

Storms Under Water: Wind-driven impacts on a north temperate deep stratified lake

Miranda S. Rummell

Lake Champlain Research Institute

Eric M. Leibensperger

Center of Humanities and Sciences

Grayson P. Huston

ghust001@plattsburgh.edu

Lake Champlain Research Institute

Danielle E. Garneau

Center for Earth and Environmental Studies

Timothy B. Mihuc

Lake Champlain Research Institute

Research Article

Keywords: Thermal stratification, Metalimnion collapse, Localized turbulent entrainment, Storm detection, Disturbance event, Thermal stability

Posted Date: September 10th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10985765/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Storms Under Water: Wind-driven impacts on a north temperate deep stratified lake

Authors

Miranda S. Rummell [0009-0008-4653-1364; mrumm001@plattsburgh.edu]¹,

Eric M. Leibensperger [0000-0002-1906-2688; eleibensperger@ithaca.edu]²,

*Grayson P. Huston [0009-0009-4863-4284; ghust001@plattsburgh.edu]¹,

Danielle E. Garneau [0000-0003-2717-7036; dgarn001@plattsburgh.edu]³, and

Timothy B. Mihuc [0009-0008-2157-7577; mihuctb@plattsburgh.edu]^{1,3}

Affiliations

¹Lake Champlain Research Institute, SUNY Plattsburgh, Plattsburgh, NY, USA

²School of Humanities and Sciences, Ithaca College, Ithaca, NY, USA

³Center for Earth and Environmental Science, SUNY Plattsburgh, Plattsburgh, NY, USA

*Corresponding Author

Abstract

Lake Champlain is a deep, temperate freshwater lake that experiences summer stratification, which limits interactions between surface and deep waters. Wind-induced storms disrupt this phenomenon by altering thermal stability. We collected high-frequency vertical temperature profiles in Lake Champlain's Main Lake segment during the warm seasons 2016-2025 in 50 m water. We estimated the frequency, timing, and intensity of thermal changes in the water column and classified them into five severity levels (Level 1-5). From 2016 to 2025, a total of 77 storms exceeded an epilimnion depth of 25m between July 15 and September 15. These events occurred five to ten times each fall, with the highest frequency in 2018 with the occurrence of ten storms. The lowest frequency occurred in 2024 with just five events, however they were mainly intense storms (Levels 3-5). Each storm exhibited distinct dynamics likely influenced by variations in wind forcing and stratification strength. Combining storm detections and classifications with nearby wind observations, we compiled a mean state of storm levels (*i.e.*, Level 1-5) and created level-specific metrics. Wind forcing and epilimnion response occurred faster at the onset than during their respective recovery. Levels 4 and 5 were shown to be strong enough to temporarily collapse the metalimnion below the stratification threshold, consistent with localized turbulent entrainment (LTE). These findings establish a baseline for characterizing storm-induced thermal disturbances and suggest that seiche or internal wave activity may contribute to subsurface impacts that continue after surface wind forcing has weakened or dissipated.

Keywords

Thermal stratification, Metalimnion collapse, Localized turbulent entrainment, Storm detection, Disturbance event, Thermal stability

Statements and Declarations

Conflicts of Interest

The authors declare no competing interests.

Funding

This project was supported by the Lake Champlain Research Institute with funding provided by the Great Lakes Fishery Commission.

Data Availability Statement

Data and code generated in this study are available for peer-review at Zenodo [[https://zenodo.org/records/20939214?preview=1&token=eyJhbGciOiJIUzUxMiIsImIhdCI6MTc0Mjc2MTAzNiwiZXhwIjoxNzk4Njc1MTk5fQ.eyJpZCI6ImMxN2QwOWIyLWE5NDItNDNjNy1iYjEzLWRhNTYzNGMzYjI3MSIsImRhGEiOnt9LCJyYW5kb20iOiI3MGMxNWYxNTlkNjJjMGFiMzczOTNhYmExN2QwMmU5NCJ9.d4r42T4ZnDAZXhIwiZ-SS3LbANBgeH3T6ZR0L3j9mDBcJ2gt92sHO7bC0k87tBDjF_7A-koiTXRO1dcN9gCTfQ;](https://zenodo.org/records/20939214?preview=1&token=eyJhbGciOiJIUzUxMiIsImIhdCI6MTc0Mjc2MTAzNiwiZXhwIjoxNzk4Njc1MTk5fQ.eyJpZCI6ImMxN2QwOWIyLWE5NDItNDNjNy1iYjEzLWRhNTYzNGMzYjI3MSIsImRhGEiOnt9LCJyYW5kb20iOiI3MGMxNWYxNTlkNjJjMGFiMzczOTNhYmExN2QwMmU5NCJ9.d4r42T4ZnDAZXhIwiZ-SS3LbANBgeH3T6ZR0L3j9mDBcJ2gt92sHO7bC0k87tBDjF_7A-koiTXRO1dcN9gCTfQ;DOI: 10.5281/zenodo.20939214) and will be made publicly available upon acceptance of this manuscript.

Author Contribution Statement

Miranda Rummell: Conceptualization (equal); Data Curation (equal); Investigation (lead); Methodology (equal); Visualization (equal); Writing- Original Draft Preparation (lead); Writing- Review & Editing (equal). **Eric Leibensperger:** Conceptualization (equal); Data Curation (equal); Formal analysis (lead); Methodology (equal); Resources (equal); Visualization (equal); Writing-

62 Review & Editing (equal). **Timothy Mihuc**: Conceptualization (equal); Funding Acquisition
63 (lead); Project Administration (lead); Resources (equal); Supervision (lead); Visualization (equal);
64 Writing-Review & Editing (equal). **Grayson Huston**: Formal Analysis (supporting); Writing-
65 Review & Editing (equal). **Danielle Garneau**: Writing-Review & Editing (equal).

66

Introduction

Large, deep lakes are warming more rapidly due to shorter periods of ice cover, decreasing cloud cover, and rising air temperatures (Austin et al., 2007; O'Reilly et al., 2015). As a result, these lakes are experiencing earlier and stronger stratification events (Winslow et al., 2014; Mesman et al., 2022), with potential negative implications for lake biodiversity, including phytoplankton growth (*e.g.*, nutrient depletion in the epilimnion; Reynolds, 1997) and cold-water fish species (*e.g.*, hypoxic hypolimnion; Pettersson et al., 2003; Nowlin et al., 2005; North et al., 2014; Butcher et al., 2015; Woolway et al., 2022). Lake stratification is shown to be largely impacted by wind disturbance, especially in autumn due to convective cooling (Yang et al., 2018). Unlike oceans, the energy input in freshwater lakes relies solely on wind to redistribute oxygen and nutrients throughout the water column (Mesman et al., 2022), underscoring the importance of wind events for lake mixing and dynamics.

“In meteorological terms, storms are defined as either atmospheric disturbances in prevailing winds and pressure ranging from tornadoes (1 km across) to extratropical cyclones (2000–3000 km across), or wind speeds between 48 and 55 knots” (25 and 28 m s⁻¹; Beaufort scale wind force 10; World Meteorological Organization, 1967, p. 148). However, in more regional contexts and for the purposes of this study, storms are defined as periods of rapid vertical temperature change in the water column (Stockwell et al., 2020), during which wind speeds exceed 6 m s⁻¹; for a prolonged period of time and can begin altering thermal stratification (Wu et al., 2015; Wang et al., 2022). These events can displace organisms and their resources, redistributing populations, communities, and ecosystems, with the scale of these disturbances influenced by storm frequency, intensity, and duration, all of which are increasing with climate change (Lake, 2000; Guilbert et al., 2014; Woolway et al., 2018). In deep, temperate lakes, this process typically

occurs when hypolimnetic water is displaced toward one end of the lake and epilimnetic water is forced downward, resulting in localized thermocline displacement.

Whenever lake stratification is altered, “habitats will open or close” causing organisms within these habitats to experience shifting population dynamics and potential alterations of food webs and other limnological variables such as nutrient cycling (Nixon, 1988). Although temperate lake stratification is well studied in eutrophic lakes (MacIntyre, 1993; Kimura et al., 2017; Yang et al., 2018), to date, most studies exploring the impact of storms on lake characteristics have focused on medium, or shallow lakes (James et al., 2008; Havens et al., 2016; Doubek et al., 2021), with less attention given to deep and/or oligotrophic systems. Deep, temperate lakes are of importance due to their large freshwater storage capacity and sensitivity to climate change (Butcher et al., 2015). While studies on larger, deep lakes are more limited, one by Andersen et al., (2020) documented storm-driven reductions in Schmidt stability, thermocline depth, and lake number - a dimensionless metric of mixing intensity - with subsequent alterations to nutrient and carbon availability lasting days to months. Kraemer et al., (2015) suggested that deep lakes may experience fewer mixing events overall, but exhibit greater changes in stability, and deeper thermoclines when mixing does occur. This suggestion was validated during an extreme event described by Woolway et al., (2018), which highlighted a short-lived mixing and rapid thermocline deepening, that altered seiche dynamics and thermal structure with effects on the vertical distribution of oxygen and nutrients, influencing phytoplankton growth and distribution. The extent of thermocline deepening has been shown to depend on storm duration and wind speed (Andersen et al., 2020), while rapid temperature changes can also impact other aquatic organisms, from plankton and macroinvertebrates (Scrine et al., 2017) to fish (Johnson et al., 2024). Understanding storm thresholds is critical for assessing event intensity and predicting varying

ecosystem responses of deep lakes, especially when thresholds are dependent on local geography and bathymetry.

Lake Champlain is an economic driver for the Champlain Valley of New York, Vermont, and Quebec, including recreational, agricultural, and tourism purposes (Guilbert et al., 2014), but is sensitive to environmental stressors (Smeltzer et al., 2012). Additionally, global change has impacted the lake with the introduction of invasive species (Marsden and Hauser 2009; Arnwine et al., 2025) and warming (Stager and Thill 2010) impacting its vitality.

Potentially representative of the Great Lakes (Facey et al., 2012), Lake Champlain's long and narrow shape and predominant along-axis wind pattern make it an ideal site to study hydrodynamics such as seiches, or internal oscillations. Currents have been previously shown to substantially alter the water column, particularly the hypolimnion (Manley et al., 1999; Manley 2004). Under typical, warm-season conditions, currents above and below the metalimnion are reversed in direction and the primary driver of summer circulation in the Main Lake (Myer and Gruendling 1979; Manley et al., 1999). However, a characterization of storm events and the resulting ecological impacts has yet to be completed.

In Lake Champlain, high-wind events lasting more than one day, such as storms, can rapidly displace the metalimnion, creating a surge of epilimnetic water that moves upwind, as well as an internal bore in deep water layers that travels in the opposite direction (Figure 1). Several of these internal bore events have been observed in the Main Lake, particularly around Valcour Island, most often during periods of weak stratification in early summer and late fall—when low Schmidt stability facilitates greater metalimnion oscillations (Manley et al., 1999).

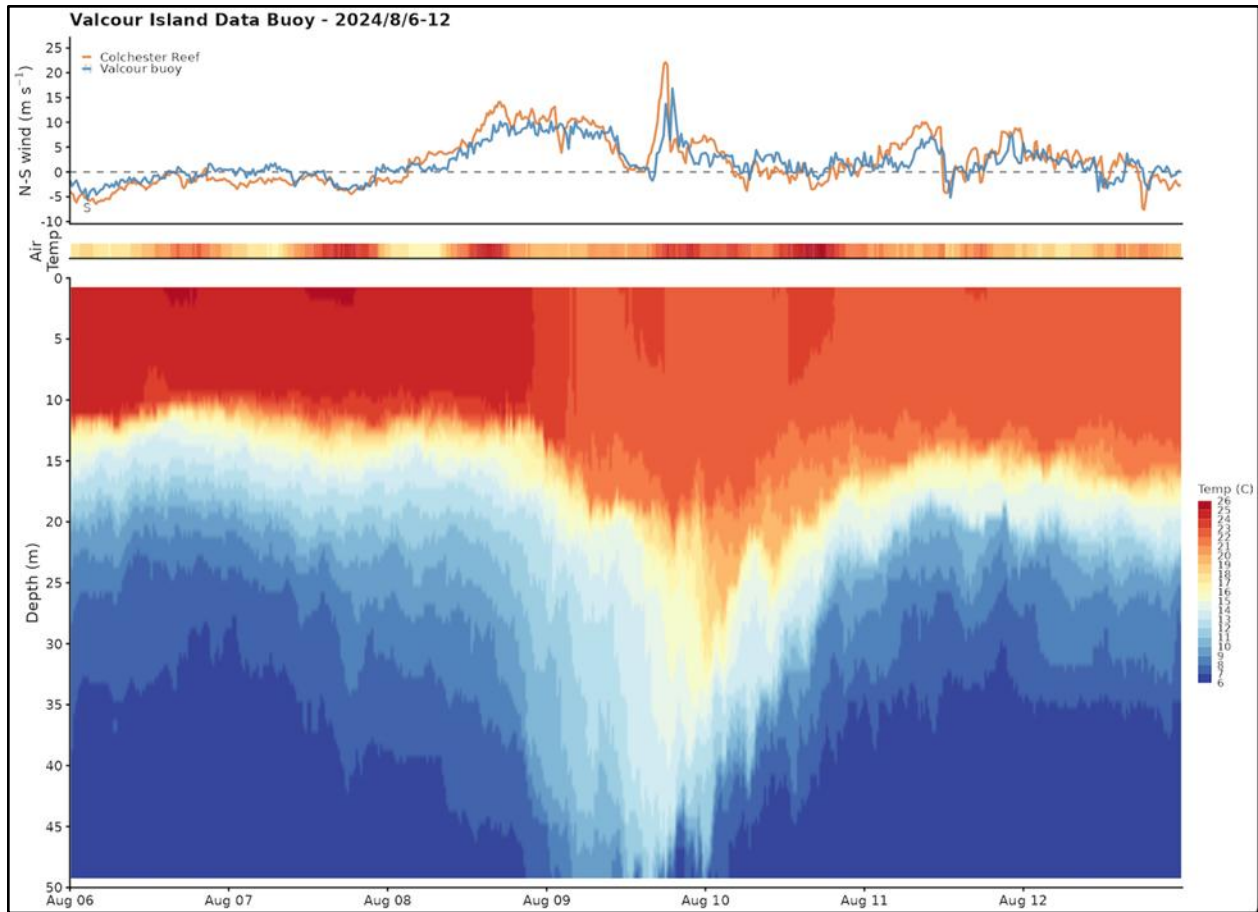


Figure 1. Thermal temperature profile at the Valcour buoy site with a change in structure following a wind event on 8/09/24.

Although extreme events, including storms, can be difficult to physically study in large, deep lakes, as they are often rare, short-lived, hard to predict, and pose safety concerns (Mesman et al., 2022), the deployment and utilization of higher frequency monitoring buoy data offers a unique perspective to understand the influence of storms on these systems in real time. To help address critical knowledge gaps in deep lake limnology and improve the understanding of wind events on deep lake stratification, we use 10 years of monitoring-buoy data to characterize the impacts of storm events on Lake Champlain, a large, dimictic temperate lake that has been subject to more frequent and extreme weather events in recent decades (Jeppesen et al., 2021). Specifically, we aim to assess the magnitude and frequency of wind-driven disruptions to deep

lake stratification and temperature profiles in Lake Champlain's Main Lake basin; as well as categorize and analyze these storm events by quantifying their intensity, duration, and the time required for thermal conditions to return to pre-storm conditions. By characterizing events in this lake, we aim to establish a foundation for how storms may impact Lake Champlain, and other similar deep-lake ecosystems.

Data and Methods

Study Site

Lake Champlain is a 1,127 km² freshwater lake with a mean and maximum depth of 19.5 m and 122 m, respectively (Myer and Gruendling, 1979; Cohn et al., 2007). The lake has a complex bathymetry and comprises five distinct basins: South Lake, Malletts Bay, Northeast Arm, Missisquoi Bay, and Main Lake - the deepest basin and focus of this study (Figure 2; Myer and Gruendling, 1979; Facey et al., 2012). Winds in this region are primarily southerly (*i.e.*, from the south), and are tunneled by the surrounding Adirondack and Green Mountains (Laird et al., 2009). The Main Lake basin of Lake Champlain is located just south of Valcour Island. With a surface area of 682 km², it contains approximately 80% of Lake Champlain's total water volume. It exhibits considerable internal variability and is classified as oligotrophic to mesotrophic (Myer and Gruendling, 1979). At the onset of summer stratification, the Main Lake's long, deep, and narrow bathymetry cause currents and internal seiches with a typical period of 3.9 - 4.6 days (Hunkins, 1998; Manley et al., 2004). Summer stratification, resulting in a distinct epi-, meta- and hypolimnion, typically begins in June and persists until late September to November (Myer and Gruendling, 1979).

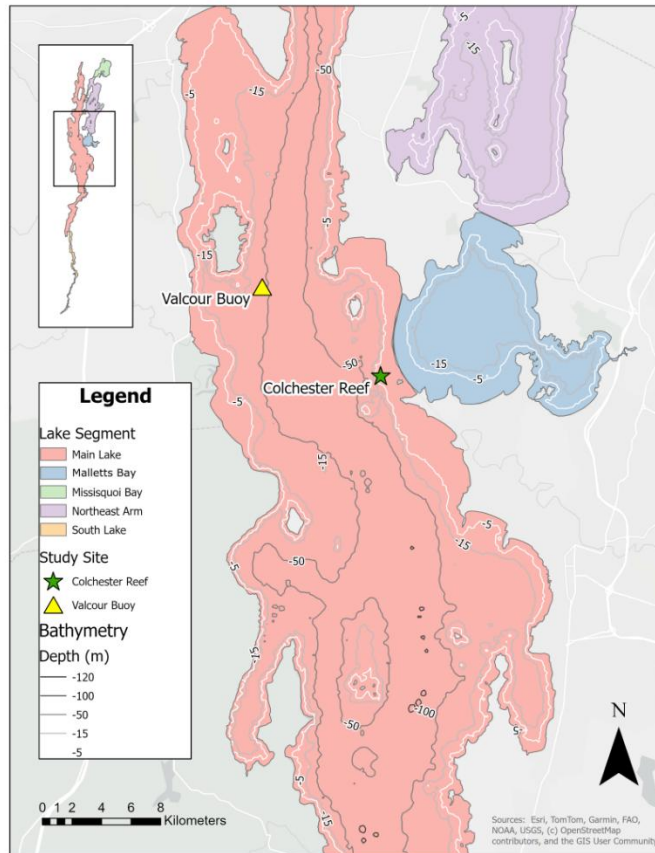


Figure 2. Bathymetric map of Lake Champlain’s Main Lake basin depicting the location of the Valcour Island data buoy (44° 36’ 0” N, 73° 23’ 38.4” W) and Colchester Reef Meteorological Station (44° 33’ 18.36” N, 73° 19’ 45.12” W) which provided wind speed and direction.

Field Methods

Each year since 2016, a NexSens CB-450 model data buoy (hereafter referred to as the Valcour buoy) was deployed north of the Main Lake midpoint in 50 m of water for approximately five months (*i.e.*, May to October; Figure 2). From 2016 to 2023, the Valcour buoy was equipped with an AirMar 200WX weather sensor providing real-time measurements of air temperature and atmospheric pressure. In 2024 it was replaced with a Lufft WS-502 Series Smart Weather Sensor to provide additional information on UV solar radiation and humidity, and a NexSens wave sensor (SVS-603HR) to measure wave height, direction, and period. A NexSens ADCP (Aanderaa 5400,

Acoustic Doppler Current Profiler Sensor) was mounted to the buoy in 2025 and programmed to measure current velocity and direction at 5 m intervals from 2.5 m to 47.5 m water depth. Finally, throughout the entire 10-year monitoring period, a NexSens TS210 thermistor string was attached to the buoy to provide 1 m spatial resolution for the first 30 m and 2 m resolution thereafter to a depth of 49 m.

Data were downloaded every 15 minutes to NexSens' WQ Data Live interface, facilitating real-time conditions of developing and on-going storm events. Although data for this project were available between May-October from 2016-2025, our focus was on late summer and fall (*i.e.*, July 15-September 15) when the Main Lake has stratified, and storm and high-wind events are more frequent in the region.

Data Analysis

Detecting and Categorizing Storms

All data processing and visualization to analyze seasonal patterns, thermal profiles, and storm events was completed in R (R core Team, 2026; version 4.4.1) using the *tidyverse* package (Wickham et al., 2019), the *lubridate* package for date-time manipulation (Grolemund and Wickham, 2011), the *rLakeAnalyzer* package for water analyses (Winslow et al., 2019), and the *strucchange* package for breakpoint analyses (Zeileis et al., 2002; 2003). To categorize and quantify storms, we used the *meta.depths* and *thermo.depth* functions in *rLakeAnalyzer* to determine the depths of the thermocline, top of the metalimnion (epilimnion), and bottom of the metalimnion (hypolimnion) (Winslow et al., 2019). Although using raw temperature data to diagnose stratification is widely used, the water density method utilized by *rLakeAnalyzer* is more physically fundamental and provides more consistent epilimnion conditions in mid-summer months (Wilson et al., 2020).

The `meta.depths` function calculates both the top and bottom depths of the metalimnion in a stratified lake; however, we primarily focused on the bottom of the epilimnion (*i.e.*, top of the metalimnion), as it is common in biological limnology to relate the bottom of the epilimnion to productivity (Wilson et al., 2020). Additionally, although the default settings in *rLakeAnalyzer* identifies stratification if the density gradient is larger than 0.10 kg/m³, we found this condition to be too lax for Lake Champlain and increased it to 0.15 kg/m³ to provide stricter conditions for thermocline detection (Winslow et al., 2019). This larger threshold was determined through extensive evaluation of observed conditions throughout the warm season.

Storm events were identified by detecting instances when the maximum epilimnion depth exceeded 25 m. Detected events were then classified into 5 severity levels based on the maximum depth the epilimnion reached in a given event: 25-30 m (Level 1), 30-35 m (Level 2), 35-40 m (Level 3), 40-45 m (Level 4), 45-50 m (Level 5). All 77 storms were cataloged and assigned a unique storm ID number. Previous work by Andersen et al., (2020) attempted to detect storms using a wind energy input calculation but found it ineffective due to a highly erratic wind output. As a result, they relied on “smoothed wind speed data” to detect storms. Our methods deviated from this approach. We used changes in thermal gradient to detect storms, which enables further classification. Specifically, this method captures variations in energy transfer that wind speed alone cannot represent, providing a more comprehensive measurement of the transfer of wind energy into the water.

Wind Speed and Direction

Long-term wind data, spanning 2016-2025, were obtained from the nearby Colchester Reef Meteorological Station, located ~7 km from the buoy and positioned ~8 m above the lake surface (Figure 2). Weather data were measured every 15 minutes resulting in comparable time increments

to the Valcour data buoy. Average wind speed (m s^{-1}) for each mean storm behavior level was calculated with standard deviation following methods similar to Doubek et al., (2021). However, whereas Doubek et al., (2021) calculated the average wind speed of storms from 00:00 to 23:59, we calculated mean wind speed using data gathered 24 hours before and after the date and time in which the maximum epilimnion was reached. Wind and storm data were combined and used to calculate the mean wind velocity and direction.

Mean State of Storms

To capture the mean state condition of each storm level, observations collected within a 96-hour window surrounding each maximum epilimnion depth were compiled (*i.e.*, 48 hours before and after the maximum epilimnion depth occurred). Mean conditions were extracted from a total of 40 Level 1, 15 Level 2, 8 Level 3, 4 Level 4, and 7 Level 5 storms using 15-minute rolling averages ($k = 10$; Table 1; Figure S1; Table S1). Of the 77 total storms, only one Level 4 (storm ID 95) and one Level 5 (storm ID 44) event were discarded due to irregular behavior and the onset of late season fall turnover, which resulted in irregular values of the pycnocline.

To further characterize each storm, the temporal rate of change in wind and epilimnion depth were calculated throughout the storm forcing and recovery stages using the following criteria (Table 2). For Level 1-3 events, storm forcing for wind and epilimnion depth began when wind speeds reached $>5 \text{ m s}^{-1}$ and continued until a maximum wind speed and epilimnion depth were reached. For Level 4 and 5 events, storm forcing began once wind speeds started to continuously increase, with wind forcing persisting until the maximum wind speed was recorded. Epilimnion forcing was calculated until the metalimnion collapse began, at which point the slopes of the metalimnion collapse were determined using the point where the collapse was continuous up until the maximum epilimnion depth was reached. For both wind and epilimnion depth, storm recovery

was determined by calculating the slope between maximum wind speed and/or epilimnion depth and their corresponding values 48 hours later.

Acoustic doppler current profiler (ADCP) data, available only for the 2025 season, were utilized to better understand Lake Champlain hydrodynamics (*i.e.*, current direction and velocity). Specifically, we focused on one Level 5 event spanning August 23-27, 2025 to look for any potential seiche activity. Although only one high-intensity event was analyzed, this facilitates understanding of basin-scale water movement, rather than at a single buoy site.

Results

Water Temperature

Trends in maximum surface temperatures followed a consistent pattern of warming followed by seasonal cooling across 2016-2025, with the maximum surface temperature ranging from 23.14-26.21°C, typically occurring between July 20 and August 23 (Figure 3). Following these maximum dates, temperatures declined as convective cooling began.

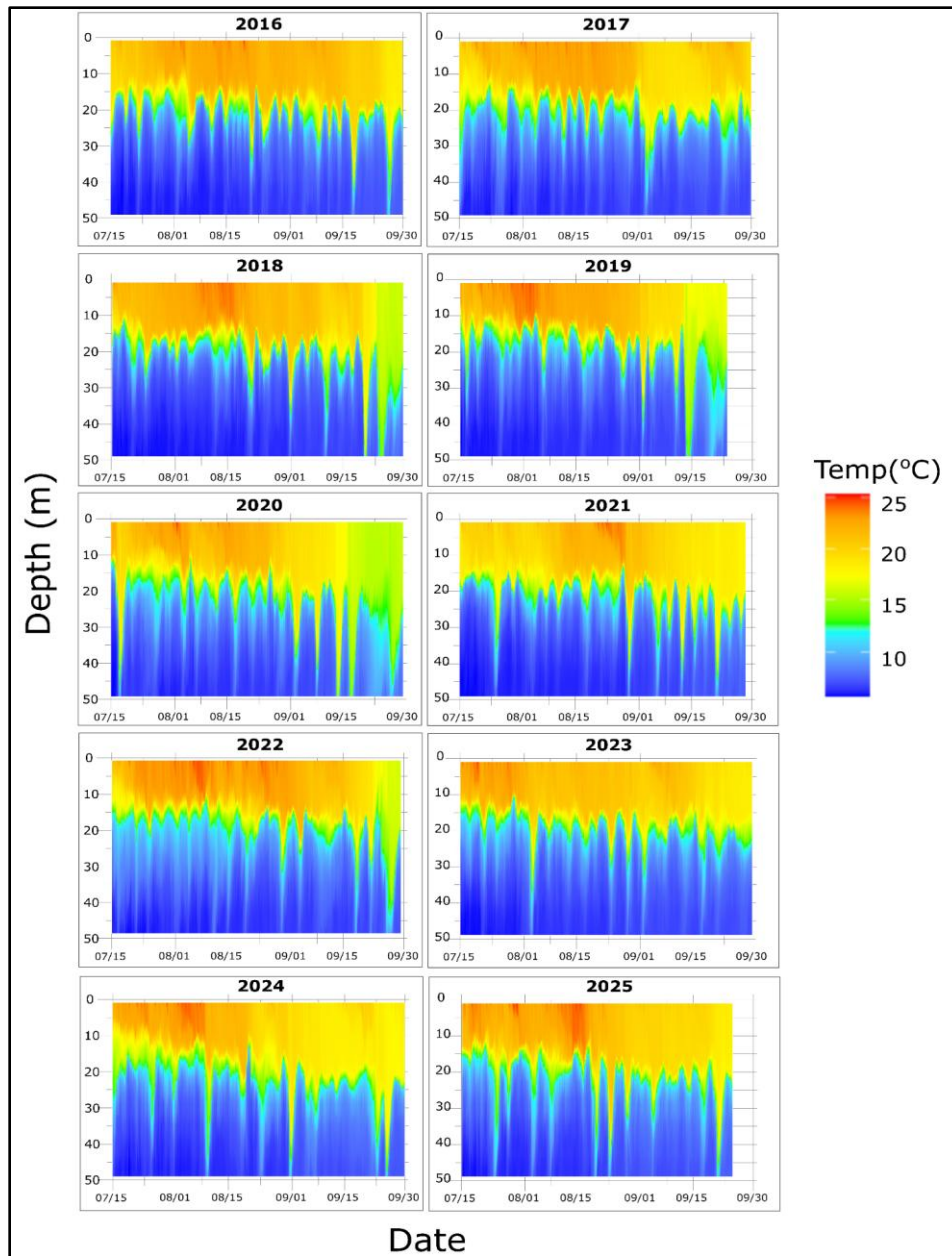


Figure 3. Annual (2016-2025) vertical thermal temperature profiles at the Valcour Buoy from July 15-September 30.

Across the entire dataset and monitoring season, 2020 was the warmest year overall, reaching the highest maximum surface temperature (Figure 3). Similarly, 2017 was the coolest year overall with the lowest maximum surface temperature. Notably, 2021 had the second highest

maximum temperature, but was the second coolest year overall, reaching its maximum temperature the latest, while 2023 had the earliest warmup date out of the dataset.

Storm Frequency, Intensity, and Seasonality

A total of 77 storms occurred between 2016 and 2025, during which the epilimnion exceeded 25 m depth; however, storm frequency and intensity was highly variable across years, with highest frequency storms recorded in 2018, and least in 2024 (Figure 4a). Low-intensity (Level 1) storms occurred most frequently, accounting for 52% of the total storms. Storm counts generally decreased as severity increased, with Level 2-5 storms accounting for the remaining 19, 10, 8, and 10 percent of total storms, respectively. Although 2018 experienced the highest frequency of storms, it did not include any high-intensity (Level 4, 5) storms. Similarly, 2016 and 2017 were dominated by low-intensity (Level 1, 2) storms, with only a single event reaching Level 3 and Level 4, respectively. In contrast, beginning in 2019, at least one Level 4 or 5 storm occurred annually, during which the epilimnion reached the lake bottom, with the exception of 2022, which had the second lowest storm frequency and lowest intensity. Despite this observed pattern, breakpoint analysis revealed no significant shift in the frequency of storm intensity over time (*strucchange* package: $p = 0.59$).

A distinct seasonal pattern of storm events was observed over time, with Level 1 storms occurring regularly throughout the study period, and higher-severity storms (Level 3 or greater) generally restricted to late summer (*i.e.*, post-August 15; Figure 4b). This pattern is particularly apparent between 2016-2019, when no Level 3-5 storms occurred until late August. In contrast, beginning in 2020, Level 3-5 storms began to form earlier in the season, between July 19th and August 8th. Breakpoint analysis confirmed this trend and detected a shift in the timing of high-intensity storms beginning in 2021 ($p = 0.018$).

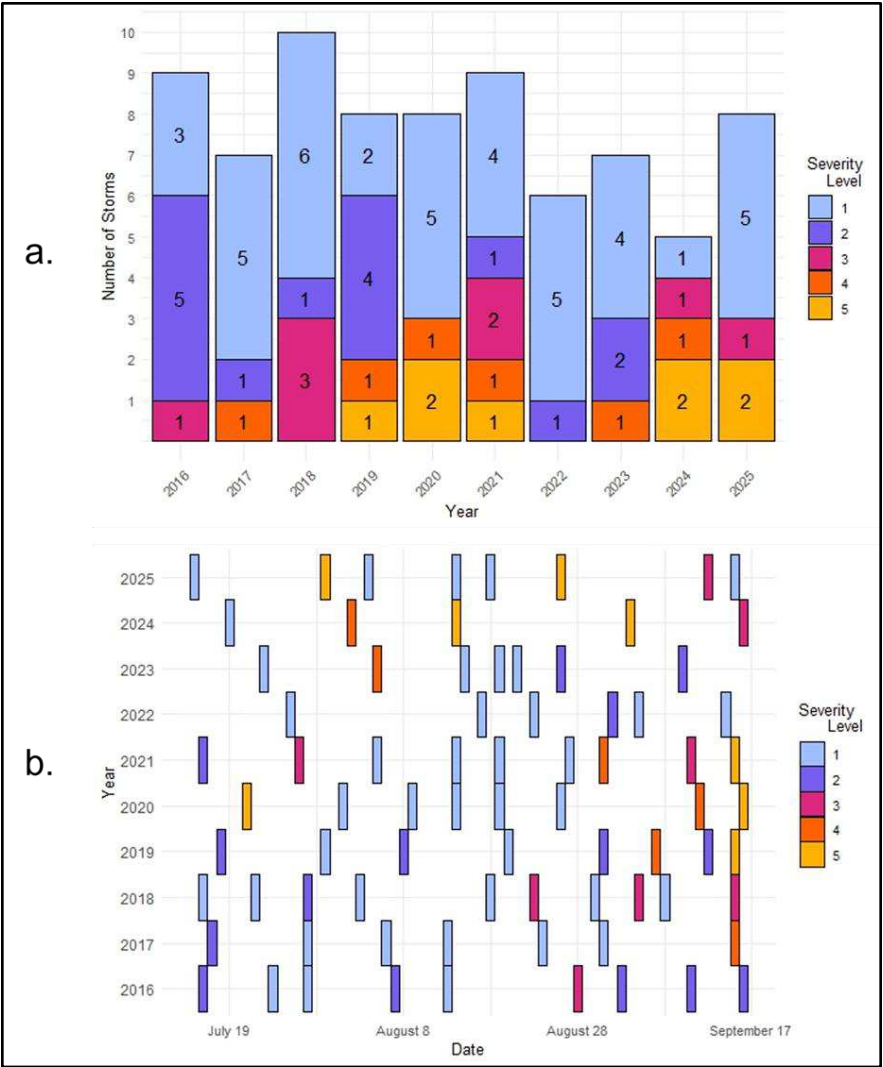


Figure 4. (a) Total number of storms from 2016-2025 and (b) Seasonality of storms between July 15 and September 15, grouped by Severity Level – 1 through 5 (*i.e.*, the maximum depth reached by the epilimnion).

Wind

Winds associated with storm events were strongly directional, dominated by southerly (150°-210°) followed by notably smaller south-easterly winds (120°-150°; Figure 5a; Table S2). Westerly winds were the third most dominant, whereas easterly winds were almost entirely absent. Southerly wind speed was similar across years, ranging from 20,000~27,000 m s⁻¹ with little

variation, aside from 2022 when total southerly wind speeds did not exceed 10,000 m s⁻¹ (Figure 5b). Wind speed was typically lower (70% of the time) during the early fall period (mid-July to mid-August) compared to later in the season (mid-August to mid-September), particularly during 2022, where southerly winds were near absent until the end of the fall season (Figure 5c).

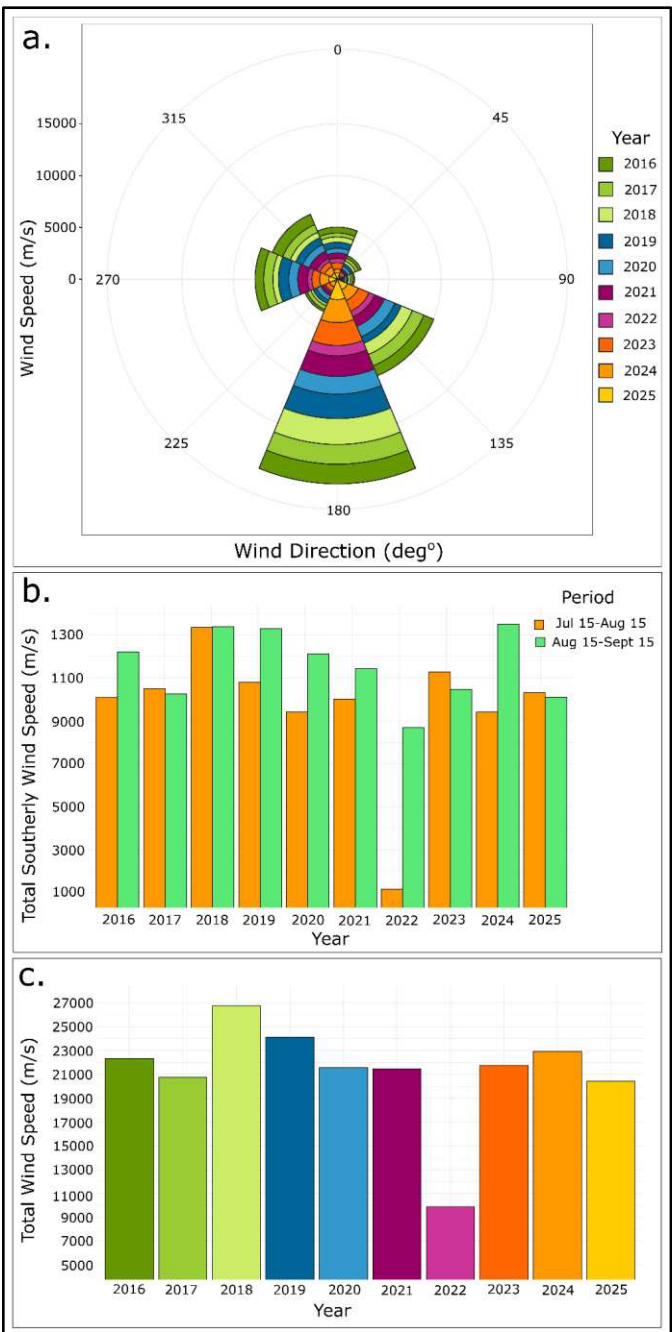


Figure 5. (a) Wind speed (m s^{-1}) and direction (deg°) annually from July 15-September 15, (b) total southerly wind speed (m s^{-1}) annually from July 15-September 15, (c) wind speed binned into beginning of fall (Jul. 15-Aug. 15) compared to late (Aug. 15-Sept.15) season. All wind data were derived from the Colchester Reef Meteorological Data (FEMC 2017).

Valcour Buoy Average Storm Behavior

Level 1 category storms maintained a consistent metalimnion throughout the storm duration (96-hour monitoring period), where both the top and bottom layers were pushed down collectively, never fully converging (Figure 6a). During these events, the epilimnion and hypolimnion maximum depths reached average values of 24.04 m and 24.85 m, respectively. Winds were primarily southerly with wind speeds peaking to approximately 8.25 m s^{-1} , roughly 17.3 hours prior to the maximum epilimnion depth. Wind forcing persisted for 26 hours before speeds began to decrease.

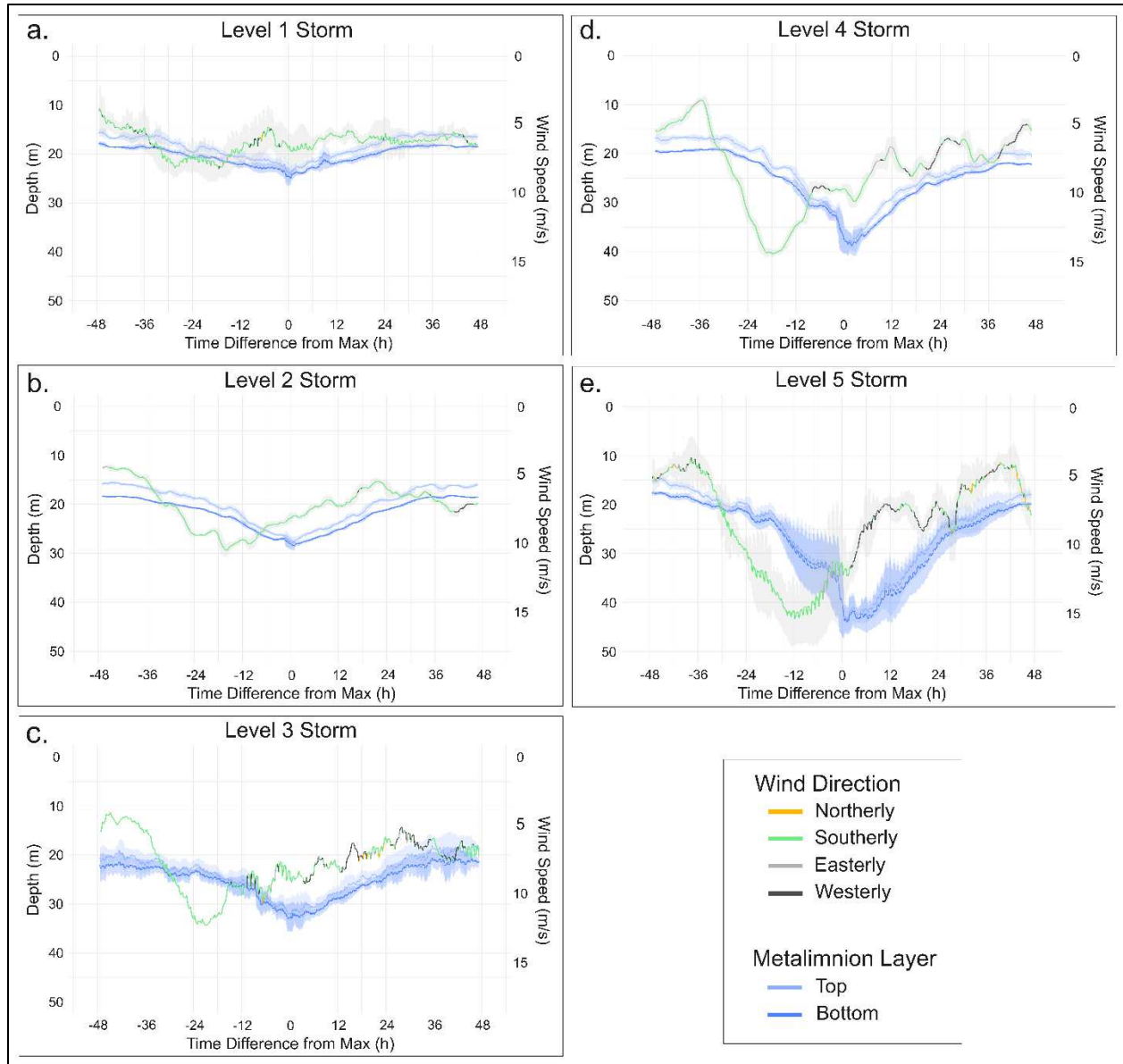


Figure 6. Mean conditions at the top (epilimnion) and bottom (hypolimnion) of the metalimnion across all 40, Level 1 (a), 15 Level 2 (b), 8 Level 3 (c), 4 Level 4 (d), and 7 Level 5 (e) storms from 2016-2025. Mean wind speed (m s^{-1}) over the same periods is shown on a secondary axis, with wind direction (deg°) depicted by different colors.

Level 2 category storms behaved similarly to Level 1's, maintaining a defined metalimnion throughout the storm events despite the epilimnion and hypolimnion reaching maximum depths of 27.80 m and 28.43 m respectively (Figure 6b). Southerly winds dominated, with speeds peaking

at 10.56 m s^{-1} , approximately 16 hours prior to the maximum epilimnion depth. Wind forcing duration was slightly shorter than Level 1 storms, persisting for approximately 22.75 hours before beginning to decrease.

Unlike Level 1 or 2 storms, Level 3 category storms were characterized by multiple, intermittent collapses of the metalimnion (*i.e.*, the same top and bottom metalimnion values), creating an intermediate state between stable stratification and complete lake mixing (Figure 6c). Specifically, over 20 instances were recorded beginning 30 hours prior to the maximum epilimnion depth, with each intermittent collapse persisting for approximately 15 minutes. During these events, the epilimnion and hypolimnion reached maximum depths of 32.24 m and 32.91 m respectively. Winds were primarily from the south, with peak speeds of approximately 12.32 m s^{-1} occurring about 16.75 hours prior to the maximum epilimnion depth. The duration of wind forcing was shorter than Level 1 or 2 storms, lasting roughly 16.75 hours before decreasing.

Once storms reached category Level 4 and the epilimnion declined to 33 m depth, the metalimnion collapses and remains collapsed for longer than the 15-minute periods observed in Level 3's, in what we refer to as a metalimnion continuous collapse period (MCCP; Figure 6d). During these events, the metalimnion remains collapsed for 1.75 hours on average, beginning roughly 0.5 hours prior the maximum epilimnion depth. As with Levels 1-3 storms, winds were predominantly from the South. However, prior to the MCCP, both the epilimnion and hypolimnion depths plateaued, coincident with a near simultaneous plateau in wind speed and shift in wind direction. Epilimnion and hypolimnion depths remained constant for ~3 hours before rapidly declining to maximum depths of approximately 38 m. Wind speeds peaked at 14.47 m s^{-1} , occurring 17.75 hours prior to the maximum epilimnion depth on average. As with Level 3 storms, wind forcing duration persisted for 16 hours before beginning to decrease.

Finally, Level 5 category storms also exhibited metalimnion continuous collapse periods (MCCPs), beginning once the epilimnion reached depths of roughly 41.61 m (Figure 6e). As with Level 4 events, the MCCPs began 0.5 hours prior to the maximum epilimnion depth (47.54 m). However, unlike Level 4's, the metalimnion reformed following maximum epilimnion depth, and instead experienced intermittent collapses for the next 6 hours more like Level 3 storms. Winds were predominantly southerly, with maximum speeds of approximately 15.57 m s^{-1} occurring roughly 11.75 hours prior to the maximum epilimnion depth, and an average wind forcing duration of 21.58 hours. Interestingly, the largest decrease in epilimnion depth and formation of the MCCP corresponds with a reduction in wind speed and shift in direction.

Table 1 Summary metrics for Severity Level 1–5 storms calculated from the mean state using a moving average ($k = 10$).

Severity Level	Epilimnion Max Depth (m)	Hypolimnion Max Depth (m)	Peak Wind Speed (m s^{-1})	Wind Forcing Duration (h)	Lag Time (h)	MCCP (h)	Potential Impacts on Biota
1	24.04	24.85	8.25	26.00	-17.3	NA	Weak
2	27.80	28.43	10.26	22.75	-16.0	NA	Weak
3	32.24	32.91	12.32	16.75	-20.8	NA	Intermediate
4	38.22	38.81	14.47	16.00	-17.8	1.75	Strong
5	43.48	43.93	15.57	21.58	-11.8	0.50	Strong

Table 2 Storm metric slopes for each storm level.

Severity Level	Wind Speed Storm Forcing	Wind Speed Recovery	Epilimnion Storm Response	Epilimnion Storm Response – if MCCP	Metalimnion Collapse, LTE	Epilimnion Recovery
1	-0.12	0.04	-0.15	NA	NA	0.15
2	-0.24	0.08	-0.31	NA	NA	0.25
3	-0.43	0.13	-0.29	NA	NA	0.24
4	-0.59	0.17	NA	-0.58	-7.48	0.40
5	-0.49	0.22	NA	-0.62	-11.86	0.53

Opportunistic ADCP data collected during an August 23-27 Level 5 storm event helps demonstrate the relationship between wind and water currents (Figure 7). Sustained southerly wind forcing creates north moving currents throughout the water column, with peak current velocity (30

364 cm/s) corresponding with maximum wind speeds. Following this peak, both current velocity and
365 wind speeds decreased for approximately 12 hours before current velocity increased again despite
366 simultaneous reductions in wind speed. During this second increase in current velocity, winds
367 remained southerly and began to shift westerly, whereas currents rotated direction 180 degrees and
368 began flowing south throughout the water column, consistent with reversals in flow observed by
369 Myer and Gruendling (1979).

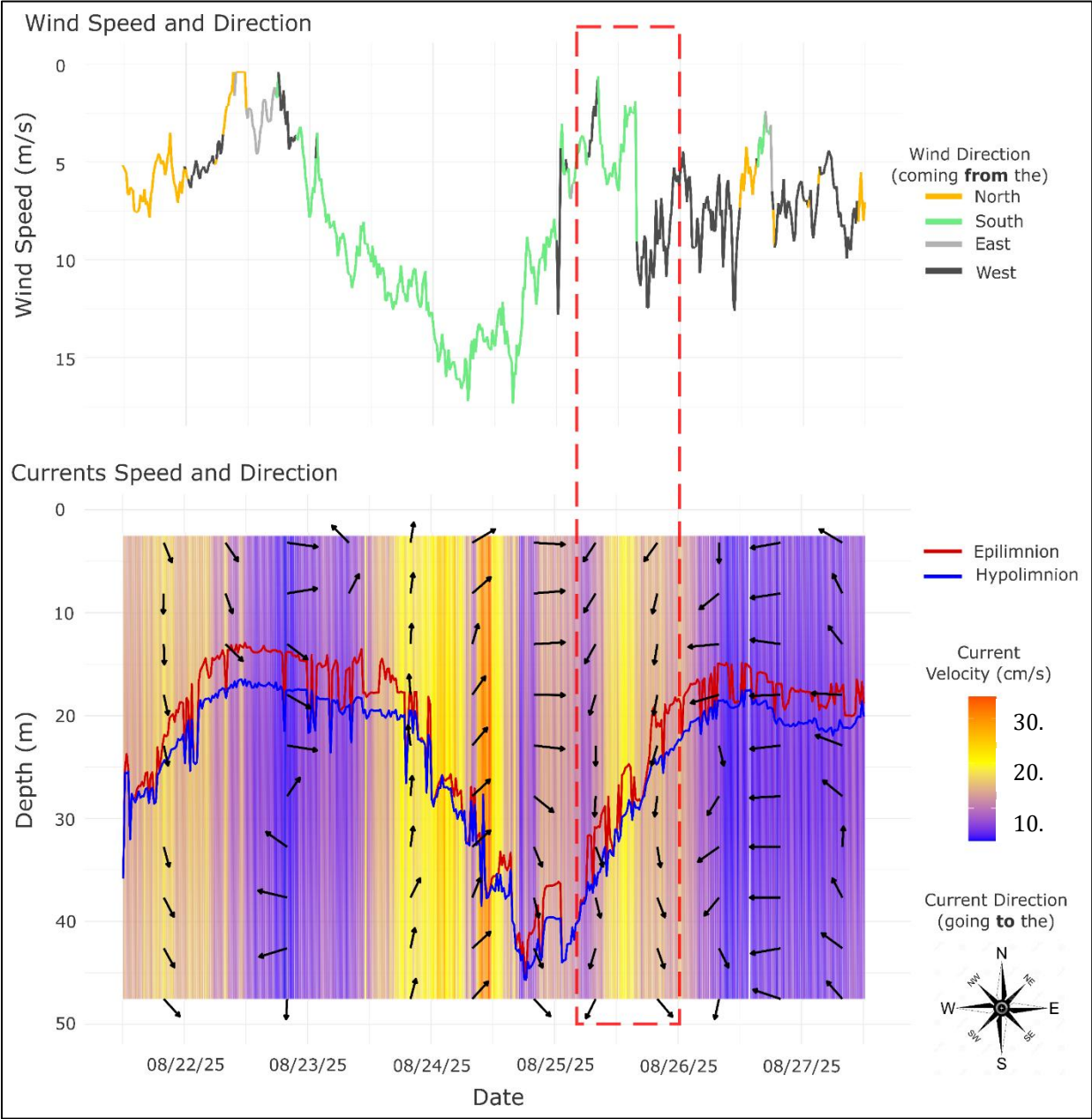


Figure 7. Wind speed and direction (top) and corresponding water current velocity and direction (bottom) captured during a Level 5 storm in August 2025. Colored lines for wind indicate the direction from which winds derive. Colored backgrounds for currents indicate current velocity with black arrows indicating the direction currents are flowing towards at 2.5 m depth intervals. Red and blue lines represent epilimnion and hypolimnion depths throughout the storm event with the red dashed box highlighting a period consistent with seiche-driven tilting or the passage of an internal bore/wave.

Discussion

While storm events have been increasing in frequency and duration in recent years, most studies have focused on characterizing their impacts on medium and small shallow lakes, with limited work on large, deep freshwater systems. To address this knowledge gap, we utilized a long-term dataset of high-resolution data buoy observations to improve the understanding of the effects of storms on Lake Champlain. Results suggest that the frequency and timing of high-intensity storms (Levels 3-5) vary widely and can trigger metalimnion continuous collapse periods (MCCPs). Intense storms occurring irregularly, and the resulting localized mixing during the MCCPs has important implications for biological and chemical processes. These findings demonstrate the extreme impacts of more frequent and severe storms on deep lake limnology and highlight the importance of continued monitoring to comprehensively characterize these events over prolonged timescales.

Storm Frequency and Intensity 2016-2025

Collectively, Level 1 and 2 storms were the most dominant storm type throughout the study period, comprising 71% of Lake Champlain storm events. Storm intensity is related to initial thermal structure and resulting Schmidt stability. Generally, low-intensity storms require less

energy and thus can occur more frequently. In comparison, the high-intensity Level 3-5 storms are incited by greater wind forcing and more specific atmospheric conditions. However, the thresholds shift as the degree of stability changes through the seasons (Jennings et al., 2012). Although our observations do not suggest an increased frequency in high-intensity storms over the past decade, there has been a shift since 2021 of strong storms able to influence lake stratification beginning earlier in the season. The majority of Level 3-5 storms still occurred after August 15, in concert with seasonal cooling and further driving the breakdown of stratification (Yan et al., 2018). Epilimnion temperature declines in discrete steps during the late summer/fall strong storms, consistent with sequential entrainment events tied to individual wind pulses within the storm, rather than a single continuous mixing process.

Epilimnion thickness is influenced by factors such as lake morphology, seasonality, fetch, and wind action, including storm events (Boeher and Schultz, 2008). Accordingly, our findings show a positive relationship between epilimnion depth and storm intensity coupled with wind speed, with a deeper epilimnion associated with increased storm intensity (Table 1). However, once storms reach Level 3, the top and bottom values of the metalimnion begin to converge, with longer and more pronounced MCCPs in Level 4-5 events. During both Level 4 and Level 5 storms, the MCCP began 0.5 hours before the maximum epilimnion depth. Surprisingly, the continuous collapse period for Level 5 storms was shorter than Level 4's, persisting for only 0.5 hours total before experiencing intermittent collapses for the following 6 hours. To our knowledge, magnitude and locality of metalimnion collapse events have not been studied but are analogous to the temporary entrainment documented in Woolway et al. (2018).

Wind

Lake Champlain weather events have been documented primarily under northerly or southerly winds during winter conditions (Laird et al., 2009). This pattern is consistent with our late summer-fall observations, which were dominated by southerly winds, likely reflecting tunneling by the surrounding Adirondack and Green Mountains (Laird et al., 2009).

These primarily uni-directional wind events have important implications for lake dynamics. Wind energy is transferred to the surface water through friction, generating waves, currents, and turbulence that redistribute heat, nutrients, and dissolved oxygen throughout the water column (Nixon, 1988; Bohrer and Schultze, 2008). The magnitude of these effects depends on wind speed and duration, as well as lake fetch and bathymetry (Nixon, 1988). Stronger, sustained winds along a narrow, long lake like Lake Champlain can deepen the epilimnion which can initiate interaction between the epi- and hypolimnion and weaken stratification (Bohrer and Schultze, 2008). This interaction is occurring in our Level 4 and 5 storms, potentially resulting in temporary nutrient and oxygen exchange, whereas wind stress for lower intensity Level 1-3 storms, likely only impacts the surface/epilimnion waters (Boyce et al., 1989).

In Lake Champlain, strong storms caused temporary metalimnion continuous collapse periods (MCCPs) lasting between 0.5 and 1.75 hours, before the metalimnion reformed and returned to equilibrium over the next 12-24 hours. This recovery in thermal stratification indicates that our observations of storm responses before September 15 are a result of localized deepening of the metalimnion rather than complete basin overturn, which typically occurs in Lake Champlain in late fall (Manley et al., 1999). Long-term observations from the Main Lake basin of Lake Champlain indicates warming of the hypolimnion (Manley et al., 1999); however, the mechanisms driving this warming remain uncertain. Manley et al., (1999) suggested that these temperature increases may result either from surface outcropping of hypolimnetic waters during periods of

reduced stratification or from enhanced internal mixing at the shoaling ends of the lake, processes that can be intensified by strong wind events. A third suggestion based on findings from this study could be that storm-induced mixing delivers warm epilimnetic water to the lake bottom, with more frequent, high-intensity storms gradually increasing hypolimnetic temperatures over time. It is also likely that all three possibilities work in concert to warm the hypolimnion prematurely, with potentially negative implications for aquatic species, though exploring this possibility was beyond the scope of this manuscript.

Lake Champlain Storm Behavior

Wind forcing duration varied across storm severity levels, though generally decreased with storm severity, except for Level 5 storm events, which had the third longest total wind forcing duration. Wind speed and epilimnion depths exhibited steeper slopes during storm forcing than during post-storm recovery, underscoring the positive relationship between wind speed and thermal structure.

All storms (Levels 1-5) exhibited a consistent lag period between peak wind speed and maximum epilimnion depth, ranging from 11.8 hours (Level 5) to 20.8 hours (Level 3). This delay indicates continued epilimnion deepening after peak wind forcing. In Level 4 and 5 storms, this leads to a metalimnion collapse period. Support for this can be seen in our opportunistic ADCP which captured a late season Level 5 storm in 2025 and highlights several instances of increased current velocity, independent of wind speed and direction (Figure 7). Specifically, it is possible that southerly winds could be driving basin-scale tilting of the water column, pushing epilimnetic waters to the north (as depicted in Figure 8). As a result, localized metalimnion displacement may be forced downward at the buoy site until the wind speeds reduce or change direction as the meteorological front passes. Afterwards, we suspect that the basin undergoes a seiche response as

the water column attempts to return to equilibrium, further depressing the metalimnion beyond the initial wind forced displacement as the system rebounds due to weakened stratification strength. This behavior is most prominent in Level 3-5 storms, likely because the magnitude of the response depends on wind forcing itself (Imberger, 1998; Andersen et al., 2020). As wind stress increases, the resulting turbulent motions deepen the epilimnion further and erode the density gradient of the metalimnion, potentially causing the MCCPs, or localized turbulent entrainment observed in Level 4 and 5 events.

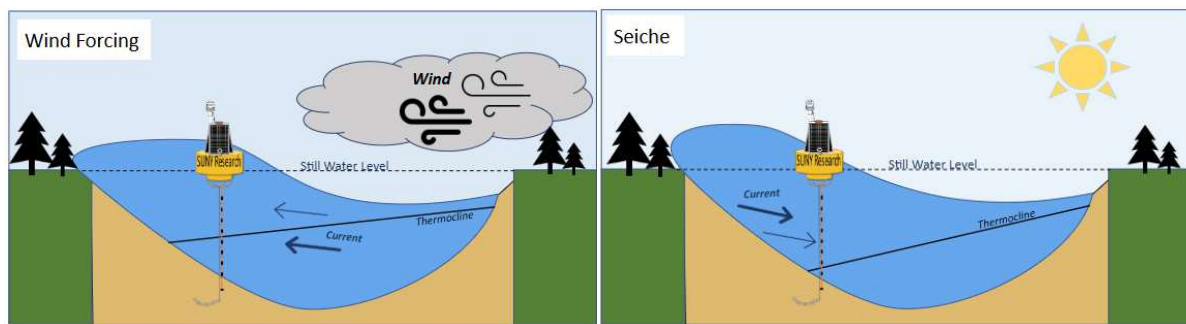


Figure 8. Conceptual diagram depicting influence of wind forcing followed by potential seiche activity, further influencing lake thermal structure and metalimnion depth during storm events.

These high-intensity events likely impact not only the lakes' thermal structure, but also results in rapid changes in overall lake dynamics (Jennings et al., 2012; Woolway et al., 2018). These events are also likely only exhibited in the Main Lake segment, as other segments of the lake vary in depth, fetch, and overall ecology (Myer and Gruendling, 1979). In the future, consideration of wind forcing duration rates and slopes, could potentially be predictive of when and how deep the epilimnion will react and respond along with the ecosystem as a whole.

Potential Impacts on Biota

Although more work is needed to characterize seiche responses to storm events and the relationship to epilimnion depth, the consistent lag times between maximum wind speed and epilimnion depth associated with each storm level can be predictive of when and how deep the

epilimnion will decline. This predictive information could be extremely valuable to future studies, allowing researchers to narrow their focus on when and where to sample to better characterize changes in the physical and biological limnology throughout these events. This is especially important because wind events in Lake Champlain show increasing physical and biological impacts with storm severity. Based on findings by Doubek et al., (2021), low-level storms should have limited influence on biotic responses, with potential implications for lake biota beginning with Level 3 events as the metalimnion begins to experience intermittent collapses. In contrast, Level 4 and 5 storms are likely to have a strong effect on lake communities, as a continuous metalimnion collapse and strong deepening of the epilimnion may facilitate increased vertical interaction between layers. This idea is supported by previous research documenting a redistribution of cyanobacteria and nutrient-rich hypolimnetic water into the surface layer following a moderate to strong wind event (Planas and Paquet, 2016; Weinke and Biddanda, 2019). However, because biological implications were beyond the scope of this study, future work should prioritize understanding biological responses and interactions before, during, and after storms in this region, including how long systems and communities remain in flux. For instance, while thermal structure in this study returned to pre-storm conditions within 48 hours of maximum epilimnion depth, other studies have found stability changes to persist for up to 45 days (Jennings et al., 2012; Andersen et al., 2020), suggesting a lag between biological and physical response times.

Study Limitations

One potential limitation of this study involves its relatively short timescale. Although we synthesize 10 years of data totaling 77 storms, there were relatively few high-intensity storm events (e.g., only 7 total Level 5 events), limiting statistical power and the ability to fully characterize

their impacts. Future work should therefore continue monitoring storm events and recording patterns in thermal structure to build a more comprehensive database characterizing high-intensity storm disturbances. Additionally, the present study was restricted to one monitoring buoy (*i.e.*, sampling point) in Lake Champlain's Main Lake, limiting our ability to fully assess basin-scale impacts and directly tease apart horizontal advection versus diapycnal mixing. The incorporation of additional sampling points in the Main Lake, particularly north and south of the Valcour buoy site should be considered, as these additional sites could help target and characterize seiche activity and responses to storm events, such as oscillation period. Higher frequency observation rates are also needed to completely distinguish LTE from the passage of an internal bore or wave.

Conclusions

As lakes experience greater warming and altered thermal structure from increased storm activity, there is an ever-pressing need to understand the impacts of these storms on large, deep freshwater systems. By categorizing 10 years of storm data into five severity levels based on maximum epilimnion depth, we provide a comprehensive description of the impacts of storm frequency and intensity on Lake Champlain's thermal structure. All storms (Levels 1-5) were driven by sustained southerly winds with the duration of wind forcing and maximum wind speed influencing epilimnion depth. Levels 1 and 2 storms were most frequent but experienced the weakest change in thermal structure, with a distinct metalimnion present throughout each storm event. Beginning with Level 3 events, the metalimnion begins to experience intermittent metalimnion collapses, with full metalimnion continuous collapse periods (MCCPs) lasting up to 1.75 hours observed in stronger Level 4 and 5 storms, likely caused by localized turbulent entrainment and compounded by post-storm seiche activity. This interaction between wind forcing and seiche activity is potentially responsible for the lag time observed between maximum wind

speed and maximum epilimnion depth observed in all storm levels. While more work is needed to better understand this interaction, we propose that in the interim, these lag times can be used to inform future sampling events to collect and begin characterizing biological responses to each storm level. Collectively, this research provides a groundwork for understanding the effect of winds, storms, and subsequent seiches on deep lake limnology and thermal structure.

Acknowledgements

This project was made possible through the support of the Lake Champlain Research Institute and funding provided by the Great Lakes Fishery Commission. Additionally, the authors would like to extend special thanks to Luke Myers, Marshall Arnwine, Allison Morrow, John Hanosek, Steve Cluett, and Mary Alldred for their various contributions to this study.

References

- Andersen, M. R., de Eyto, E., Dillane, M., Poole, R., & Jennings, E. (2020). 13 years of storms: An analysis of the effects of storms on lake physics on the Atlantic fringe of Europe. *Water*, 12(2), 318. <https://doi.org/10.3390/w12020318>
- Arnwine, M., Mihuc, T., Myers, L., Lamay, M., & Cutter, Z. (2025). Vertical distribution patterns of crustaceous zooplankton associated with invasive *Bythotrephes longimanus* and *Cercopagis pengoi* in Lake Champlain (USA). *Diversity*, 17(6), 371.
- Austin, J. A., & Colman, S. M. (2007). Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice–albedo feedback. *Geophysical Research Letters*, 34(6), 1–5. <https://doi.org/10.1029/2006GL029021>
- Boehrer, B., & Schultze, M. (2008). Stratification of lakes. *Reviews of Geophysics*, 46(2), 1-27.
- Boyce, F. M., Donelan, M. A., Hamblin, P. F., Murthy, C. R., & Simons, T. J. (1989). Thermal structure and circulation in the Great Lakes. *Atmosphere-Ocean*, 27(4), 607–642.
- Butcher, J. B., Nover, D., Johnson, T. E., & Clark, C. M. (2015). Sensitivity of lake thermal and mixing dynamics to climate change. *Climatic Change*, 129, 295–305. <https://doi.org/10.1007/s10584-015-1326-1>
- Churchill, J. H., & Kerfoot, W. C. (2007). The impact of surface heat flux and wind on thermal stratification in Portage Lake, Michigan. *Journal of Great Lakes Research*, 33(1), 143–155.
- Doubek, J. P., Anneville, O., Dur, G., Lewandowska, A. M., Patil, V. P., Rusak, J. A., Salmaso, N., Seltmann, C. T., Straile, D., Urrutia-Cordero, P., & Venail, P. (2021). The extent and variability of storm-induced temperature changes in lakes measured with long-term and high-frequency data. *Limnology and Oceanography*, 66(5), 1979–1992.

563 Facey, D. E., Marsden, J. E., Mihuc, T. B., & Howe, E. A. (2012). Lake Champlain 2010: A
 564 summary of recent research and monitoring initiatives. *Journal of Great Lakes Research*,
 565 38, 1–5. <https://doi.org/10.1016/j.jglr.2011.12.001>

566 Forest Ecosystem Monitoring Cooperative. (2017). *Colchester Reef meteorological monitoring*.

567 Grolemond, G., & Wickham, H. (2011). Dates and times made easy with lubridate. *Journal of*
 568 *Statistical Software*, 40(3), 1–25. <https://www.jstatsoft.org/v40/i03/>

569 Guilbert, J., Beckage, B., Winter, J. M., Horton, R. M., Perkins, T., & Bombliès, A. (2014).
 570 Impacts of projected climate change over the Lake Champlain Basin in Vermont. *Journal*
 571 *of Applied Meteorology and Climatology*, 53, 1861–1875. <https://doi.org/10.1175/JAMC->
 572 [D-13-0338.1](https://doi.org/10.1175/JAMC-D-13-0338.1)

573 Havens, K., Paerl, H., Philips, E., Zhu, M., Beaver, J., & Srifa, A. (2016). Extreme weather
 574 events and climate variability provide a lens to how shallow lakes may respond to climate
 575 change. *Water*, 8(6), 229. <https://doi.org/10.3390/w8060229>

576 Hunkins, K. L., Manley, T. O., Manley, P. L., & Saylor, J. H. (1998). Numerical studies of the 4-
 577 day oscillation in Lake Champlain. *Journal of Geophysical Research: Oceans*, 103(C9),
 578 18425–18436. <https://doi.org/10.1029/98JC01450>

579 James, T. R., Chimney, M. J., Sharfstein, B., Engstrom, D. R., Schottler, S. P., East, T., &
 580 KangRen, J. K. (2008). Hurricane effects on a shallow lake ecosystem, Lake
 581 Okeechobee, Florida (USA). *Journal of Great Lakes Research*, 34(Supplement 1), 86–97.

582 Jennings, E., Jones, S., Arvola, L., Staehr, P. A., Gaiser, E., Jones, I. D., Weathers, K. C.,
 583 Weyhenmeyer, G. A., Chiu, C. Y., & de Eyto, E. (2012). Effects of weather-related
 584 episodic events in lakes: An analysis based on high-frequency data. *Freshwater Biology*,
 585 57(3), 589–601.

586 Jeppesen, E., Pierson, D., & Jennings, E. (2021). Effect of extreme climate events on lake
 587 ecosystems. *Water*, 13(3), 282. <https://doi.org/10.3390/w13030282>

588 Kimura, N., Wen-Cheng, L., Jeng-Wei, T., Chih-Yu, C., Kratz, T. K., & Tai, A. (2017).
 589 Contribution of extreme meteorological forcing to vertical mixing in a small, shallow
 590 subtropical lake. *Journal of Limnology*, 76(1), 116-128.

591 Kraemer, B. M., Anneville, O., Chandra, S., Dix, M., Kuusisto, E., Livingstone, D. M., Rimmer,
 592 A., Schladow, S. G., Silow, E., Sitoki, L. M., Tamatamah, R., Vadeboncoeur, Y., &
 593 McIntyre, P. B. (2015). Morphometry and average temperature affect lake stratification
 594 responses to climate change. *Geophysical Research Letters*, 42, 4981–4988.
 595 <https://doi.org/10.1002/2015GL064097>

596 Laird, N. F., Desrochers, J., & Payer, M. (2009). Climatology of lake-effect precipitation events
 597 over Lake Champlain. *Journal of Applied Meteorology and Climatology*, 48(2), 232–250.

598 MacIntyre, S. (1993). Vertical mixing in a shallow, eutrophic lake: Possible consequences for the
 599 light climate of phytoplankton. *Limnology and Oceanography*, 38(4), 798–817.

600 Manley, T. O., Hunkins, K. L., Saylor, J. H., Miller, G. S., & Manley, P. L. (1999). Aspects of
 601 summertime and wintertime hydrodynamics of Lake Champlain. In *Lake Champlain in*
 602 *transition: From research toward restoration 1*, 67–115.

603 Manley, T. O. (2004). Hydrodynamics of the South Main Lake and South Lake, Lake
 604 Champlain. In T. O. Manley, P. L. Manley, & T. B. Mihuc (Eds.), *Lake Champlain:*
 605 *Partnerships and research in the new millennium* (pp. 349-383). Springer.
 606 https://doi.org/10.1007/978-1-4757-4080-6_19

607 Marsden, J. E., & Hauser, M. (2009). Exotic species in Lake Champlain. *Journal of Great Lakes*
 608 *Research*, 35(2), 250–265. <https://doi.org/10.1016/j.jglr.2009.01.006>

609 Mesman, J. P., Ayala, A. I., Goyette, S., Kasparian, J., Marce, R., Markensten, H., Stelzer, J. A.
 610 A., Thayne, M. W., Thomas, M. K., Pierson, D. C., & Ibelings, B. W. (2022). Drivers of
 611 phytoplankton responses to summer wind events in a stratified lake: A modeling study.
 612 *Limnology and Oceanography*, 67(4), 856–873. <https://doi.org/10.1002/lno.12040>
 613 Myer, G. E., & Gruendling, G. K. (1979). *Limnology of Lake Champlain*. Lake Champlain Basin
 614 Study. New England River Basins Commission, Burlington, VT.
 615 National Weather Service. (n.d.). *Time series for Burlington, VT (UVM02)*. National Oceanic and
 616 Atmospheric Administration. Retrieved September 4, 2025, from
 617 https://www.weather.gov/wrh/timeseries?site=UVM02&units=english_k
 618 Nixon, S. W. (1988). Physical energy inputs and the comparative ecology of lake and marine
 619 ecosystems. *Limnology and Oceanography*, 33(4, Part 2), 1005–1025.
 620 North, R. P., North, R. L., Livingstone, D. M., Koster, O., & Kipfer, R. (2014). Long-term
 621 changes in hypoxia and soluble reactive phosphorus in the hypolimnion of a large
 622 temperate lake: Consequences of a climate regime shift. *Global Change Biology*, 20,
 623 811–823. <https://doi.org/10.1111/gcb.12371>
 624 Nowlin, W. H., Evarts, J. L., & Vanni, M. J. (2005). Release rates and potential fates of nitrogen
 625 and phosphorus from sediments in a eutrophic reservoir. *Freshwater Biology*, 50, 301–
 626 322. <https://doi.org/10.1111/j.1365-2427.2004.01316.x>

627 O'Reilly, C.M., Sharma, S., Gray, D.K., Hampton, S.E., Read, J.S., Rowley, R.J., Schneider, P.,
 628 Lenters, J.D., McIntyre, P.B., Kraemer, B.M. and Weyhenmeyer, G.A. (2015). Rapid and
 629 highly variable warming of lake surface waters around the globe. *Geophysical Research*
 630 *Letters*, 42(24), 10773–10781. <https://doi.org/10.1002/2015GL066235>
 631 Pettersson, K., Grust, K., & Weyhenmeyer, G. (2003). Seasonality of chlorophyll and nutrients
 632 in Lake Erken—effects of weather conditions. *Hydrobiologia*, 506, 75–81.
 633 <https://doi.org/10.1023/B:HYDR.00000008582.61851.76>
 634 Planas, D., & Paquet, S. (2016). Importance of climate change—physical forcing on the increase
 635 of cyanobacterial blooms in a small, stratified lake. *Journal of Limnology*, 75, 201–214.
 636 R Core Team (2026). *_R: A Language and Environment for Statistical Computing_*. R
 637 Foundation for Statistical Computing, Vienna, Austria. doi:10.32614/R.manuals
 638 <<https://doi.org/10.32614/R.manuals>>. <<https://www.R-project.org/>>.
 639 Read, J.S.R, Hamilton, D. P., Jones, I. D., Muraoka, K., Winslow, L. A., Kroiss, R., Wu, C. H.,
 640 & Gaiser, E. (2011). Derivation of lake mixing and stratification indices from high-
 641 resolution lake buoy data. *Environmental Modelling & Software*, 26(11), 1325–1336.
 642 <https://doi.org/10.1016/j.envsoft.2011.05.006>
 643 Reynolds, C. S., 1997. On the vertical distribution of phytoplankton in the middle Rio Doce Vale
 644 lakes. In Tundisi, J. G. Y. & Saijo (eds), *Limnological Studies on the Rio Doce Valley*
 645 *Lakes, Brazil*. Brazilian Academy of Sciences, Rio de Janeiro: 227–241.
 646 Smeltzer, E., Shambaugh, A. D., & Stangel, P. (2012). Environmental change in Lake
 647 Champlain revealed by long-term monitoring. *Journal of Great Lakes Research*, 38, 6–
 648 18. <https://doi.org/10.1016/j.jglr.2012.01.002>

649 Stager, J. C., & Thill, M. (2010). *Climate change in the Lake Champlain Basin: What natural*
 650 *resource managers can expect and do*. The Nature Conservancy, Keene Valley, NY, and
 651 Montpelier, VT.

652 Stockwell, J.D., Doubek, J.P., Adrian, R., Anneville, O., Carey, C.C., Carvalho, L., De
 653 Senerpont Domis, L.N., Dur, G., Frassl, M.A., Grossart, H.P. and Ibelings, B.W., 2020.
 654 Storm impacts on phytoplankton community dynamics in lakes. *Global Change*
 655 *Biology*, 26(5), pp.2756-2784. <https://doi.org/10.1111/gcb.15033>

656 Wang K., Yao J., Wang J., Liu H. & Yin K. (2022). Role of Winds in Interrupting the Formation
 657 of Coastal Hypoxia. *Front. Mar. Sci.* 9:839812. doi: 10.3389/fmars.2022.839812

658 Weinke, A. D., & Biddanda, B. A. (2019). Influence of episodic wind events on thermal
 659 stratification and bottom water hypoxia in a Great Lakes estuary. *Journal of Great Lakes*
 660 *Research*, 45(6), 1103–1112.

661 Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D., François, R., Grolemond,
 662 G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T. L., Miller, E., Bache, S. M.,
 663 Müller, K., Ooms, J., Robinson, D., Seidel, D. P., Spinu, V., Takahashi, K., Vaughan, D.,
 664 Wilke, C., Woo, K., & Yutani, H. (2019). Welcome to the tidyverse. *Journal of Open*
 665 *Source Software*, 4(43), 1686. <https://doi.org/10.21105/joss.01686>

666 Wilson, H. L., Ayala, A. I., Jones, I. D., Rolston, A., Pierson, D. C., de Eyto, E., Grossart, H. P.,
 667 Perga, M. E., Woolway, R. I., & Jennings, E. (2020). Variability in epilimnion depth
 668 estimations in lakes. *Hydrology and Earth System Sciences*, 24(11), 5559–5577.

669 Winslow, L. A., Read, J. S., Hansen, G. J. A., & Hanson, P. C. (2014). Small lakes show muted
 670 climate change signal in deepwater temperatures. *Geophysical Research Letters*, 42(2),
 671 355–361. <https://doi.org/10.1002/2014GL062325>

Winslow, L., Read, J., Woolway, R., Brentrup, J., Leach, T., Zwart, J., Albers, S., & Collinge, D.
 (2019). *rLakeAnalyzer: Lake physics tools* (Version 1.11.4.1) [R package].
<https://CRAN.R-project.org/package=rLakeAnalyzer>

Woolway, R. I., Simpson, J. H., Spiby, D., Feuchtmayr, H., Powell, B., & Maberly, S. C. (2018).
 Physical and chemical impacts of a major storm on a temperate lake: A taste of things to
 come? *Climatic Change*, 151, 333–347. <https://doi.org/10.1007/s10584-018-2302-3>

Woolway, R. I., Jennings, E., Shatwell, T., Golub, M., Pierson, D. C., & Maberly, S. C. (2021).
 Lake heatwaves under climate change. *Nature*, 589(7842), 402–407.
<https://doi.org/10.1038/s41586-020-03119-1>

Woolway, R. I., Denfeld, B., Tan, Z., Jansen, J., Weyhenmeyer, G. A., & La Fuente, S. (2022).
 Winter inverse lake stratification under historic and future climate change. *Limnology
 and Oceanography Letters*, 7(4), 302–311.

World Meteorological Organization. (1967). *International Meteorological Vocabulary* (No. 182,
 TP. 91). Secretariat of the World Meteorological Organization.

Wu, T., Qin, B., Brooks, J.D., Shi, K., Zhu, G., Zhu, M., Yan, W., & Wang, Z. (2015). The
 influence of changes in wind patterns on the areal extension of surface cyanobacterial
 blooms in a large shallow lake in China. *Science of the Total Environment*, 518-519, 24-
 30.

Yang, Y., Wang, Y., Zhang, Z., Wang, W., Ren, X., Gao, Y., Liu, S., & Lee, X. (2018). Diurnal
 and seasonal variations of thermal stratification and vertical mixing in a shallow
 freshwater lake. *Journal of Meteorological Research*, 32(2), 219–232.

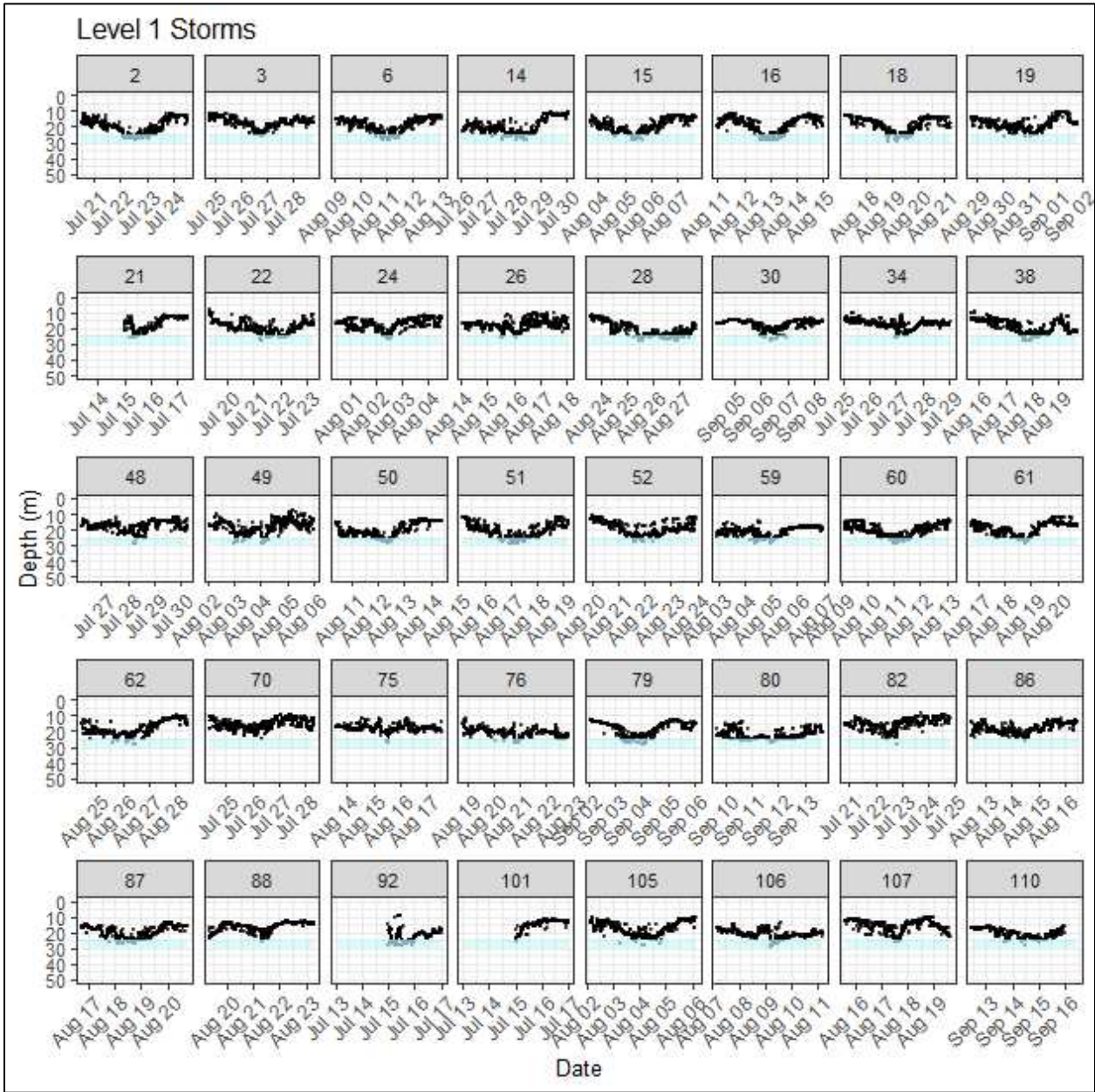
693 Zeileis, A., Leisch, F., Hornik, K., Kleiber, C. (2002). “strucchange: An R Package for Testing
694 for Structural Change in Linear Regression Models.” *Journal of Statistical Software*,
695 7(2), 1-38. Doi:10.18637/jss.v007.i02

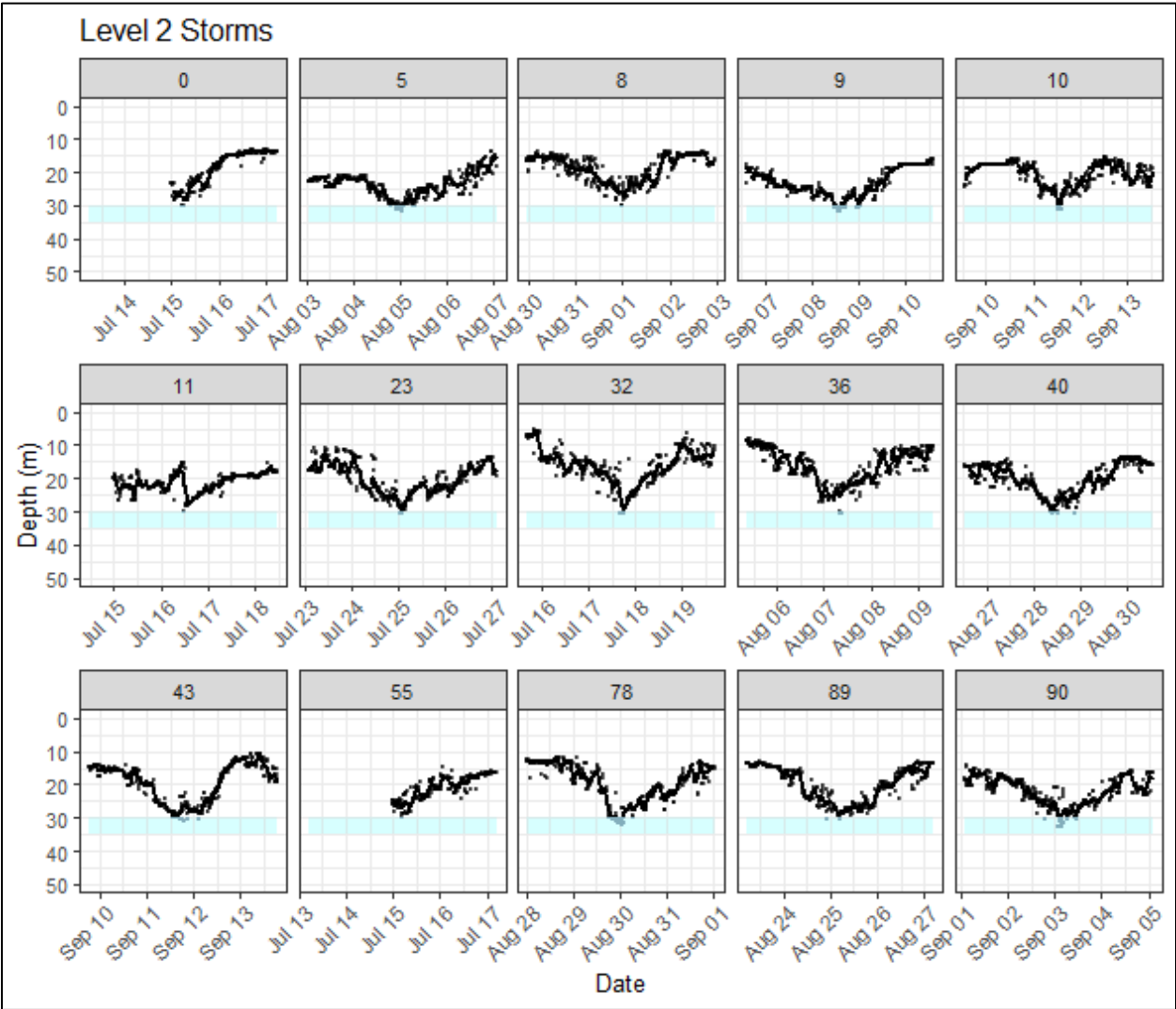
696 Zeileis, A., Kleiber, C., Kramer, W., Hornik, K. (2003). Testing and Dating of Structural
697 Changes in Practice. *Computational Statistics & Data Analysis*, 44(1-2), 109-123.
698 Doi:10.1016/s0167-9473(03)00030-6

Supplemental Information

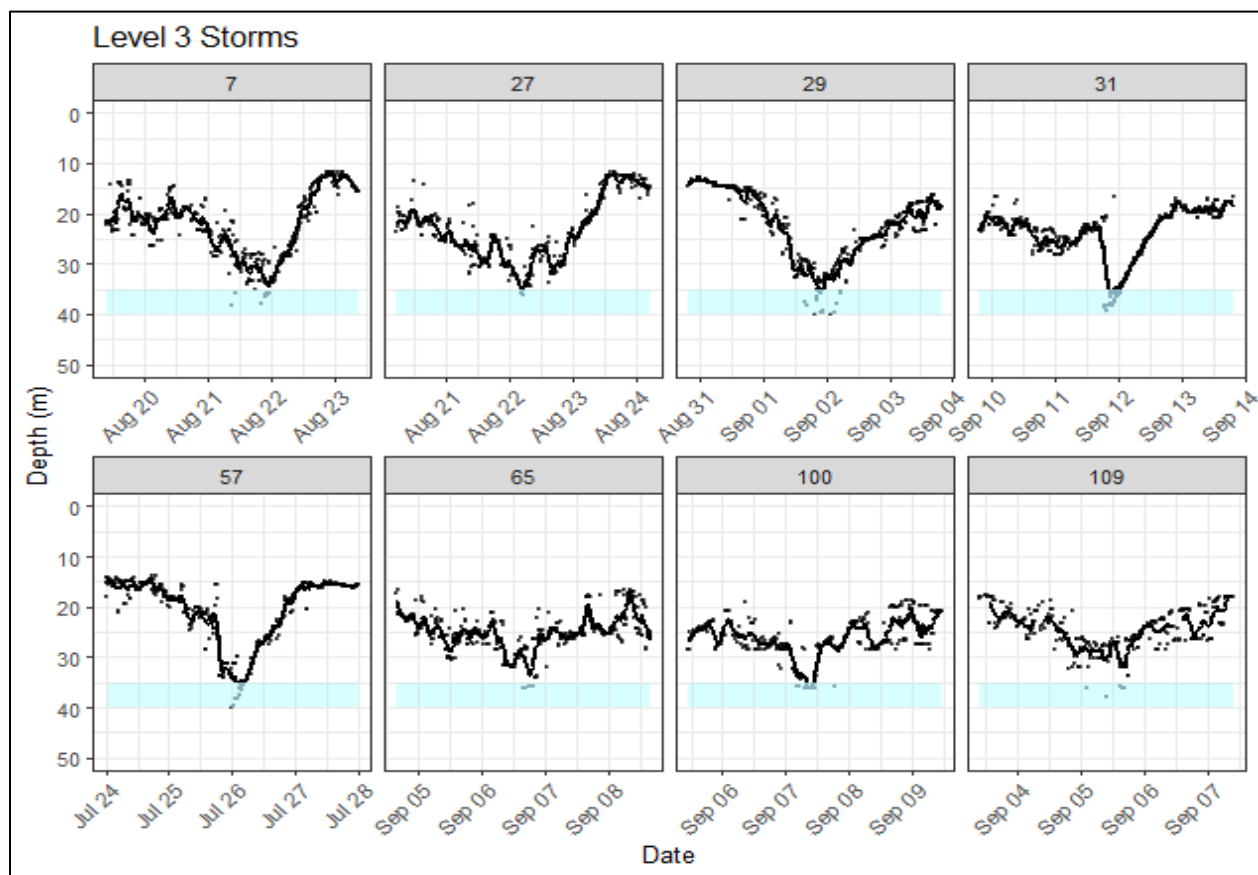
Figure S1. Plots depicting the moving average ($k = 10$) of the epilimnion for each storm

captured between Jul 15-Sept 15, from 2016-2025. Unique storm ID numbers are above each storm with storms further divided into the 5 intensity levels.



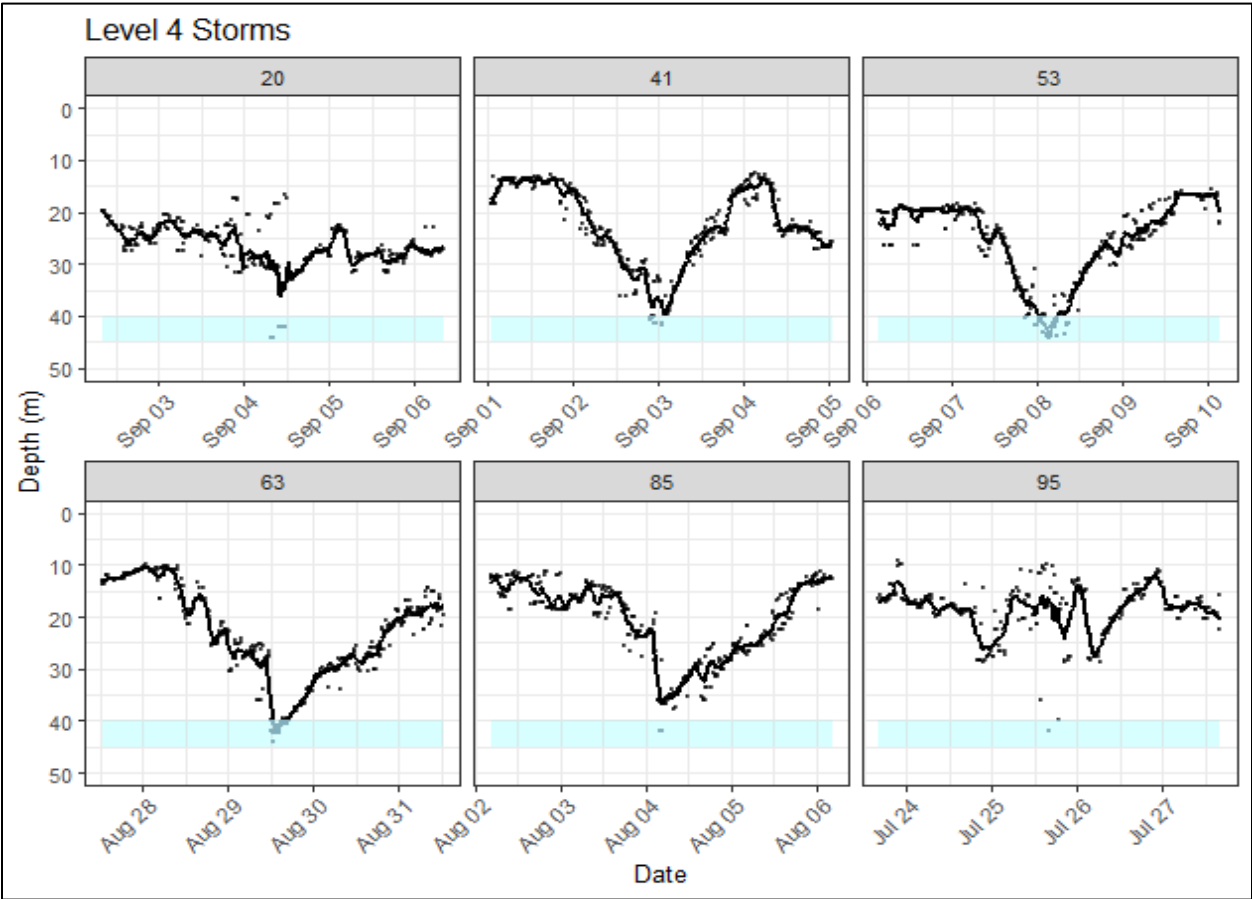


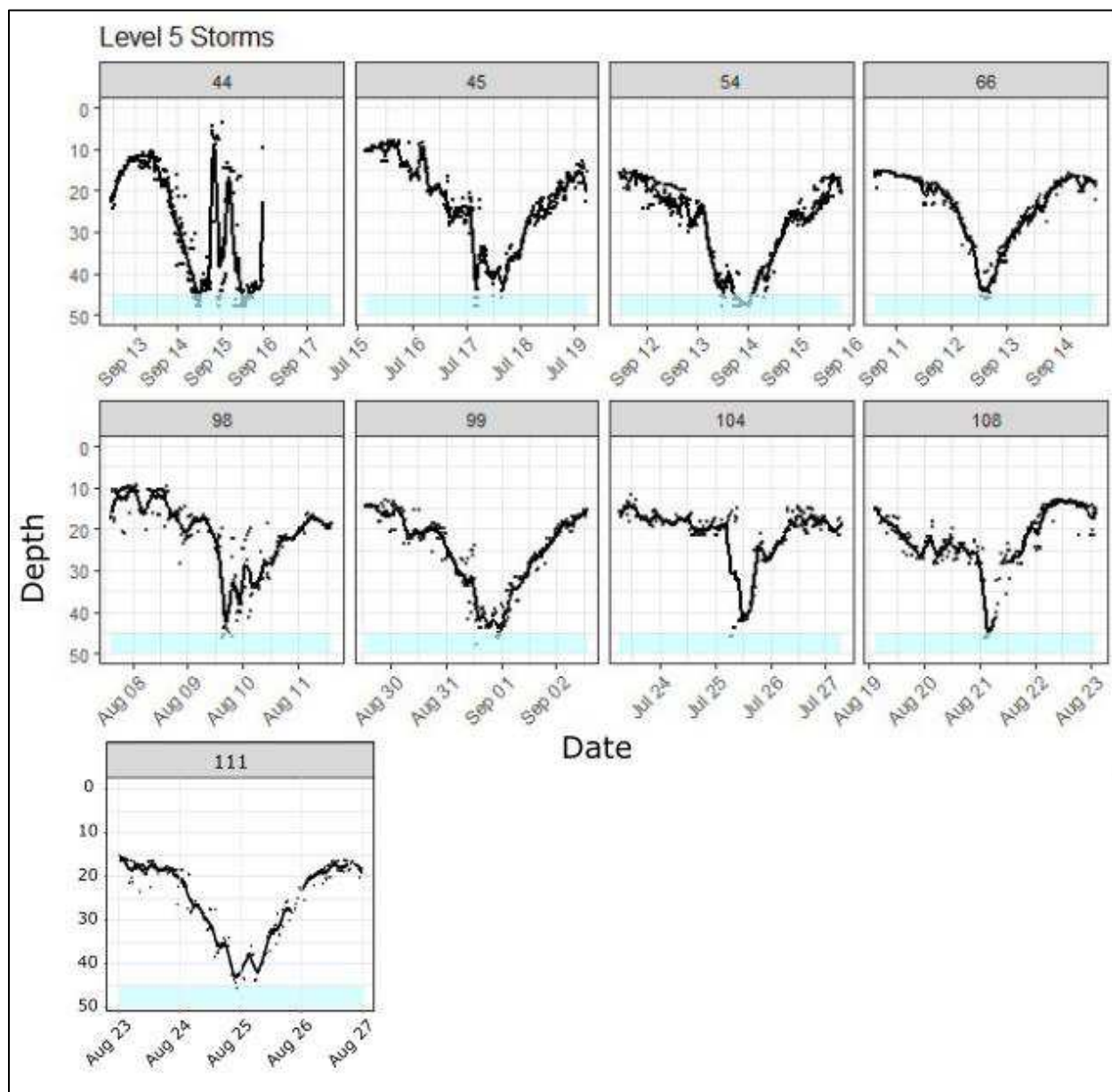
706 Figure S1 continued...



707

708 **Figure S1 continued...**





712 **Table S1.** Detected storm metrics per ID including the maximum depths of the epilimnion and
713 hypolimnion with their corresponding dates as well as the storm severity.

Storm ID	Start Date	Max Date	End Date	Epi Max	Hypo Max	Severity
2	7/20/16 13:00	7/22/16 13:00	7/24/16 13:00	27.80208153	28.82143832	1
3	7/24/16 19:00	7/26/16 19:00	7/28/16 19:00	25.91831257	25.91831257	1
6	8/9/16 2:15	8/11/16 2:15	8/13/16 2:15	28.79567334	28.79567334	1
14	7/26/17 2:00	7/28/17 2:00	7/30/17 2:00	28.5233695	28.59058431	1
15	8/3/17 17:00	8/5/17 17:00	8/7/17 17:00	28.55470675	28.72519094	1
16	8/11/2017	8/13/2017	8/15/2017	28.49722957	28.57032359	1
18	8/17/17 5:15	8/19/17 5:15	8/21/17 5:15	29.87347969	30.25488604	1
19	8/28/17 19:30	8/30/17 19:30	9/1/17 19:30	25.64915544	25.64915544	1
21	7/13/18 9:30	7/15/18 9:30	7/17/18 9:30	25.60960127	25.60960127	1
22	7/19/18 7:15	7/21/18 7:15	7/23/18 7:15	27.49298346	27.49298346	1
24	7/31/18 11:45	8/2/18 11:45	8/4/18 11:45	26.58205939	26.63668691	1
26	8/14/18 2:00	8/16/18 2:00	8/18/18 2:00	26.26011071	26.26011071	1
28	8/23/18 15:00	8/25/18 15:00	8/27/18 15:00	28.48409644	28.81039098	1
30	9/4/18 8:30	9/6/18 8:30	9/8/18 8:30	27.62233443	27.62233443	1
34	7/25/19 1:00	7/27/19 1:00	7/29/19 1:00	25.47766835	25.47766835	1
38	8/15/19 17:15	8/17/19 17:15	8/19/19 17:15	28.48505432	28.48505432	1
48	7/26/20 6:15	7/28/20 6:15	7/30/20 6:15	28.46705277	28.46705277	1
49	8/2/20 1:00	8/4/20 1:00	8/6/20 1:00	28.59644645	29.03026102	1
50	8/10/20 10:00	8/12/20 10:00	8/14/20 10:00	28.48715224	28.48715224	1
51	8/15/20 4:45	8/17/20 4:45	8/19/20 4:45	28.68756018	28.68756018	1
52	8/19/20 22:30	8/21/20 22:30	8/23/20 22:30	27.58251362	27.58251362	1
59	8/2/21 23:15	8/4/21 23:15	8/6/21 23:15	28.48988463	28.48988463	1
60	8/9/21 3:00	8/11/21 3:00	8/13/21 3:00	28.50429158	28.50429158	1
61	8/16/21 17:45	8/18/21 17:45	8/20/21 17:45	28.50047394	28.50047394	1
62	8/24/21 11:00	8/26/21 11:00	8/28/21 11:00	28.53233586	28.53233586	1
70	7/24/22 8:30	7/26/22 8:30	7/28/22 8:30	25.42792169	25.42792169	1
75	8/13/22 14:00	8/15/22 14:00	8/17/22 14:00	27.40558494	27.40558494	1
76	8/18/22 20:15	8/20/22 20:15	8/22/22 20:15	27.68798381	27.68798381	1
79	9/2/22 1:30	9/4/22 1:30	9/6/22 1:30	28.42126188	28.42126188	1
80	9/9/22 16:30	9/11/22 16:30	9/13/22 16:30	27.51253296	27.51253296	1
82	7/20/23 19:45	7/22/23 19:45	7/24/23 19:45	28.44468125	28.44468125	1
86	8/12/23 11:15	8/14/23 11:15	8/16/23 11:15	26.35126998	26.35126998	1
87	8/16/23 18:00	8/18/23 18:00	8/20/23 18:00	27.12401164	27.12401164	1
88	8/19/23 7:45	8/21/23 7:45	8/23/23 7:45	25.57711354	25.57711354	1
92	7/13/24 0:20	7/15/24 0:20	7/17/24 0:20	28.5042861	28.5042861	1
101	7/13/25 0:20	7/15/25 0:20	7/17/25 0:20	25.43746606	25.43746606	1
105	8/2/25 3:20	8/4/25 3:20	8/6/25 3:20	28.38702447	28.38702447	1
106	8/7/25 4:40	8/9/25 4:40	8/11/25 4:40	28.57578722	28.57578722	1
107	8/15/25 14:20	8/17/25 14:20	8/19/25 14:20	25.59240705	25.72990022	1
110	9/12/25 11:00	9/14/25 11:00	9/16/25 11:00	27.43103018	27.43103018	1
0	7/13/16 6:00	7/15/16 6:00	7/17/16 6:00	30.36095237	30.36095237	2
5	8/3/16 1:00	8/5/16 1:00	8/7/16 1:00	31.68146521	32.60584056	2
8	8/29/16 23:15	8/31/16 23:15	9/2/16 23:15	30.08170707	30.08170707	2
9	9/6/16 14:15	9/8/16 14:15	9/10/16 14:15	31.62074747	31.62074747	2
10	9/9/16 13:15	9/11/16 13:15	9/13/16 13:15	31.46186726	31.73165626	2
11	7/14/17 11:30	7/16/17 11:30	7/18/17 11:30	30.16496607	30.16496607	2
23	7/23/18 2:00	7/25/18 2:00	7/27/18 2:00	30.69754214	30.69754214	2
32	7/15/19 16:45	7/17/19 16:45	7/19/19 16:45	30.54593234	30.54593234	2
36	8/5/19 8:15	8/7/19 8:15	8/9/19 8:15	30.33861999	30.33861999	2
40	8/26/19 13:00	8/28/19 13:00	8/30/19 13:00	30.32493505	30.32493505	2

43	9/9/19 18:45	9/11/19 18:45	9/13/19 18:45	30.9599507	31.01731598	2
55	7/13/21 4:45	7/15/21 4:45	7/17/21 4:45	30.12545805	30.12545805	2
78	8/28/22 0:30	8/30/22 0:30	9/1/22 0:30	31.95431924	31.98684996	2
89	8/23/23 5:00	8/25/23 5:00	8/27/23 5:00	30.52517548	30.85812717	2
90	9/1/23 2:15	9/3/23 2:15	9/5/23 2:15	32.53760949	32.53760949	2
7	8/19/16 9:15	8/21/16 9:15	8/23/16 9:15	38.12042996	38.12042996	3
27	8/20/18 5:30	8/22/18 5:30	8/24/18 5:30	36.20336376	36.20336376	3
29	8/30/18 19:45	9/1/18 19:45	9/3/18 19:45	39.93072989	39.93072989	3
31	9/9/18 19:15	9/11/18 19:15	9/13/18 19:15	39.4552211	39.4552211	3
57	7/24/2021	7/26/2021	7/28/2021	39.92589998	39.92589998	3
65	9/4/21 16:00	9/6/21 16:00	9/8/21 16:00	36.23938537	36.23938537	3
100	9/5/24 11:00	9/7/24 11:00	9/9/24 11:00	36.13824693	36.13824693	3
109	9/3/25 9:40	9/5/25 9:40	9/7/25 9:40	38.00901622	38.00901622	3
20	9/2/17 8:00	9/4/17 8:00	9/6/17 8:00	44.36798118	44.36798118	4
41	9/1/19 0:45	9/3/19 0:45	9/5/19 0:45	41.68581582	41.68581582	4
53	9/6/20 3:45	9/8/20 3:45	9/10/20 3:45	44.16447088	44.16447088	4
63	8/27/21 12:30	8/29/21 12:30	8/31/21 12:30	43.9336694	43.9336694	4
85	8/2/23 4:15	8/4/23 4:15	8/6/23 4:15	41.99252136	41.99252136	4
95	7/23/24 16:20	7/25/24 16:20	7/27/24 16:20	42.00502482	42.00502482	4
44	9/12/19 10:45	9/14/19 10:45	9/16/19 10:45	48	48	5
45	7/15/20 3:30	7/17/20 3:30	7/19/20 3:30	48	48	5
54	9/11/20 11:30	9/13/20 11:30	9/15/20 11:30	48	49	5
66	9/10/21 15:15	9/12/21 15:15	9/14/21 15:15	46.16253252	46.16253252	5
98	8/7/24 14:40	8/9/24 14:40	8/11/24 14:40	46.11595655	46.63528444	5
99	8/29/24 13:20	8/31/24 13:20	9/2/24 13:20	48	48	5
104	7/23/25 7:00	7/25/25 7:00	7/27/25 7:00	45.94788827	45.94788827	5
108	8/19/25 2:40	8/21/25 2:40	8/23/25 2:40	46.34450814	46.34450814	5
111	8/23/25 2:40	8/24/25 22:20	8/27/25 0:00	45.64415	45.64415	5

714
715 **Table S2** Mean wind speed was calculated in a 24-hour window surrounding the max peak date
716 across different severity levels.

Storm Severity Level	Mean Wind Speed (m s ⁻¹) (24hr before max wind)	Standard Deviation	Number of Storms (n)
1	6.46	1.560	40
2	8.02	1.700	15
3	9.02	2.194	8
4	9.81	1.582	6
5	9.61	2.130	8