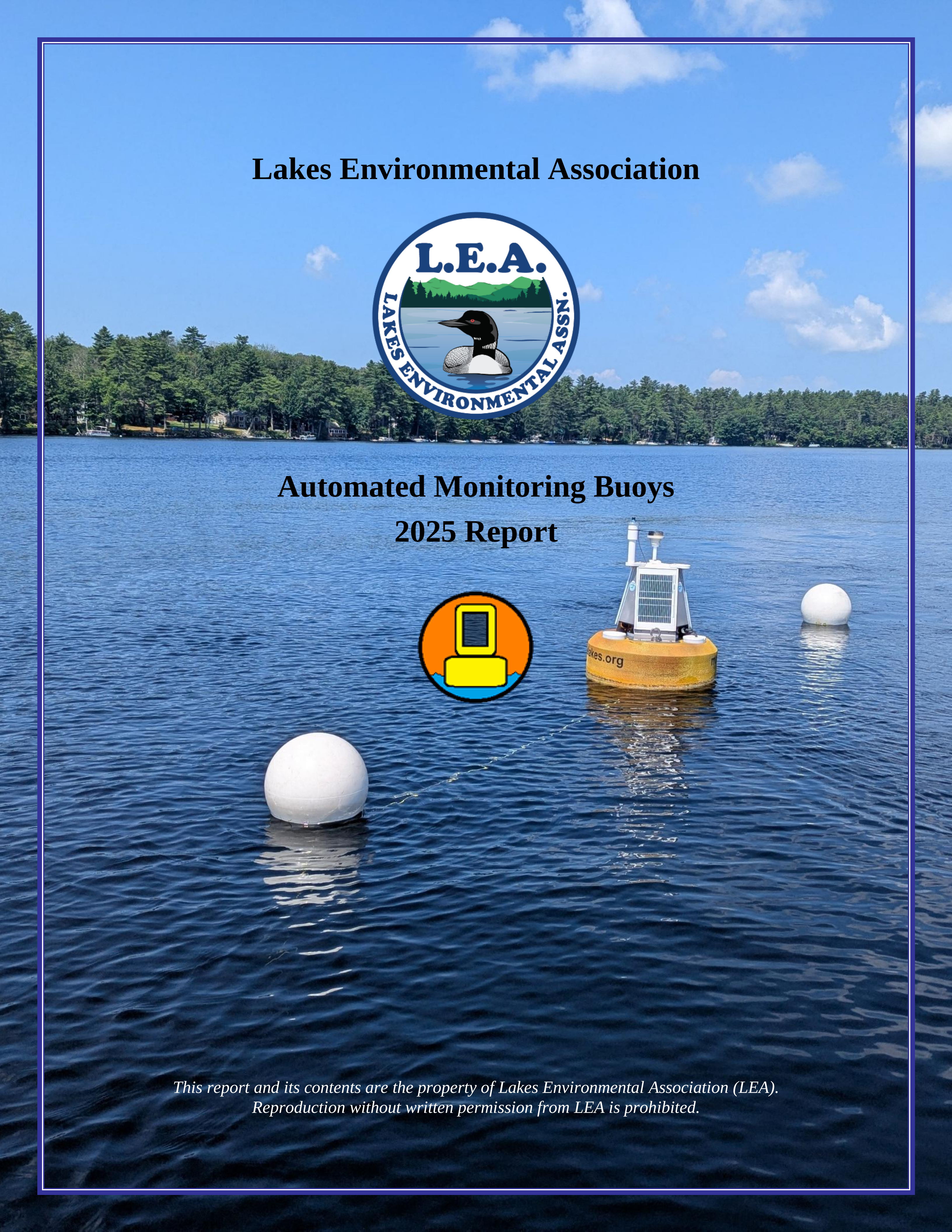
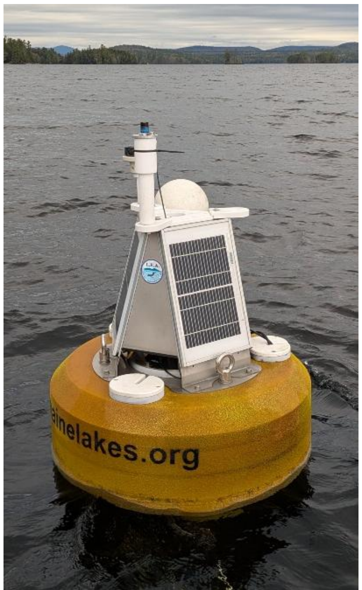


Lakes Environmental Association

Automated Monitoring Buoys
2025 Report

LEA's Automated Buoys

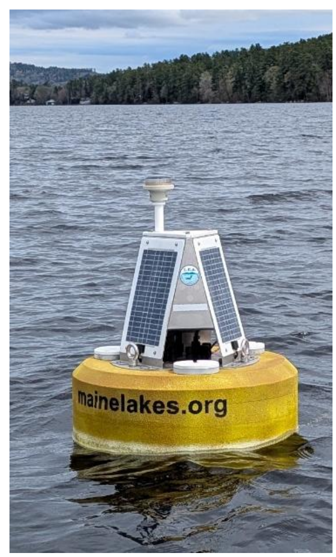


Highland Lake buoy

Each year, LEA deploys two fully automated monitoring buoys – one on Highland Lake and one on Long Lake in the north basin (see map next page). These buoys collect water quality information at 15-minute intervals throughout the spring, summer, and fall. This data is transmitted to us in real time, so we can see conditions change on the lake as they happen. The goals of LEA's monitoring buoy program are to better understand the condition of our lakes, to raise awareness of water quality issues locally, and to contribute to worldwide research and knowledge on lakes.

The Highland Lake buoy was first deployed in 2014 and has seven combined temperature and oxygen sensors mounted at 2-meter (6.6-ft) intervals from the surface of the lake to near the bottom. Also mounted on the buoy are two solar radiation sensors and a single chlorophyll sensor. The Long Lake buoy was first deployed in August 2016. Like the Highland Lake buoy, it has oxygen and temperature sensors at 2-meter intervals (total of eight) and a single chlorophyll sensor. Both buoys use three 10-watt solar panels and a rechargeable battery as their power supply (see schematic next page).

The advantages of these buoys are that they automate and enhance the water quality monitoring process. Our traditional (boat-based) water testing program collects data once every two weeks from each lake, usually around the same time of day. In contrast, the buoys automatically record readings from each sensor every 15 minutes, or 96 times per day and can be left in the water longer than the traditional monitoring season. Even though the buoys measure fewer water quality parameters than the testing program does (for instance phosphorus is not measured), the wealth of additional data gives us an incredibly detailed picture of what is happening in the lake at any given time throughout the open-water season. The simultaneous measurements of water temperature, dissolved oxygen, and algae (chlorophyll) conditions lets us see the effects of air temperature, wind, and precipitation events in real time, thus allowing us to better interpret how these factors affect lake conditions.



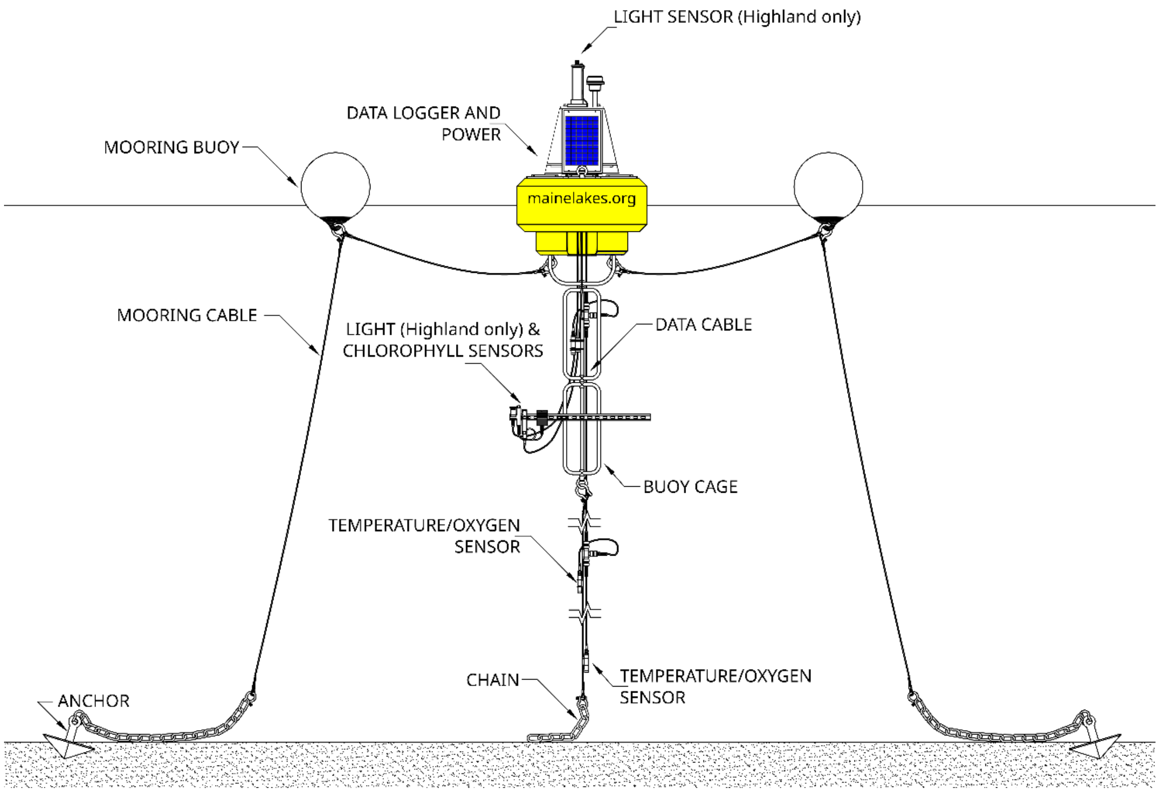
Long Lake buoy

Another aspect of the buoy program is our ability to collaborate with researchers on a larger scale by sharing ideas and methods and contributing to research. Buoys similar to LEA's can be seen in lakes throughout New England and the world. An international organization called GLEON (Global Lake Ecological Observatory Network) helps to connect researchers that collect and use lake data, particularly from automated monitoring buoys, for a variety of projects. GLEON's mission is "to understand, predict, and communicate the impact of natural and anthropogenic influences on lake and reservoir ecosystems".

LEA could not have acquired either buoy without a great deal of support from several sources. The Highland buoy was funded by a grant from an anonymous foundation and contributions from landowners around Highland Lake. The Long Lake buoy was funded by a very generous donation from a resident of Long Lake, foundation funding, and contributions from lakefront landowners. LEA worked closely with Colby College professor Dr. Whitney King and Fondriest Environmental to design and set up the buoys.

LEA's Automated Buoys

Map of buoy locations



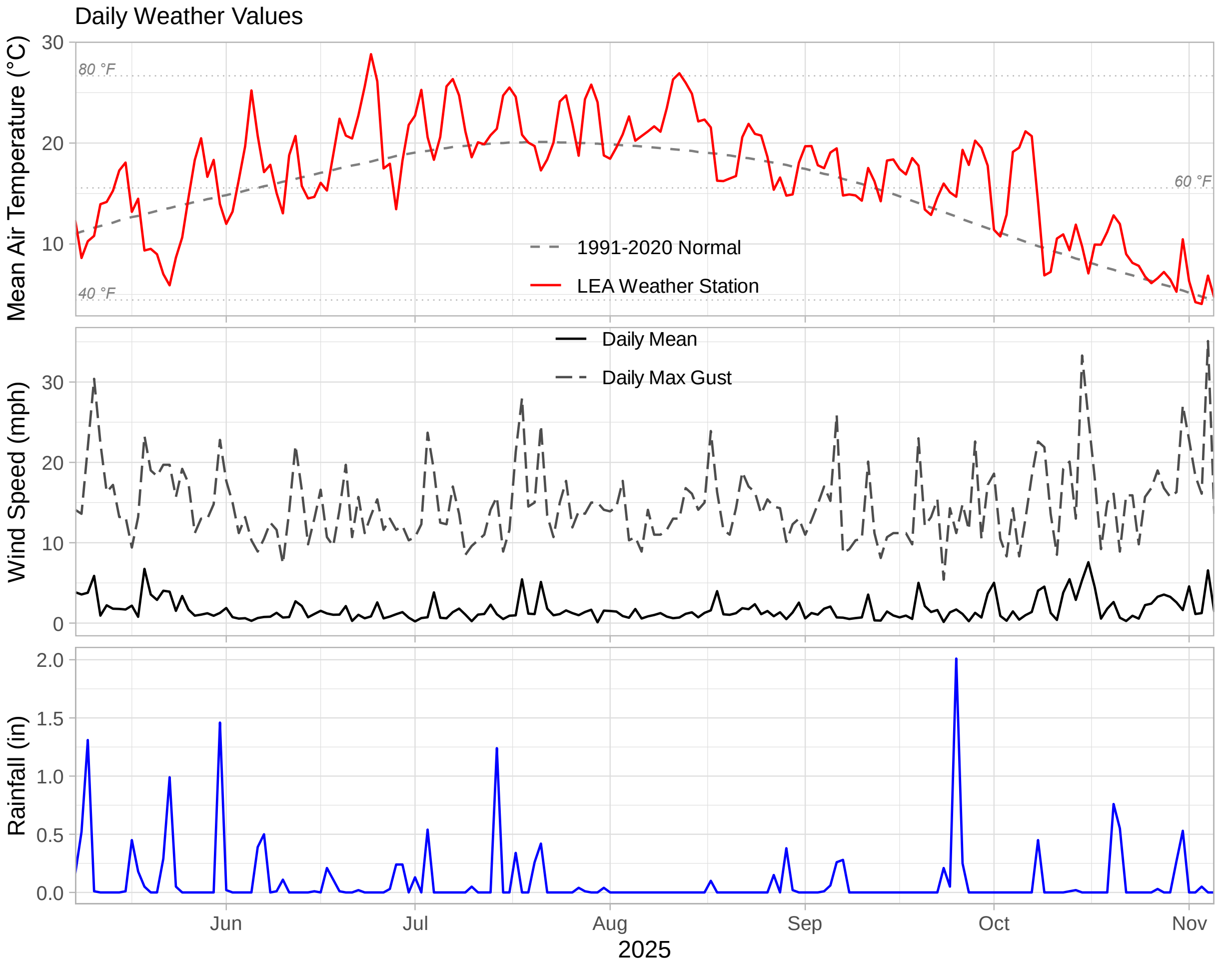
Automated Buoy Schematic

2025 Buoy Deployment

We present the latest buoy findings in three sections beginning with a summary of weather conditions that impacted local lakes followed by a general summary of the deployment and data in 2025. Those data are then presented for each lake in the remaining two sections.

Deployment Weather

Local weather conditions play a major role in controlling lake water quality. We used data from our land-based weather station (on Upper Ridge Rd at the NADP Acid Rain site, about four kilometers from each of the buoys) for background data on temperature, wind, and rain during the deployment. Data is recorded as 15-min observations, which were then converted to daily mean, maximum or totals.



Air temperature is important for understanding the heating, cooling, stability, and evaporation of lakes. Warm weather favors stable, stratified lake conditions, while cooler temperatures reduce the energy needed to mix water layers. Air temperature at the LEA station ranged from -2.39 to 36.3 °C (27.7 to 97.3 °F) and averaged 16.8 °C (62.2 °F) during the deployment period. The daily mean values (above, top panel) followed a typical seasonal pattern and were on average 1.7 °C (3.0 °F) above the 30-year normal temperatures for the area (1991-2020 climatological normal, gray dashed line above; source: Global Historical Climatology Network, Station

USC00170844 Bridgton). Daily mean air temperature was above normal for 123 of the 182 days of deployment.

Wind also has a significant impact on lake conditions. Wind (along with temperature) controls the physical structure of a lake, including the timing and strength of stratification. Wind-driven waves can cause erosion in certain situations. The middle panel of the figure above shows daily mean and daily maximum gust wind speed in miles per hour (0.10–7.6 and 5.4–35 mph, respectively). The highest maximum gust occurred on November 4. The strongest winds were most often from the north to east compass quadrant. Mean wind was high in mid- and late June, late July, the second half of August, and throughout October into November. Winds were generally lower during the first half of June, July, and September. No major tropical storms impacted the region during this time.

Rain adds water directly to a lake and also indirectly through watershed runoff. Rain is important in maintaining lake levels, but sediment and nutrients can be delivered along with it, depending on rain amount and intensity. The bottom panel in the figure above shows daily rainfall in inches. Our weather station measured 16.9 inches of rain during the buoy deployment. Some clogs in the rain gage could have impacted that total. However, the National Weather Service office at Gray, ME reported a total of 19.7 inches or 5.9 inches below the climatological normal for May through October. The below-normal rainfall contributed to the drought conditions in the area, which ranged from abnormally dry to extreme drought by October and November (source: North American Drought Monitor, droughtmonitor.unl.edu/NADM/). The maximum rain recorded for one day at the LEA weather station was 2.0 inches on September 25. Only four days had rain events greater than an inch, but even one to two-inch rain storms can cause erosion and phosphorus inputs to lakes. Still, along with warming air and water temperature, Maine is projected to experience more precipitation and more periods of high intensity rainfall in the future (source: statesummaries.ncics.org/chapter/me/).

Deployment and Results Summary

We installed both buoys at their fixed mooring sites on May 8. The buoys remained in place recording data until November 5, when they were both removed from the lakes. Combined, the buoys collected 34,700 sets of sensor readings during their 182 days on the water. Much of this data was available in real time on our website.

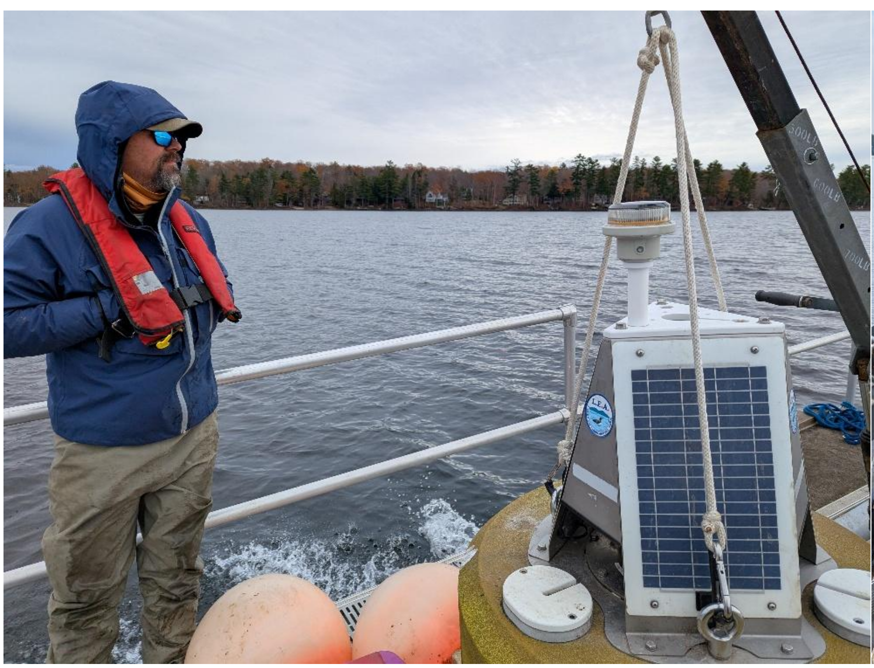
During deployment, we did four onsite visits to each buoy for maintenance and sensor replacements. During each visit, we also collected sonde data to serve as an independent standard to correct the buoy data for calibration drift. On Highland Lake, one temperature-oxygen sensor failed and had to be replaced, and the logger had gaps in the data during two days in May. The data stream from the Long Lake temperature/oxygen sensor at nine meters was unusually noisy with many out-of-range values. Those readings were filtered out using a running median filter and best judgement.

Water temperature patterns in both lakes showed the same basic response to the warmer and drier-than-average weather conditions of 2025. At the start of the deployment, both lakes were weakly stratified, which strengthened (i.e., greater temperature difference with depth) as air and water warmed. Stratified conditions lasted into October, punctuated throughout by wind mixing events that deepened the upper mixed layer. Warm and calmer periods, like early and late June, late July, and mid-August, had the opposite effect of temporarily making the mixed layer shallower. Still, the water temperature patterns did vary between the two lakes due in large part to contrasting size and shape. For example, the thermocline depth (location in the water column where temperature changes most rapidly) was often greater at the deeper Long Lake site. Also, complete mixing (lake turnover) occurred in the north basin of Long Lake ten days later than in Highland Lake.

In both lakes, dissolved oxygen declined as temperature increased and as stratification strengthened. Anoxia (absence of dissolved oxygen) occurred in each system in 2025, but as in previous years, Highland Lake’s greater oxygen consumption rate meant that it developed anoxia sooner (mid-July as opposed to mid-August) and lasted longer than at the Long Lake site. Compared to 2024, Highland Lake had a similar oxygen pattern. However, anoxia in Long Lake started earlier and lasted longer than in the previous year. This difference demonstrates how each lake basin can respond differently to the same meteorological forcing.

The temporal pattern of chlorophyll fluorescence, which is an estimate of algal abundance, was similar for Highland Lake and Long Lake, even though the Long Lake sensor was twice as deep. Chlorophyll ranged from slightly elevated in the spring and early summer to lower concentrations during the late summer and fall periods. Both lakes had generally low to moderate chlorophyll levels throughout, which confirmed the lack of algal blooms reported in these systems.

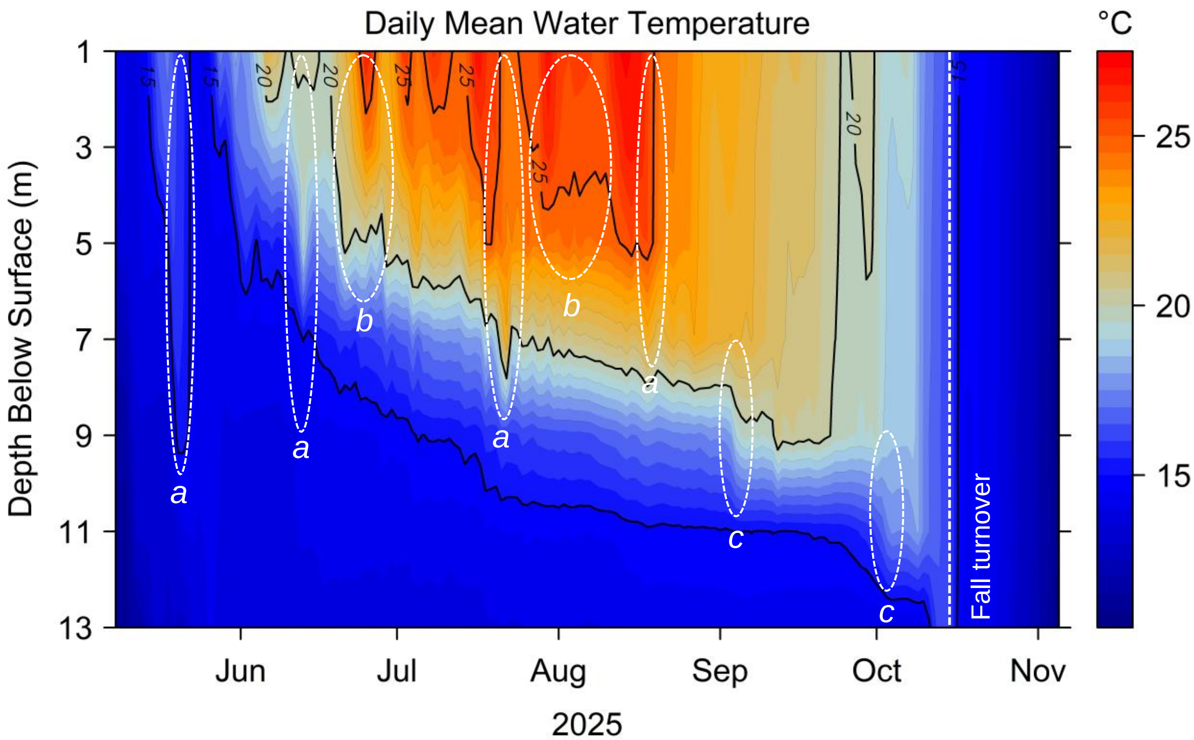
Overall, the 2025 season was quite successful, and despite a few technical issues, we were able to monitor both lakes for much of the open water season using these automated buoys. Staff members Ben Peierls, Maggie Welch, Tim Blair, Morgan Cross, and Jake Linley and interns Catherine Wheaton, Elly Burnham, and Billy O’Connor provided technical support in the field. We sincerely thank all who were involved and all who have supported the acquisition and use of the buoys in the past.



Highland Lake Conditions 2025

Water Temperature

Water temperature data forms the foundation for most water quality measures and is essential for understanding lake physical dynamics, nutrient cycling, metabolic rates, and habitat availability for fish and other aquatic organisms. Lake water temperature varies in response to heating, cooling, and winds. During ice-free periods, lakes in our area tend to stratify into a warm, upper layer (epilimnion) and a cooler, deep layer (hypolimnion).



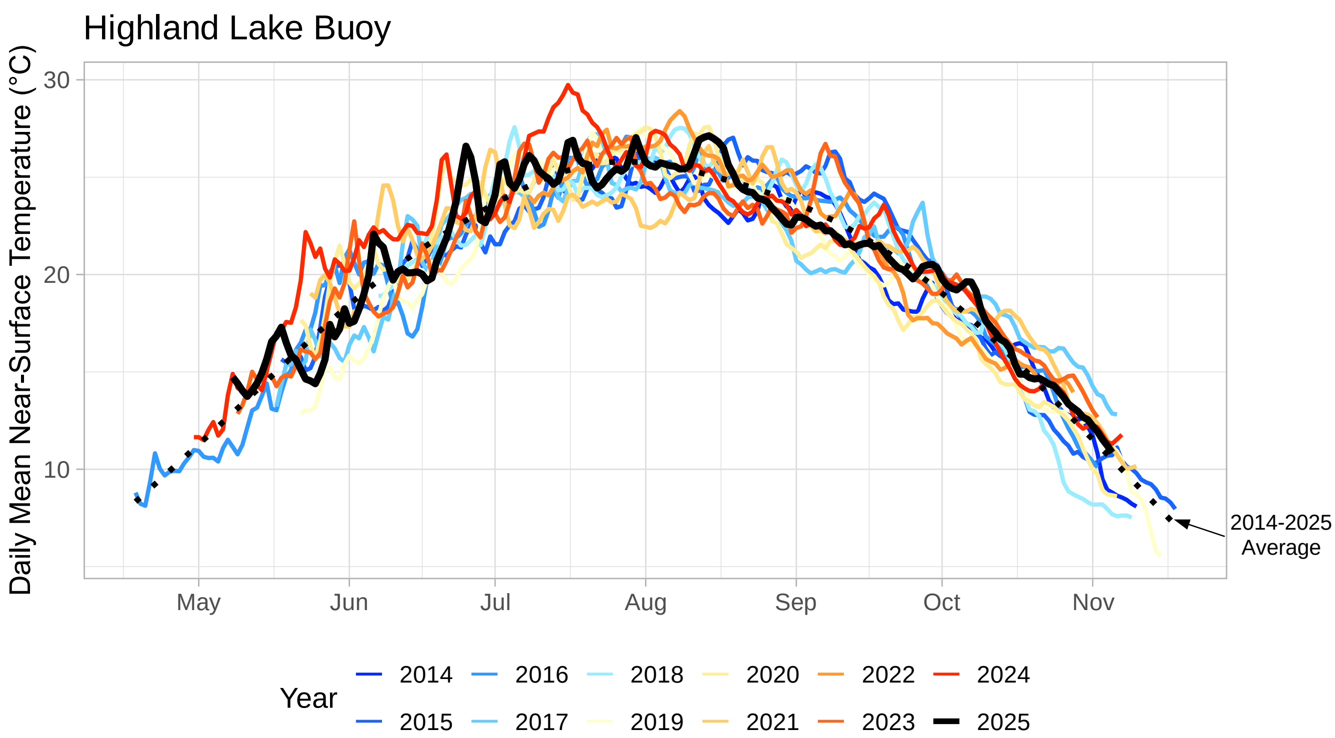
The figure above shows daily mean temperature data interpolated across depth and time in Highland Lake. Temperature is represented by colored contours, where the blue to red color gradient represents a low to high temperature range. Daily mean values were used to create smoother lines and easier visualization, since lake water temperature can vary by a degree or more in a matter of hours, depending on conditions. During the deployment, temperature ranged from 10.5 °C (51 °F) on November 5 at 13 m depth to 28.1 °C (83 °F) on August 12 at 1 m depth, which was a smaller temperature range than in 2024.

Lake stratification was just starting to set in when the buoy was deployed in early May, though the small temperature difference (about 3 °C) makes it difficult to see in the figure. Stratified conditions (where figure colors change with depth and contour lines appear more horizontal) continued into October. Warm, strongly stratified conditions stand out as darker red and orange areas throughout the summer. The thermocline depth (where temperature changes most rapidly with depth and contours come closest together) ranged from about 2 m in late-May and early June to 12 m before fall turnover. The downward sloping contours show that the upper layer (epilimnion) and thermocline generally deepened throughout the summer.

Partial and temporary water column mixing caused by cooling and/or high winds (seen as short shifts to more vertical contour lines) happened throughout the season, for example during the below normal cool spell in May, and also mid-June, mid-July, and mid-August (*a* in figure on previous page). Calmer, warmer periods usually caused the lake to re-stratify after these short mixing events (*b* in figure on previous page, for example). As air temperature decreased in late August, surface water temperature also began to decrease, which weakened stratification and deepened the thermocline (*c* in figure on previous page). Complete mixing (fall turnover; shown by vertical contour lines from top to bottom and determined when all sensors registered the same temperature for at least 12 hours) occurred on October 15 following cooling and strong winds around that time, fairly typical for this site. By comparison, the north basin of Long Lake mixed 10 days later on October 25. From October 17 through buoy retrieval, warm air caused periods of temporary re-stratification to form with as much as 1.4 °C (2.5 °F) between top and bottom readings, though this is not visible on the daily mean plot.

Date of Fall Turnover (Complete Mixing) by Year:

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Date	after 10/11	10/12	10/11	10/10	11/4?	10/16	10/9	10/8	10/24	9/24	10/14	10/16	10/15

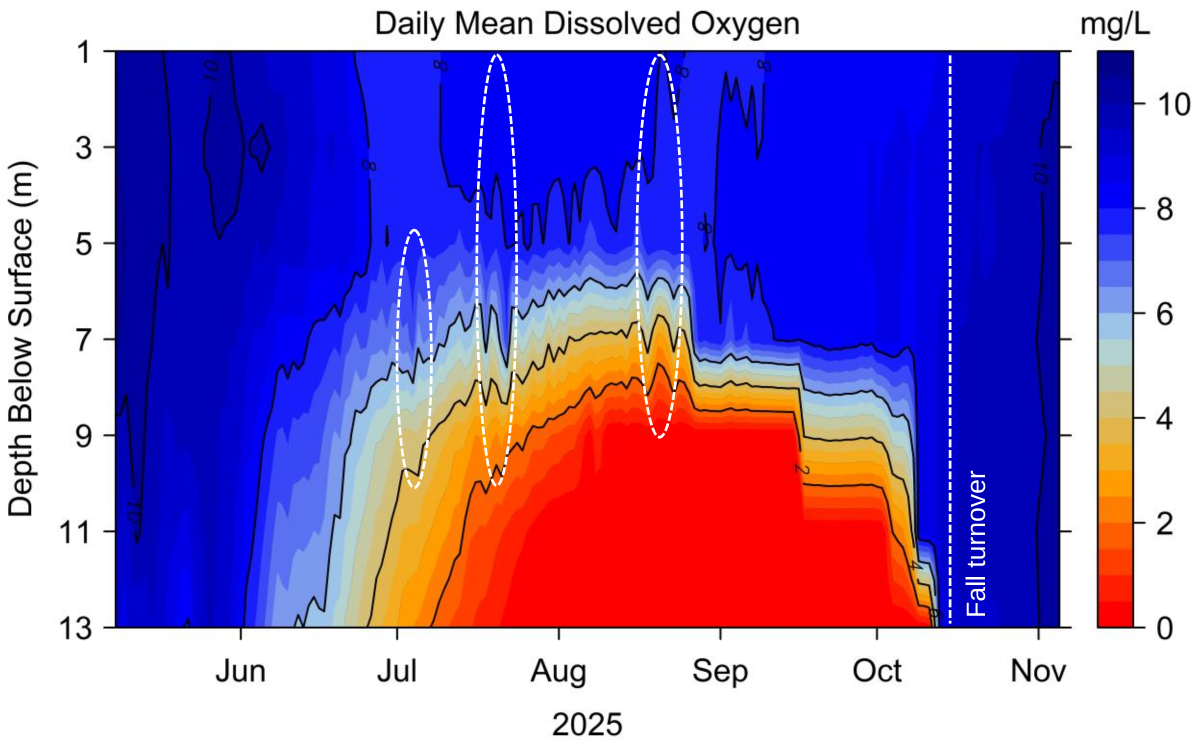


We now have 12 years of Highland Lake buoy data. The above figure shows the comparison of daily mean, near-surface water temperature for each of those years. The overall seasonal pattern is the same, but each year has a different daily pattern. Long-term data has been used to show that air and lake water temperature has been increasing in Maine and beyond. Even 12 years of buoy data, however, is not long enough yet to make out that change. The thick black line above shows that 2025 was close to the 12-year average (black dotted line) for much of the season, except for some short positive and negative deviations in May, June, August, and October.

Dissolved Oxygen

Dissolved oxygen (DO) is an important constituent of lake water that impacts the chemistry and biology of lake ecosystems. The main source of oxygen in lakes is the atmosphere, with temperature governing the amount that can dissolve in the water. Since oxygen is a byproduct of photosynthesis, algae and aquatic plants are another source of dissolved oxygen in lakes. In contrast, deep water oxygen is reduced when microbes, fish, and plants respire or "breathe" and thermal stratification prevents oxygen from being replenished from the atmosphere. Fish tend to avoid and are stressed when moving through hypoxic (see *Definitions*) areas. Anoxic (see *Definitions*) bottom waters can allow phosphorus trapped in sediments to be released into the water column for use by algae.

Definitions:
Hypoxic*: having low dissolved oxygen concentration detrimental to aquatic organisms (below about 2–4 mg/L)*
Anoxic*: having complete absence of dissolved oxygen (0 mg/L)*

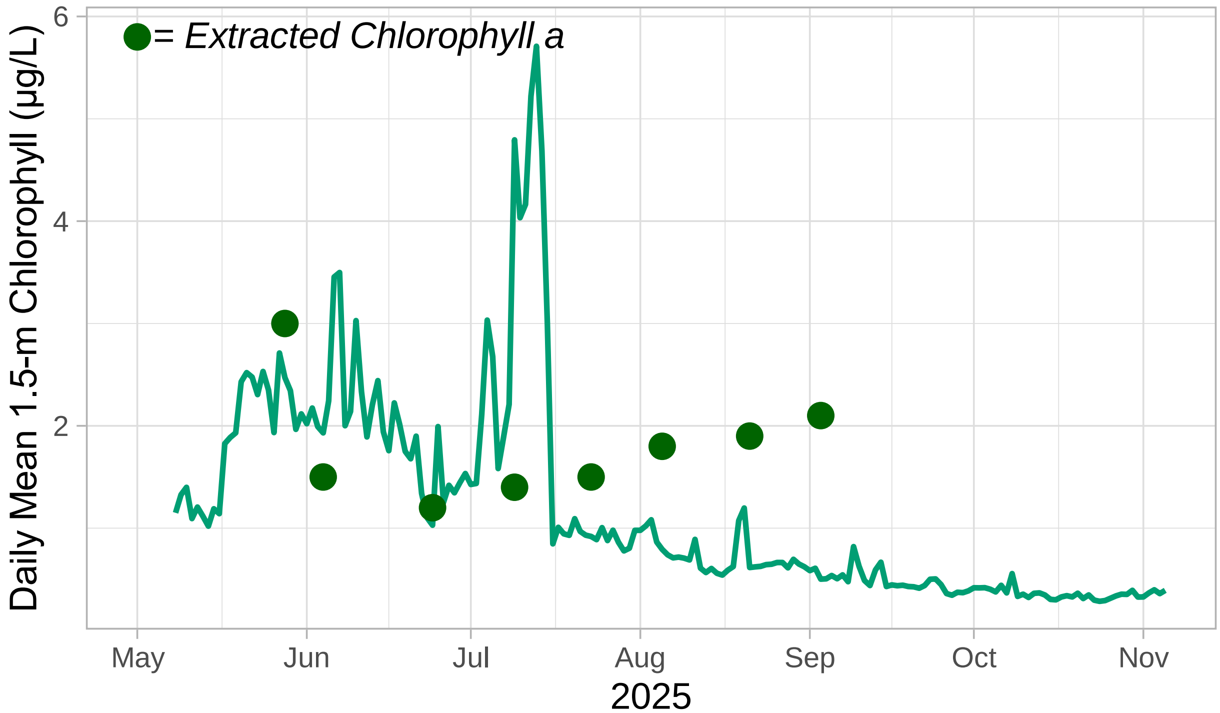


The figure above shows daily mean DO concentration data interpolated across depth and time in Highland Lake; we have reversed the color scheme from the temperature plot so that red and blue signify low and high DO, respectively. The data has been corrected for sensor drift and biofouling using independent, discrete DO measurements at the same location.

The contour plot clearly highlights the pattern of lower DO concentrations in summertime deep waters and provides a quick visual gauge of when and where hypoxic water was present. Some of the decrease in DO is due to warming, since cold water holds more DO than warm water, all else being equal. Oxygen in the deep waters, however, decreased more rapidly, and by mid-July the water at 13 m became anoxic. Water as shallow as 9 m (~30 ft) experienced anoxia during the summer. Prior to lake turnover, occasional wind events aerated deeper waters (increased the DO) through downward mixing of surface water, seen above as dips in the contour lines (*circled areas*). By mid-October, the water column was completely saturated with oxygen after temperatures decreased and winds fully mixed the lake (turnover).

Chlorophyll (Algal Biomass)

The Highland Lake buoy has one sensor mounted 1.5 m below the lake surface that measures chlorophyll concentrations using fluorescence (same as the field fluorometer used on regular testing trips and discussed in the Water Monitoring Summary). The amount of this pigment (found in all plants and algae and used for photosynthesis) can be used as a proxy for algae biomass and as a measure of lake productivity. It is important to note that field fluorescence is a relative measure and not always as accurate as the lab-based (extracted) chlorophyll *a* analysis presented in the Water Monitoring Summary.

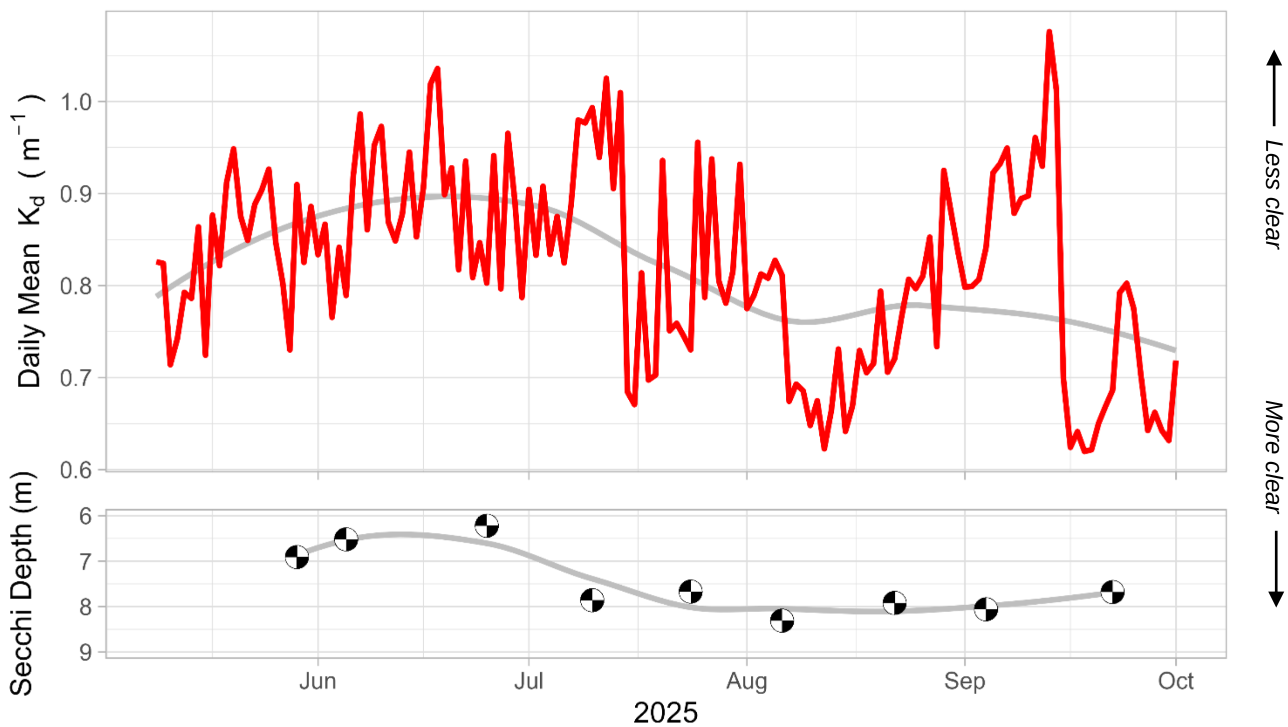


The figure above shows fluorescence-based daily mean chlorophyll concentration, after filtering out extreme outliers. Daily mean chlorophyll ranged from about 0.29 to 5.7 µg/L, and averaged 1.2 µg/L (or parts per billion), which is considered generally low to moderate chlorophyll. Chlorophyll will often increase (i.e., algae can grow) if enough nutrients (phosphorus) and light are available. Phosphorus from spring rains and increasing light and temperature may have stimulated algal growth leading to higher chlorophyll in May and June. The large peak in July was probably due to algae growing on the buoy structure given that the rapid signal drop coincided with cleaning. Other losses in chlorophyll could be from zooplankton (tiny animals that eat algae) grazing or a lack of available nutrients or both. Chlorophyll continued to decrease through November, which coincided with a deepening epilimnion (upper mixed layer of the water column). No late season surge of algal growth was evident for Highland Lake this year.

Chlorophyll fluorescence is a relative measure and often shows variation with depth (see the Water Monitoring Report). Still, the buoy chlorophyll fluorescence at 1.5 m and extracted chlorophyll *a* in the upper mixed layer (points in the figure above) were surprisingly close and within about one to two µg/L or less of each other during the period. Both chlorophyll records support the observation that Highland Lake did not experience a lake-wide algal bloom in 2025.

Light Attenuation (Water Clarity)

Light attenuation is a function of material that absorbs or reflects light like humic and tannic acids, soils and sediments, algae, and even water itself. The Highland buoy has two light sensors, one mounted on top of the buoy and one mounted at 1.5 m depth below the water surface. Both sensors measure the amount of light at visible wavelengths (400-700 nm) reaching them, but the underwater sensor receives less light because the water and the matter it contains reduces or attenuates the sunlight. This decrease in light with depth is quantified using the diffuse light attenuation coefficient (or K_d), which is calculated using the above- and below-water sensor readings. K_d is a measure of water transparency like Secchi depth, except smaller K_d values indicate clearer water. We did not use data past the end of September due to a drop in sensor output.

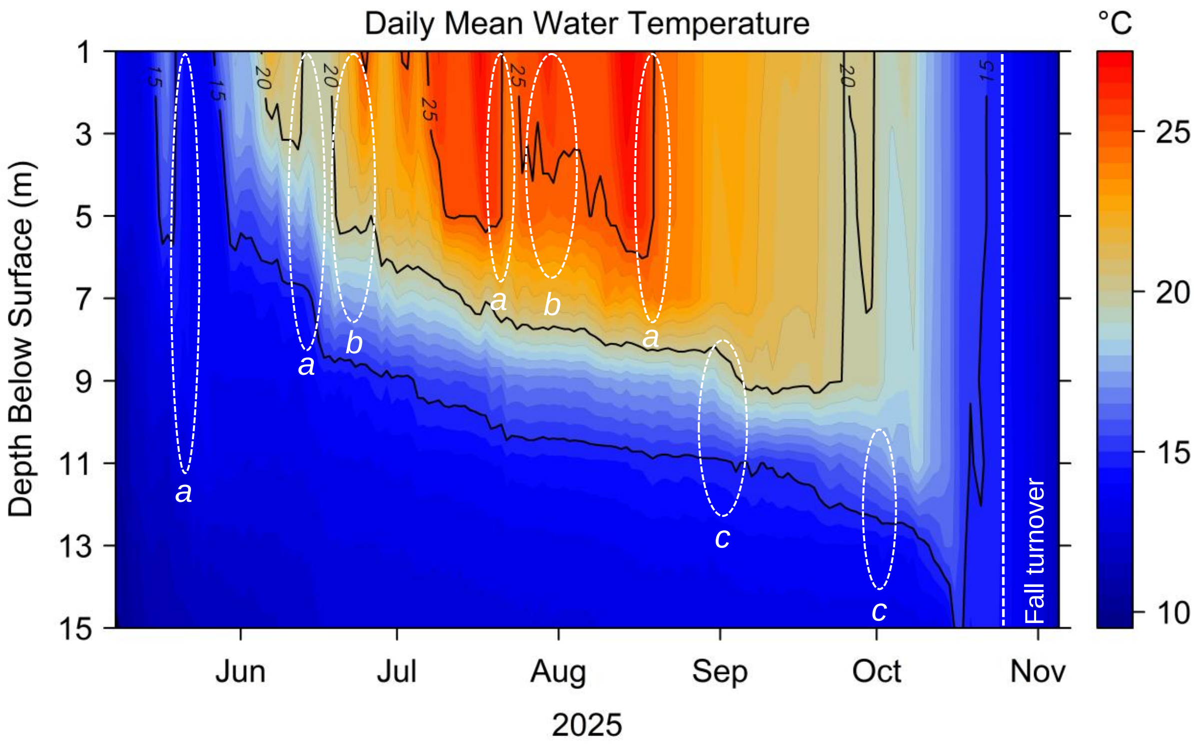


The above figure shows daily mean K_d values calculated from the buoy light sensor measurements and Secchi depths (collected during water monitoring visits), with locally smoothed trend lines shown in grey. Daily mean K_d varied from 0.62 to 1.1 m^{-1} with an overall mean of 0.82 m^{-1}. This small K_d range is equivalent to a photic zone (where light is sufficient for algal growth) depth range of about 7.7 to 4.3 m. K_d values had high daily variability, but generally increased (decreasing clarity) from May through June, and then decreased (increasing clarity) from July through the end of the deployment. The general trend in clarity was evident in the Secchi depth record as well. Wind speed can drive suspension of particles, which may explain some of the larger-scale variation in K_d. For instance, K_d sometimes increased following high winds and decreased following low-wind periods. Some high K_d values were caused by sensor fouling, since values rapidly dropped after cleaning in mid-July and mid-September. We were not able to easily explain the shorter, daily variation in K_d with the information available.

Long Lake-North Conditions 2025

Water Temperature

Water temperature data forms the foundation for most water quality measures and is essential for understanding lake physical dynamics, nutrient cycling, metabolic rates, and habitat availability for fish and other aquatic organisms. Lake water temperature varies in response to heating, cooling, and winds. During ice-free periods, lakes in our area tend to stratify into a warm, upper layer (epilimnion) and a cooler, deep layer (hypolimnion).



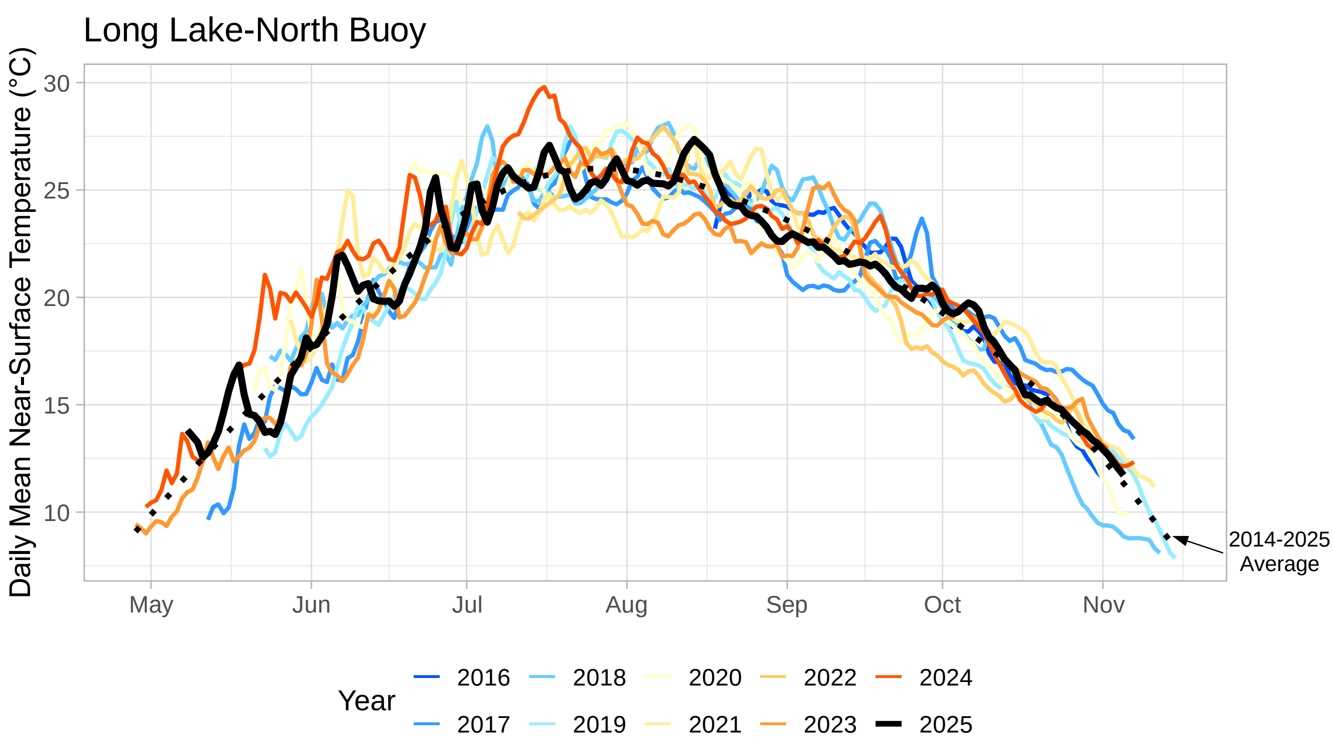
The figure above shows daily mean temperature data interpolated across depth and time in the north basin of Long Lake. Temperature is represented by colored contours, where the blue to red color gradient represents a low to high temperature range. Daily mean values were used to create smoother lines and easier visualization, since lake water temperature can vary by a degree or more in a matter of hours, depending on conditions. During the deployment, temperature ranged from 9.55 °C (49 °F) on May 9 at 15 m depth to 28.1 °C (83 °F) on July 16 at 1 m depth, which was a smaller temperature range than in 2024.

Lake stratification was just starting to set in when the buoy was deployed in early May, though the small temperature difference (about 4 °C) makes it difficult to see in the figure. Stratified conditions (where figure colors change with depth and contour lines appear more horizontal) continued into October. Warm, strongly stratified conditions stand out as darker red and orange areas throughout the summer. The thermocline depth (where temperature changes most rapidly with depth and contours come closest together) ranged from about 2 m in late-May to 14 m before fall turnover. The downward sloping contours show that the upper layer (epilimnion) and thermocline generally deepened throughout the summer.

Partial and temporary water column mixing caused by cooling and/or high winds (seen as short shifts to more vertical contour lines) happened throughout the season, for example during the below normal cool spell in May, and also mid-June, mid-July, and mid-August (*a* in figure on previous page). Calmer, warmer periods usually caused the lake to re-stratify after these short mixing events (*b* in figure on previous page, for example). As air temperature decreased in late August, surface water temperature also began to decrease, which weakened stratification and deepened the thermocline (*c* in figure on previous page). Complete mixing (fall turnover; shown by vertical contour lines from top to bottom and determined when all sensors registered the same temperature for at least 12 hours) occurred on October 25 following cooling and strong winds around that time, fairly typical for this site. By comparison, Highland Lake mixed 10 days earlier on October 15. From October 26 through buoy retrieval, warm air caused periods of temporary re-stratification to form with as much as 0.5 °C (0.9 °F) between top and bottom readings, though this is not visible on the daily mean plot.

Date of Fall Turnover (Complete Mixing) by Year

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Date	10/25	10/23	N/A	N/A	11/4	10/18	10/18	10/8	10/27	10/14	10/23	10/27	10/25

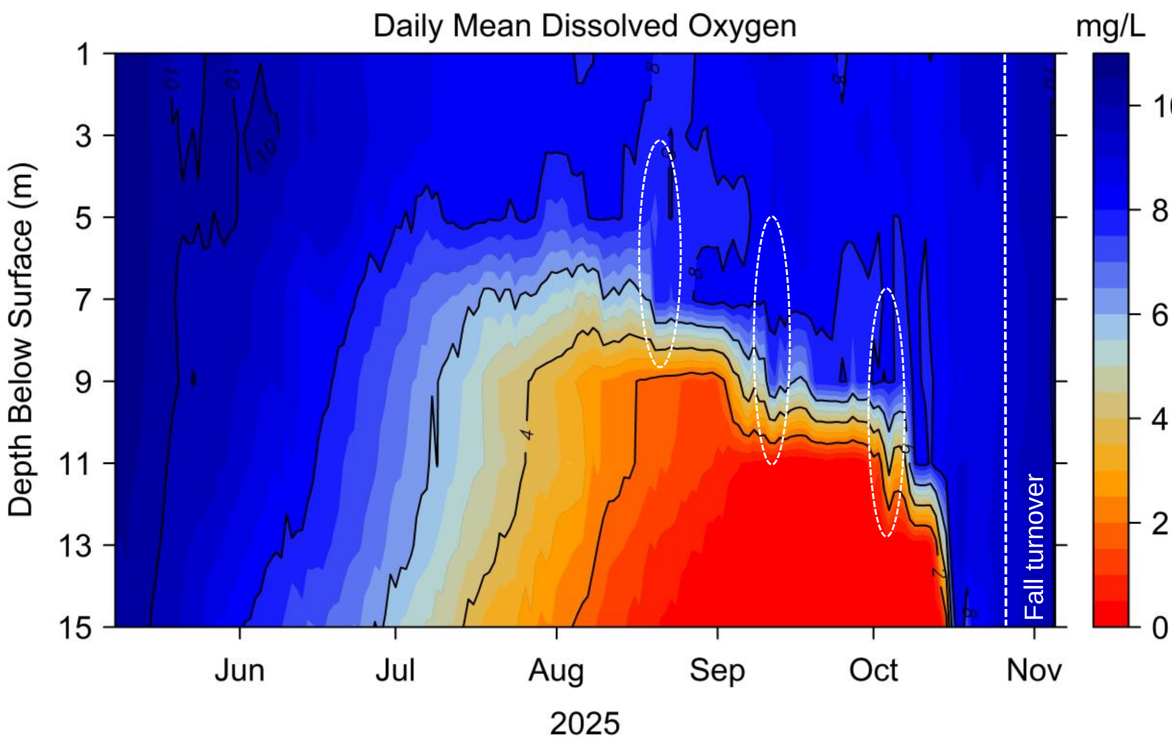


We now have 10 years of the Long Lake buoy data. The above figure shows the comparison of daily mean, near-surface water temperature for each of those years. The overall seasonal pattern is the same, but each year has a different daily pattern. Long-term data has been used to show that air and lake water temperature has been increasing in Maine and beyond. Even 10 years of buoy data, however, is not long enough yet to make out that change. The thick black line above shows that 2025 was close to the 10-year average (black dotted line) for much of the season, except for some short positive and negative deviations in May, June, August, and October.

Dissolved Oxygen

Dissolved oxygen (DO) is an important constituent of lake water that impacts the chemistry and biology of lake ecosystems. The main source of oxygen in lakes is the atmosphere, with temperature governing the amount that can dissolve in the water. Since oxygen is a byproduct of photosynthesis, algae and aquatic plants are another source of dissolved oxygen in lakes. In contrast, deep water oxygen is reduced when microbes, fish, and plants respire or "breathe" and thermal stratification prevents oxygen from being replenished from the atmosphere. Fish tend to avoid and are stressed when moving through hypoxic (see *Definitions*) areas. Anoxic (see *Definitions*) bottom waters can allow phosphorus trapped in sediments to be released into the water column for use by algae.

> ***Definitions:***
> **Hypoxic**: *having low dissolved oxygen concentration detrimental to aquatic organisms (below about 2–4 mg/L)*
> **Anoxic**: *having complete absence of dissolved oxygen (0 mg/L)*

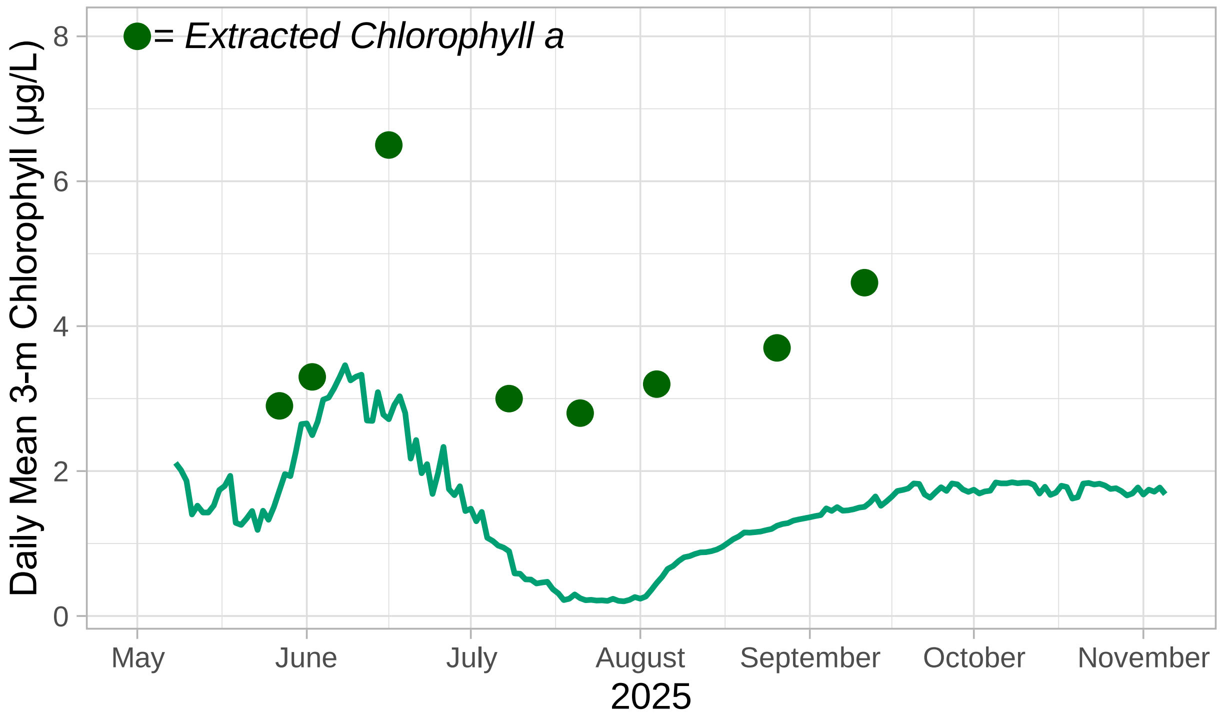


The figure above shows daily mean DO concentration data interpolated across depth and time in the north basin of Long Lake; we have reversed the color scheme from the previous plot so that red and blue signify low and high DO, respectively. The data has been corrected for sensor drift and biofouling using independent, discrete DO measurements at the same location.

The contour plot clearly highlights the pattern of lower DO concentrations in summertime deep waters and provides a quick visual gauge of when and where hypoxic water occurred. Some of the decrease in DO is due to warming, since cold water holds more DO than warm water, all else being equal. Oxygen in the deep waters, however, decreased more rapidly, and by mid-August the water at 15 m became anoxic. Water as shallow as 11 m (~36 ft) experienced anoxia during the deployment. Prior to lake turnover, occasional wind events aerated deeper waters through downward mixing of surface water, seen above as dips in the contour lines (*circled areas*). By late October, the water column was completely saturated with oxygen after temperatures decreased and winds fully mixed the lake (turnover).

Chlorophyll (Algal Biomass)

The Long Lake buoy has one sensor mounted 3 m below the lake surface that measures chlorophyll concentrations using fluorescence (same as the field fluorometer used on regular testing trips and discussed in the Water Monitoring Summary). The amount of this pigment (found in all plants and algae and used for photosynthesis) can be used as a proxy for algae biomass and as a measure of lake productivity. It is important to note that field fluorescence is a relative measure and not always as accurate as the lab-based (extracted) chlorophyll *a* analysis presented in the Water Monitoring Summary.



The figure above shows fluorescence-based daily mean chlorophyll concentration, after filtering out extreme outliers. Daily mean chlorophyll ranged from about 0.2 to 3.5 µg/L, and averaged 1.5 µg/L (or parts per billion), which is considered generally low to moderate chlorophyll. Chlorophyll will often increase (i.e., algae can grow) if enough nutrients (phosphorus) and light are available. Phosphorus from spring rains and increasing light and temperature may have stimulated algal growth leading to higher chlorophyll in June. The decrease in chlorophyll starting in July could be due to losses from zooplankton (tiny animals that eat algae) grazing or a lack of available nutrients or both. Chlorophyll increased slightly into September, then remained low and essentially constant through the end of the deployment. No late season surge in algal growth was evident at the Long Lake site this year.

As was mentioned before, chlorophyll fluorescence is a relative measure and often shows variation with depth (see the Water Monitoring Report). Still, buoy chlorophyll fluorescence at one discrete depth and extracted chlorophyll *a* in an integrated epilimnetic sample (upper mixed layer, represented as points in the figure above) were surprisingly close and within about three µg/L or less of each other during the period. Both chlorophyll records support the observation that the Long Lake north basin did not experience a basin-wide algal bloom in 2025.


mainelakes