest that their severity will continue to escalate in a warming world (Yao et al., 2022; Huang et al., 2024; Woolway et al., 2025). Understanding the mechanisms driving the intensification of lake heatwaves and cold-spells is therefore critical to assessing their future impacts within a more variable climate system.

Despite the growing recognition of heatwaves and cold-spells in the Great Lakes (Chen et al., 2021; Abdelhady et al., 2025), there remains a limited understanding of their

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spatial and temporal characteristics. These extreme events do not occur uniformly across the lakes or throughout the year, yet most studies focus on basin-wide averages or seasonal trends, overlooking the spatial variations between lakes and within each lake (Chen et al., 2021). Given the ecological and economic importance of the Great Lakes, it is essential to investigate where and when these events occur, as their impacts can vary significantly across different regions and timescales. Fish species, for example, rely on specific thermal habitats that may be disrupted by these temperature extremes, affecting their distribution, spawning cycles, and food availability (Till et al., 2019; Lynch et al., 2010; Holbrook et al., 2020). Similarly, temperature fluctuations influence lake stratification, ice cover, biogeochemical processes, the growth of benthic plants and invasive mussels, and the frequency and intensity of harmful algal blooms (HABs) all of which play a role in shaping ecosystem dynamics (Holbrook et al., 2020; Smale et al., 2019). By examining the spatial and temporal variability of heatwaves and cold-spells, we can gain deeper insight into their drivers and improve our ability to anticipate and mitigate their effects in a changing climate.

Changes in the surface temperature of the Great Lakes are influenced by a combination of global, regional, and local factors. Large-scale climate teleconnections, such as the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), have been shown to affect the Great Lakes' surface temperature and ice cover (Bai et al., 2012; Lin et al., 2022; Venumuddula et al., 2024). In addition to these broad-scale drivers, regional climate variability — including fluctuations in air temperature, wind patterns, and cloud cover — also plays a significant role in shaping lake surface temperatures and ice cover (Abdelhady & Troy, 2025; Gronewold et al., 2021). Local lake-specific conditions, such as ice cover distribution and upwelling events, further contribute to temperature variability by altering heat exchange processes at the lake surface (Fujisaki et al., 2013; Plattner et al., 2006). While these factors are known to influence the thermal dynamics of the Great Lakes, their combined impact on extreme temperature events has not been explored.

In this study, simulated surface temperature data from a 3D hydrodynamic-ice model are analyzed to examine the spatiotemporal variability of lake heatwaves and cold-spells in the Great Lakes over the past 80 years. Spatial averages and trends in these extreme events are first assessed to identify the most affected regions. To further investigate dominant patterns of variability, rotated Empirical Orthogonal Function (EOF) analysis is applied to characterize the primary modes of both heatwaves and cold-spells. Potential drivers of these modes are then explored by evaluating the influence of climate teleconnection patterns. Finally, spatial anomalies in key atmospheric and lake-related factors are examined to better understand the mechanisms shaping the observed variability.

2 Methods and Data

2.1 Lake surface temperature data

This study utilizes lake surface temperature (LST) data generated by (Abdelhady et al., 2025) using a 3D Finite Volume Community Ocean Model (FVCOM, version 4.4.2) for the period 1941 to 2023 (Abdelhady, 2025). The model domain encompassed all five Laurentian Great Lakes (Superior, Michigan-Huron, Erie, and Ontario) and Lake St. Clair, with an average horizontal spatial resolution of 4.75 km and 21 sigma levels, with the uppermost sigma layer used to define the surface temperature. The model resolves horizontal mixing using the Smagorinsky scheme, while vertical mixing is handled via the modified Mellor-Yamada Level 2.5 turbulence closure scheme, which allows the vertical structure of temperature to influence surface dynamics. The FVCOM model incorporates ice dynamics through a coupled ice model based on the Los Alamos Sea Ice Model (CICE) (Gao et al., 2011). The meteorological forcing for the model was provided by the ERA5 reanalysis product, which offers 3-hourly atmospheric data at approximately 31

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km horizontal resolution for the region (Hersbach et al., 2020). The long-term model output was validated against historical in situ temperature records from Lake Erie, showing good agreement (see Supplementary Figure S4).

The LST data were detrended following the approach described in (Abdelhady et al., 2025) to isolate internal variability from the long-term warming signal. Nonlinear trends were identified and removed using the Seasonal and Trend decomposition with Loess (STL) method (Cleveland et al., 1990). The nonlinear trend was calculated for each model grid cell and each day of the year (DOY) to account for seasonal variations in warming rates. The calculated trend was then subtracted from the original LST data to produce the detrended lake surface temperature (DLST), which was used in subsequent analyses to examine variability in heatwaves and cold-spells.

2.2 Heatwaves and cold-spells calculation

Heatwaves and cold-spells in this study are defined as periods when the DLST exceeds the seasonally varying 90^{th} percentile (heatwaves) or falls below the 10^{th} percentile (cold-spells) for at least five consecutive days, following the criteria established by (Hobday et al., 2016). To calculate these thresholds, a 30-year reference period from 1941 to 1970 was used, as recommended by (Oliver et al., 2021). The calculated thresholds were then applied to the full detrended dataset spanning 1941 to 2021 to identify heatwave and cold-spell events at each grid cell.

To assess changes in these events over time, we calculated three metrics: duration (number of days), mean temperature anomaly, and accumulated degree heating or cooling days. The degree heating and cooling days, which measure event intensity, were computed as the cumulative temperature anomalies above (for heatwaves) or below (for cold-spells) the respective percentile thresholds (90^{th} and 10^{th}), following (Hobday et al., 2016; Oliver et al., 2021). Mean anomalies were also calculated relative to these thresholds, which were derived from the 1941-1970 reference period.

2.3 Rotated empirical orthogonal function (REOFs)

To examine dominant spatiotemporal patterns of heatwave (HW) and cold-spell (CS) variability across the Great Lakes, rotated Empirical Orthogonal Function (EOF) analysis was applied to absolute degree heating and cooling days. HW and CS were combined column-wise in a single dataset, and daily values were resampled quarterly (starting in November) by summation to capture large-scale seasonal variability. REOF analysis is an extension of EOF that improves the interpretability of the resulting modes by enhancing spatial localization and reducing mode mixing (Richman, 1986).

EOF decomposition and rotation were performed using the xmca Python package (Rieger, 2021), which computes eigenvectors (spatial patterns) and principal components (PCs; time series) representing dominant variability modes. Promax rotation (power = 4), an oblique method allowing non-orthogonal modes, was applied to the four leading EOFs (Hendrickson & White, 1964). Compared to orthogonal approaches like Varimax (Kaiser, 1958), Promax more effectively isolates localized, physically meaningful patterns (Richman, 1986).

2.4 Climate teleconnection patterns impact on HW and CS

The influence of large-scale climate patterns on heatwave (HW) and cold-spell (CS) variability was evaluated using multiple teleconnection indices. Two tests were conducted: (1) whether a teleconnection pattern could distinguish between HW and CS modes, and (2) whether it could differentiate among individual HW or CS modes.

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For each index, values were extracted during periods when a specific mode was dominant, defined as when its principal component (PC) exceeded 1 and surpassed all others. This threshold ensured a sufficient sample size while capturing distinct patterns. Alternative thresholds (0.5–2) were tested and yielded similar results. To assess differences, teleconnection indices during HW- and CS-dominant periods were compared, as well as among individual HW and CS modes.

Statistical significance was evaluated using both t-tests (for mean differences) and rank-sum tests (for medians), via the scipy.stats package in Python (Virtanen et al., 2020). Results were considered significant at p value <0.05 in both tests.

2.5 Regional Climate and ice condition impact on HW and CS

To evaluate the influence of regional climate and ice cover on heatwave (HW) and cold-spell (CS) variability, anomalies in air temperature, net heat radiation, wind speed/direction, and ice cover duration were analyzed. Anomalies for climate variables were calculated relative to the seasonally varying climatological mean, defined as the long-term daily average for each day of year (DOY). These daily anomalies were then averaged quarterly to match the temporal resolution of the principal component (PC) time series.

Ice cover was quantified as the number of days with >10% ice concentration per grid cell during each ice year (November–May). The corresponding PC time series was averaged annually (November–October) to align with this seasonal definition. To account for lake-to-lake variability, ice cover anomalies were standardized by dividing by the grid-cell-specific standard deviation of ice-covered days.

Anomaly values were extracted during periods when a specific HW or CS mode was dominant and averaged temporally to produce 2D spatial maps illustrating typical anomaly patterns for each mode.

3 Results

3.1 Spatial differences and general trends

The spatial distribution of heatwaves (HWs) and cold-spells (CSs) across the Great Lakes reveals distinct regional patterns in temperature anomalies, event duration, and degree days. HW temperature anomalies are highest in Lake Erie and along the coasts of Lakes Michigan, Huron, and Ontario, averaging around 1°C above the 90^{th} percentile of the DLST (Figure 1-a), which can correspond to anomalies exceeding 10°C above the climatological mean during some days of the year. HW duration is longest in mid-lake regions of Lakes Michigan and Huron, southern Lake Ontario, and Lake Superior, with an average of 45 days (Figure 1-c). Duration also correlates significantly ($p < 0.05$) with lake depth, particularly in Lakes Michigan ($r = 0.78$), Huron ($r = 0.67$), and Ontario ($r = 0.60$).

For CSs, the strongest negative temperature anomalies (below -1°C of the 10^{th} percentile of the DLST, which can correspond to anomalies of 10°C below the climatological mean during some days of the year) occur in Lakes Michigan and Ontario, especially along their coasts (Figure 1-b). CS duration is generally consistent across lakes (50–55 days), except in Lake Ontario, where it is notably shorter (Figure 1-d). Degree days, representing the cumulative intensity, also vary spatially: HW degree days are highest in Lakes Michigan and Erie, while CS degree days are more uniform, with slightly elevated values in Lakes Michigan and Superior (Figure 1-e and f).

Seasonally, for all lakes, HW degree days peak in the second and third quarters, while CS degree days are highest in the third and fourth (Figures S1, S2). Both, HWs and CSs, have the longest duration in the second quarter; however, second-quarter CS

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temperature anomalies are weak, resulting in lower CS degree days. However, both, HWs and CSs, have the largest temperature anomalies in the third quarter.

Long-term trends reveal a significant increase in HW and CS durations, but little change in their associated temperature anomalies (Figure 2). HW duration has increased by ~ 0.5 day/year in Lake Superior and northern Lakes Michigan and Huron. CS duration trends are steeper, increasing by ~ 1 day/year in Lakes Superior, Erie, Huron, and northern Lake Michigan. While trends in temperature anomalies vary spatially, most are statistically insignificant ($p<0.05$). HW degree days have increased significantly in northern Lakes Michigan-Huron and Lake Superior. In contrast, CS degree days exhibit broader significant trends across all lakes, except in Lake Superior.

3.2 Rotated EOFs results

The application of rotated EOFs reveals four primary modes of variability in heatwaves (HWs) and cold-spells (CSs) across the Great Lakes, with two dominant modes identified for each (Figure 3). Mode 1 and 2 represent the heatwaves, while mode 3 and 4 represent cold-spells. Together, these modes explain nearly 70% of the total variance in HW and CS events, with the HW modes explaining slightly larger percentage of the overall variance. The use of Promax rotation enhanced the physical representation of the modes and allowed for clearer spatial patterns and localized peaks in the principle components (PCs) compared to the original EOFs and rotated EOFs with Varimax (Figure 3).

For HWs, the first mode exhibits a pronounced northwest-to-southeast gradient, with the strongest warming anomalies observed in Lake Superior and the northern regions of Lakes Michigan and Huron (Figure 3-a). The second HW mode, in contrast, shows widespread warming across all the Great Lakes except for Lake Superior (Figure 3-c). The spatial patterns of CS modes reveal a different structure, characterized by a west-to-east gradient within each lake. The third mode indicates stronger cold-spell anomalies on the western side of the lakes, while the fourth mode highlights more intense CSs on the eastern side (Figure 3-b and d).

The PCs associated with the HW and CS modes are dominated by spikes instead of smooth transitions, with a remarkable increase in the magnitude and frequency of these spikes in the last 25 years (Figure 3). A temporal analysis of the PCs associated with these modes shows two periods of particularly strong HW and CS events, occurring between 1995–2000 and 2010–2015. During both periods, the Great Lakes experienced either an intense HW followed by an intense CS or vice versa (Figure 3).

3.3 Climate teleconnections and REOFs modes

The Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), East Pacific-North Pacific (EPNP), and North Pacific Gyre Oscillation (NPGO) all show statistically significant differences between HW and CS modes, based on both the t-test and rank-sum test (Figure S3). In contrast, no significant differences were found for the North Atlantic Oscillation (NAO), Oceanic Nino Index (ONI), Pacific North American (PNA) pattern, Southern Oscillation Index (SOI), and Arctic Oscillation (AO).

In general, HWs tend to occur during positive phases of AMO and NPGO and negative phases of PDO and EPNP. Conversely, CSs are more frequent during negative AMO and NPGO phases and positive PDO and EPNP phases. However, these associations are not universal. Some HWs developed under background conditions typically associated with CSs (e.g., negative AMO and NPGO or positive PDO and EPNP), and vice versa. Yet, while some large-scale climate modes help distinguish HW and CS clusters overall, none of the teleconnection indices could reliably differentiate among individual HW or CS modes.

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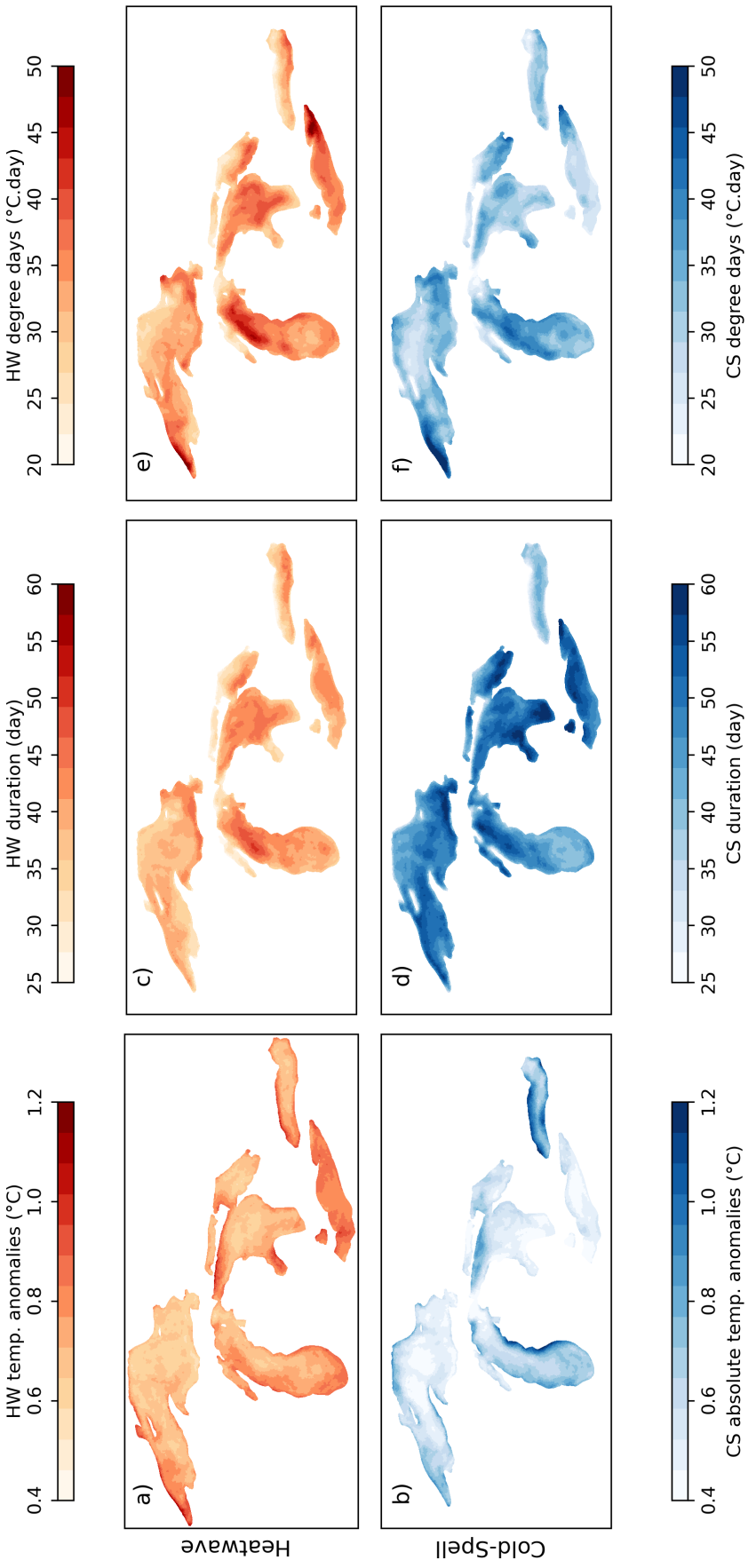


Figure 1. Yearly average for temperature anomaly, duration, and degree days of HWs and CSs for the whole record.

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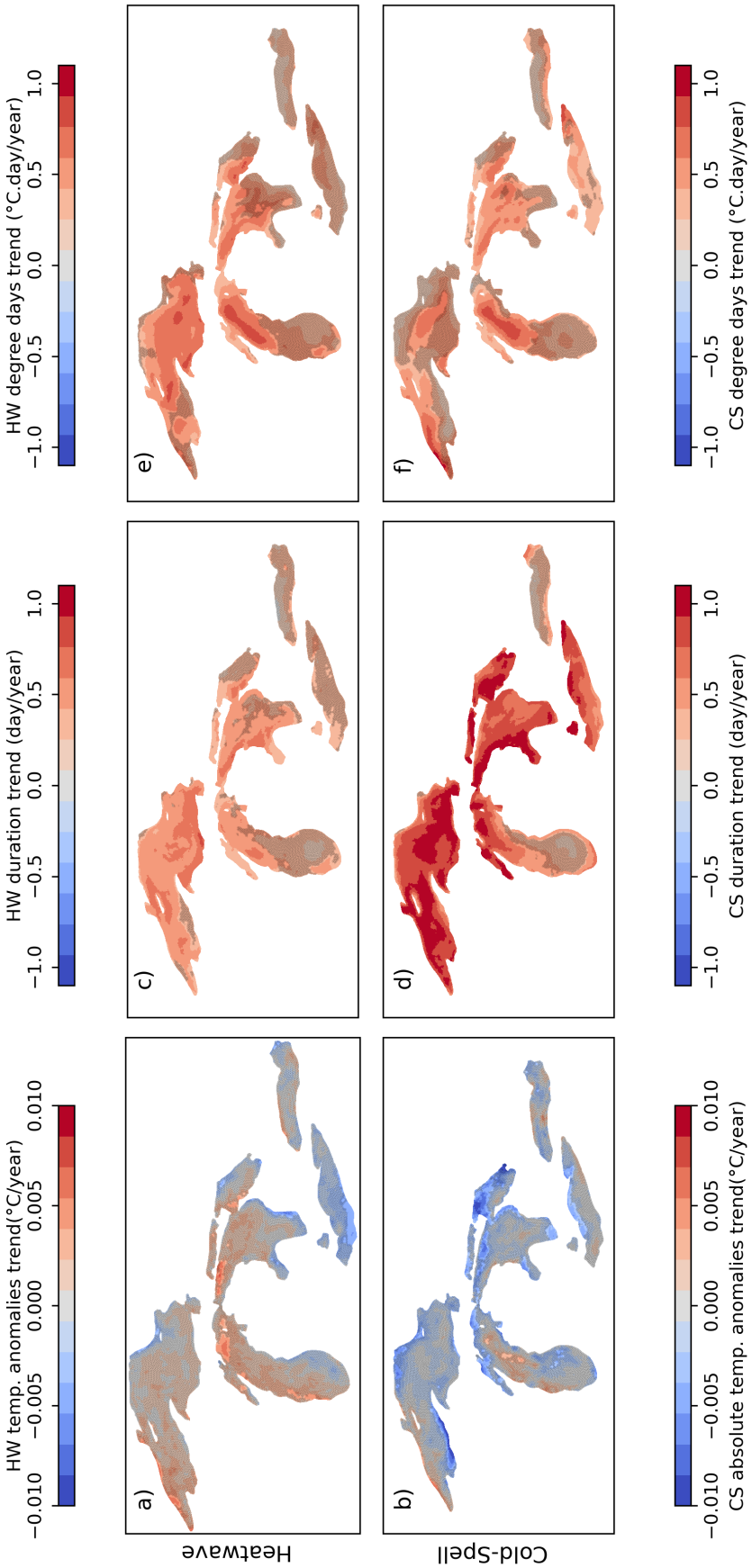


Figure 2. Trends for temperature anomaly, duration, and degree days of HWs and CSs. Grayed out areas represent area with no statistically significant trends.

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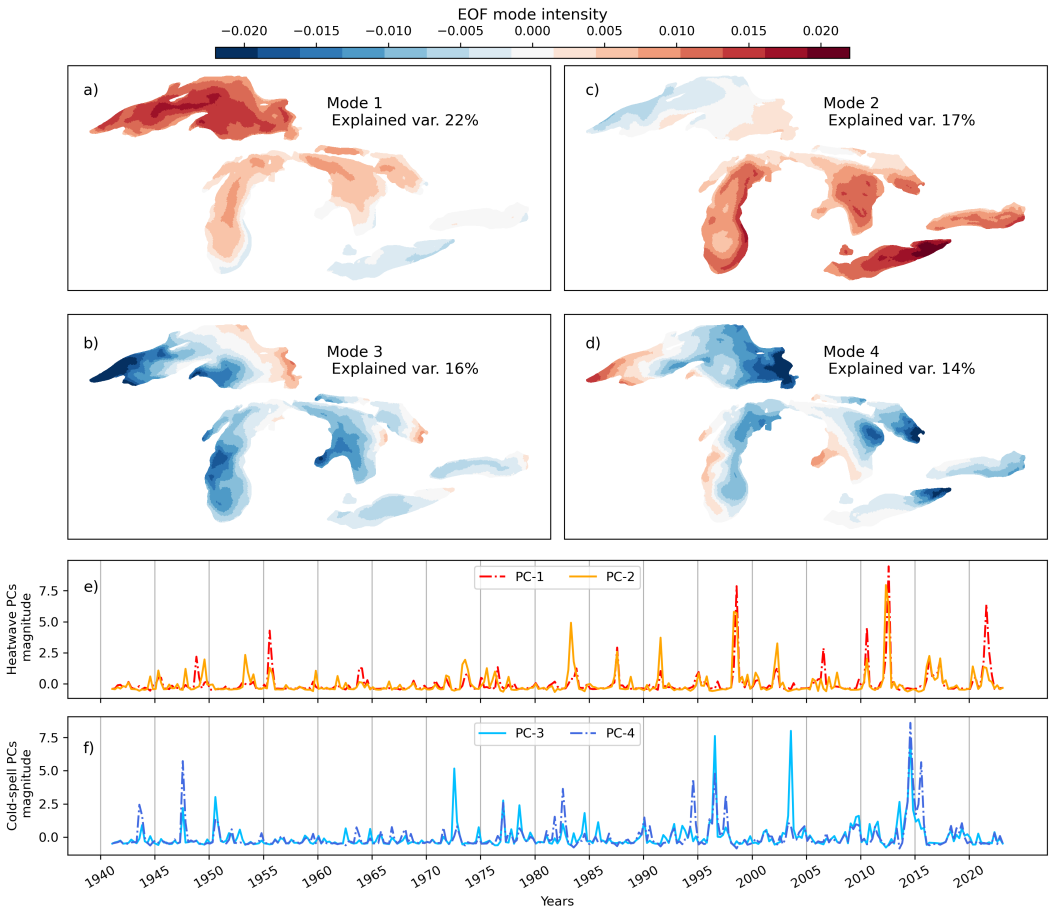


Figure 3. Dominant rotated EOF modes and their PCs for HW and CS. a) and c) represent the HW modes, while b) and d) represent the CS modes. e) shows the PCs for the first two modes (heatwave modes), while f) shows the PCs for the third and fourth modes (cold-spell modes)

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3.4 Local conditions and REOFs modes

Net heat radiation, air temperature, and normalized ice cover anomalies effectively distinguish between HW and CS modes, whereas wind anomalies show limited significance across most modes, except for the second HW mode, which is associated with strong wind anomalies. During HW events, air temperature anomalies exceed 2°C in some regions (Figure 4-a and c). In contrast, CS events exhibit slightly weaker anomalies, with minimum values approaching -1.5°C in certain areas (Figure 4-b and d). The spatial distribution of air temperature anomalies is strongly correlated with both HW modes, with correlation coefficients of 0.92 and 0.76 for modes 1 and 2, respectively. For CSs, the spatial correlation is more moderate, with coefficients of 0.59 (mode 3) and 0.54 (mode 4).

Normalized ice cover anomalies also exhibit strong spatial correlation with the first HW mode and both CS modes. Correlation magnitudes are 0.79 for mode 3, 0.68 for mode 4, and 0.63 for HW mode 1 (Figure 4). Net heat radiation shows a strong correlation only with the first HW mode and weak correlations with the other modes. Wind fields and magnitudes do not show strong spatial correlations with either HW or CS modes.

4 Discussion and Conclusion

The results show that while the frequency and duration of both heatwaves (HWs) and cold-spells (CSs) have increased over time, the temperature anomalies associated with these events have remained relatively stable. This suggests that these events are becoming more persistent rather than more intense. The observed increase in CS duration may seem counterintuitive given ongoing warming but can be attributed to disruptions in large-scale atmospheric circulation, particularly involving the Arctic. Arctic amplification—rapid warming of the Arctic relative to the global average—can weaken the polar vortex, making it more unstable and prone to stretching or splitting. This allows cold Arctic air to penetrate mid-latitudes like the Great Lakes, leading to prolonged CS events (Cohen et al., 2021; Rantanen et al., 2022). This is consistent with several strong CS events (e.g., 1996, 2003, 2014) that coincide with or directly follow a strong negative AO phases.

Among the Great Lakes, Lake Ontario stands out for experiencing notably shorter CS durations and larger temperature anomalies compared to the other lakes. This is likely due to its relatively low ice cover, Lake Ontario has the shortest ice cover season among the Great Lakes (Cannon et al., 2024). Ice cover acts as an insulating layer, reducing the transfer of heat between the atmosphere and the lake. When air temperatures drop, lakes with ice cover are insulated, preventing rapid cooling of the underlying water. In contrast, ice-free lakes like Ontario can respond more directly to atmospheric forcing, resulting in sharper but shorter cold anomalies. Additionally, ice has a higher albedo than water, which reduces heat absorption and prolongs cold conditions through the positive ice-albedo feedback (Austin & Colman, 2008). Because cold-spells tend to occur during the heavy ice season, a shorter ice cover period limits the time during which prolonged cold anomalies can develop, leading to generally shorter CS durations in Lake Ontario.

Although interannual and multidecadal climate teleconnections influence HW and CS modes, no single pattern consistently aligns with their variability. Similarly, regional climate conditions strongly correlate with HW and CS timing, but not with their spatial distribution. This suggests that variability in these extremes results from a combination of atmospheric forcing and lake-specific processes. Atmospheric conditions largely determine occurrence, but spatial patterns and intensity are shaped by factors like ice cover and water depth. For example, deeper regions with higher heat capacity—especially in Lakes Michigan, Huron, and Ontario—sustain HWs longer. These areas warm slowly but retain heat, amplifying surface temperature anomalies even after atmospheric conditions change. While the correlation between ice cover anomalies and CS modes is ex-

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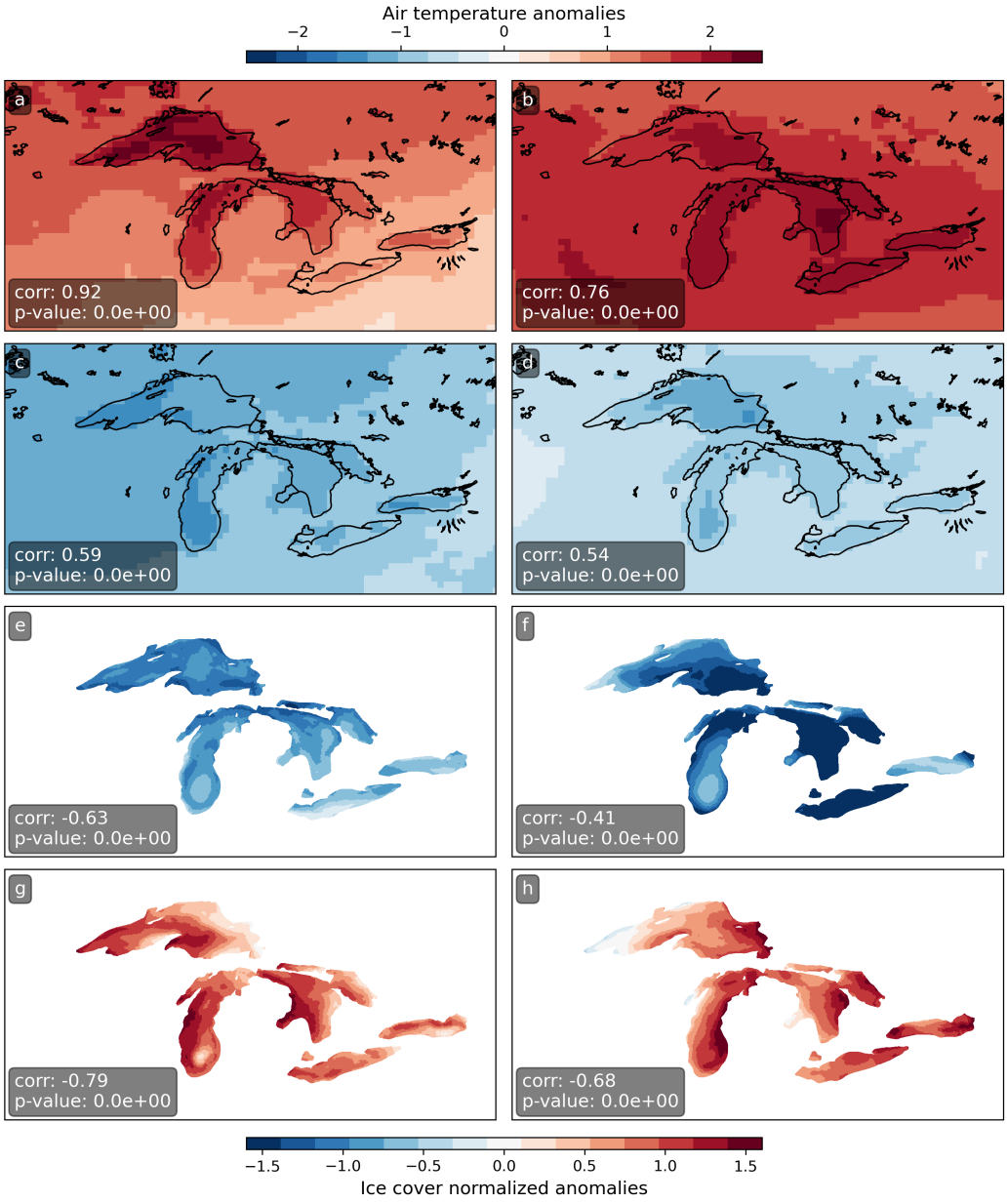


Figure 4. a), b), c), and d) are Air temperature anomalies corresponding to the dominant HW and CS modes while e), f), g), h) are for the normalized ice cover anomalies. a) and c) are air temperature anomalies corresponding to the first and second HW modes, while b) and d) are corresponding to the first and second CS modes. e) and f) are normalized ice cover anomalies corresponding to the first and second HW modes, while f) and h) are corresponding to the first and second CS modes.

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pected, ice also influences HWs by affecting spring thermal conditions. Low winter ice cover leads to more heat stored beneath the surface, priming the lakes for summer HWs. These findings highlight the complex interplay between atmospheric patterns and lake-specific dynamics in shaping extreme thermal events in the Great Lakes.

The ONI index, commonly used to identify ENSO events, was not a significant factor in distinguishing between HW and CS modes. While past studies linked strong El Niño events to reduced ice cover and warmer-than-average conditions in the Great Lakes (Wang et al., 2012; Venumuddula et al., 2024), more recent work suggests this relationship has weakened. (Lin et al., 2022) found that ENSO was significantly correlated with ice cover only until the 1997/1998 winter, after which the Eastern Pacific Oscillation (EP-NP) became more influential. Although some strong HWs, such as those in 1998 and 1983, occurred during El Niño events, others did not. This suggests ENSO's influence on extreme temperature events in the Great Lakes is inconsistent and likely mediated by other climate patterns.

The EOF analysis with Promax rotation identified key modes that explained 70% of HW and CS variability. The choice of quarterly data analyzed in this study was designed to focus on long-term variability, perhaps at the expense of explaining some shorter timescale events. The unexplained sources of variance could include various localized weather phenomena and/or lake conditions. Furthermore, additional variability exists that may be better resolved using higher-frequency data, including upwelling events (Plattner et al., 2006), which can significantly alter coastal temperatures on shorter timescales, as well as storm-scale weather variability, which may only affect local climatic conditions for a few days. Likewise, the limited influence of wind anomalies may reflect the averaging approach, as wind-driven circulation and upwelling often act over days rather than seasons.

Overall, this study shows that HWs and CSs in the Great Lakes result from interactions between large-scale atmospheric forcing, lake-specific processes, and ice cover variability. While climate teleconnections influence their occurrence, spatial patterns and persistence are more strongly governed by lake depth and ice dynamics. These findings underscore the need to consider both regional and lake-specific drivers when assessing extreme temperature events in freshwater systems. Such understanding is essential for resource management in fisheries, habitat restoration, and water quality, where temperature extremes can impact species distributions, breeding cycles, and harmful algal bloom (HAB) occurrences.

Open Research Section

The modeled lake surface temperature data used for all the analysis in this study are available from (Abdelhady, 2025).

Acknowledgments

This research is supported by the National Science Foundation (NSF OCE 2319044) and National Oceanic and Atmospheric Administration awarded to Cooperative Institute for Great Lakes Research (CIGLR) through the NOAA Cooperative Agreement with the University of Michigan (NA22OAR4320150). This is CIGLR contribution XXXX and GLERL contribution XXXX. A.D.G. and H.U.A. also received support from the NSF Global Centers program (Award No. 2330317). J.W. was supported by NOAA OAR Ocean Sciences Portfolio "Great Lakes Earth System Model" project.

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