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DATA ARTICLE

An archive of Lake Superior temperature and current measurements, 2005–2020

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Scientific Significance Statement

Multiyear, year-round records of physical parameters such as temperature or currents, especially below the surface, are exceedingly rare in the US–Canada Laurentian Great Lakes. This contribution describes an archival submission covering the first 15 years of data collected in Lake Superior. Up to 17 moorings were deployed in the lake at the same time. All of these platforms measured water temperature at multiple depths throughout the water column; a significant subset of the platforms also measured water currents. These data are now publicly available to investigators and will be useful for answering a broad array of questions about the physical properties of one of the world's largest lakes.

Abstract

Since 2005, investigators at the University of Minnesota, Duluth's Large Lakes Observatory have been maintaining subsurface moorings and surface buoys in Lake Superior to study thermal structure and currents throughout the water column and throughout the year. A single site has been continuously occupied for over 17 years as of the writing of this manuscript, another 10 sites have been occupied for multiple years, and for 3 months in summer 2017 an intensive field campaign occupied 12 sites simultaneously in western Lake Superior. All of these data are available on a publicly accessible archival site hosted by the University of Minnesota.

Background and motivation

Temperature structure is among the most fundamental characteristics of a lake, determining its mixing characteristics and ecosystem function (Wetzel 2001) and is the most direct mediator of climate change in lakes (Adrian et al. 2009; Williamson et al. 2009). A recently published decadal science plan by the International Joint Commission report (unpubl.) called out persistent and distributed temperature measurements as one of the most important and underrepresented measurements and identified them as a priority for future work. In general, long-term, continuous, and temporally resolved monitoring of the Great Lakes for parameters beyond water level are surprisingly rare. Specifically, while water temperature is measured regularly at the surface during the ice-free season, long-term year-round subsurface

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Data Availability Statement: All data described in this document are available at the following DOIs: 2005–2015: https://doi.org/10.13020/zqw9-mk81; 2015–2020: https://doi.org/10.13020/nw8b-mk79

measurements of physical parameters like temperature and velocity are rare in the Great Lakes.

There are several existing multiyear temperature datasets of note that act at some level to complement the dataset being presented here. A few very long (>100 yr) time series exist (McCormick and Fahnenstiel 1999; Austin and Colman 2008), measured at coastal power plants around the Great Lakes, typically with a temporal resolution of 1 day or less frequently. The primary repository of modern surface water temperatures is the National Data Buoy Center (NDBC), which has deployed meteorological buoys in the open waters of the Great Lakes during the ice-free season starting in 1979 (available at ndbc.noaa.gov). Since 1981, nine sites across the Great Lakes have been occupied in the ice-free season (approximately April–November) and measure near-surface (0.5 m) water temperature, initially once per hour but, more recently, every 6 min. Apart from the observations presented here, the only other long-term, subsurface, year-round time series is maintained by the Great Lakes Environmental Research Laboratory (GLERL), which has maintained equipment at a site in the southern basin of Lake Michigan since 1991 (NOAA GLERL 2019*a*; Anderson et al. 2021), making it the single longest time series of sub-surface, year-round temperature data in the Great Lakes. Shorter datasets exist for sites in Lake Huron (9 yr; NOAA GLERL 2019*b*, 2021*a*) and Superior (3 yr; NOAA GLERL 2020, 2021*b*). Multiple coastal locations have recently started collecting summer thermal structure as part of the Great Lakes Observing System's (GLOS) buildout of a coastal buoy network (available at seagull.glos.org). From a shipboard perspective, twice-yearly cruises by the US Environmental Protection Agency (Barbiero et al. 2018; data available at https://www.epa.gov/great-lakes-monitoring) produce temperature profiles from conductivity–temperature–depth casts at approximately 90 locations across the Great Lakes, starting in 1983 for Michigan, Huron and Erie, 1986 in Lake Ontario, and 1992 in Lake Superior. These cruises take place only in the spring and summer, not always on the same date, and hence not particularly useful for characterization of year-round thermal structure or long-term trends in thermal structure. Although short-term, purpose-driven measurements of currents have been made in the Great Lakes (Saylor and Miller 1976; Gottlieb et al. 1989; Choi et al. 2012) there are no other known long-term deployments of current-measuring equipment.

Starting in 2005, investigators at the University of Minnesota Duluth's Large Lakes Observatory have maintained one or more sites in Lake Superior for multiple year deployments. The moorings have instrumentation that span the water column and are, in most cases, deployed year-round, including below the ice in the winter. A subset of these have been deployed strategically to be nearly co-located (within a few km) of the NDBC buoys 45001 (central Superior), 45004 (eastern Superior), and 45006 (western Superior), and Environment and Climate Change Canada (ECCC) buoy 45136 (northern Superior). These moorings typically consist of 10–15 thermistors (more tightly spaced towards the surface, less tightly spaced deeper in the water column) and starting in 2008, frequently carried acoustic Doppler current profilers (ADCPs) to measure velocities in the upper portion of the water column, and in some cases near the bottom. Intensive field programs in 2008–2012 and in 2017 resulted in up to 17 moorings being deployed at the same time. Eleven of the sites discussed here have 2 or more years of round-the-calendar data. Sites range from 50 to 380 m deep. This represents the most spatially and temporally extensive array of physical data collected in the Great Lakes, and perhaps in any freshwater system in the world.

Data description

The data are available in two different formats: raw data, where each file represents the raw data from an individual instrument through one deployment, and hourly averaged data, where each file contains hourly averaged data collected during a single mooring deployment. We suspect that in most instances, users will prefer the hourly averaged data.

The raw data are separated into *.zip directories by year of deployment; depending on the recovery date of a given mooring, data within these directories may extend into the following year. Within each year-level directory, there are subdirectories corresponding to each individual mooring deployment. The mooring deployment sub-directory naming convention is as follows: NNsyy, where NN is the mooring name (WM, EM, GM1, etc.), s is the deployment season (S for spring, F for fall), and yy is the two-digit year (i.e., 05 for 2005). For instance, WMS14 represents data from the Spring 2014 deployment at Western Mooring. Within each mooring sub-directory, there is a "Thermistors" directory and, if appropriate, an "ADCP" directory, which contain the individual raw files.

For the thermistors, the naming convention for the raw files is ssssss_yymmdd.mat, where ssssss is the serial number of the instrument and yymmdd is the year (yy), month (mm), and day (dd) of the instrument recovery. Table 1 specifies variable names within the raw thermistor files.

For the raw ADCP data, we have used rdradcp.m code (available at http://eoas.ubc.ca/~rich) to convert from RDI's proprietary data format to MATLAB format, with no time averaging. This results in a MATLAB structure named D which contains all of the data produced by the ADCP. The most relevant variables are D.mtime, the sample time in MATLAB's time format, D.east_vel, D.north_vel, and D.vert_vel, the velocity components in ms^{-1}, D.intens, the returned signal strength intensity of all four beams, and D.config.ranges, the distance in meters of each bin from the ADCP.

Hourly averaged data are available in the zip directories "hourly data 2005–2015" and "hourly data 2015–2020." Each file within these directories represents a separate mooring deployment, with the naming convention as above, and with

Table 1. Variable names in raw thermistor files.

Variable name	Quantity	Units
t	Time	Days, MATLAB format*
SN	Serial number	
dep	Instrument depth	Corrected depth, meters
T	Temperature	°C
Z	Water depth	Meters
lat	Latitude	Deg. North
lon	Longitude	Deg. west
p**	Pressure	Absolute pressure, dBar

*MATLAB time format is decimal days since the beginning of year zero. 01 January 1970 is 719,529. All times are UTC.
**Not in every file.

an "h" appended to indicate that it is hourly data. Hourly averages are taken by a simple arithmetic average of temperature recorded from a half hour before to a half hour after the time in question. Temperature from multiple thermistors is included in a single matrix T, where each column is a time series from a different thermistor, and each row represents an hourly average of the set of thermistors. ADCP data are incorporated into the hourly files if an ADCP was present on the mooring. The velocity is split into east and north components, each a matrix where each column represents a different depth. Table 2 specifies variable names within the hourly average files.

In addition, both archival entries include a detailed description of the dataset (similar to this paper), and multiple summary tables. For the 2005–2015 entry, these tables include

- Mooring_summary_table.xlsx: A deployment summary (71 entries), consisting of basic information about each individual deployment, such as deployment and recovery date, location (latitude and longitude), water depth, and sensor payload
- Thermistor_summary_table.xlsx: A thermistor summary (773 entries), consisting of basic information about each individual thermistor dataset, including location, depth, sampling rate, sensor type, and filename.
- Pressure_summary_table.xlsx: A pressure sensor summary (87 entries), similar to the thermistor summary, but for pressure records.
- ADCP_summary_table.xlsx: An ADCP deployment summary (32 entries), including sampling interval, vertical bin size, deployment duration, location, depth, and orientation.

For the 2015–2020 archival entry, these include:

- Mooring_summary_table.xlsx (46 entries).
- Thermistor_summary_table_xlsx (514 entries).

Table 2. Variable names in hourly average files.

Variable	Quantity	Units
t	Time	Days, MATLAB format
T	Temperature	°C
dep	Instrument depths	m
Z	Water depth	m
Lat	Latitude	Deg. North
Lon	Longitude	Deg. West
SN	Serial numbers of thermistors	
east_vel*	Velocity to east	m s^{-1}
north_vel*	Velocity to north	m s^{-1}
vert_vel*	Vertical velocity. Positive up	m s^{-1}
intens*	4-beam averaged backscatter	
bins*	Depth of ADCP bins	m
adcp_SN*	Serial number of ADCP	
adcp_dep*	Depth of ADCP	m

*For deployments that included an ADCP.

- ADCP_summary_table_xlsx (26 entries).
- WireWalker_summary_table.xlsx (10 entries).

The data are accessible using two Digital Object Identifiers (DOIs) (Table 3), and are now available at the Data Repository for University of Minnesota (DRUM).

Related datasets

There are datasets that do not fall strictly into the framework specified here (Table 4). These include two purpose-built arrays in 2019 and 2021 to study radiatively driven convection (RDC), and the NDBC's archive of surface water temperatures. We strongly recommend that anybody interested in summer conditions combine the data presented here with the NDBC near-surface water temperature data, as our open water moorings do not make measurements in the top 10 m.

Methods

Locations

Over the course of the 15 yr represented here, 23 locations have been occupied (Fig. 1; Table 5). One site (WM) has been occupied nearly continuously since Fall 2005, 11 sites have been occupied for at least 2 full years, and another 12 were occupied for 3 months in 2017. The table below outlines the full names, acronyms, positions, depths, and deployment span for all sites. In addition, a Gantt chart (Fig. 2) makes

Table 3. DOIs for archival submissions.

Moored data 2005–2015	https://doi.org/10.13020/zqw9-mk81
Moored data 2015–2021	https://doi.org/10.13020/nw8b-mk79

Table 4. Related datasets.

Dataset	Source
2019 RDC deployment	https://doi.org/10.13020/1XFM-MW95
2021 RDC deployment	Pending
NDBC surface buoys	ndbc.noaa.gov

more clear periods when large numbers of moorings were deployed simultaneously.

Platforms

There are three primary platforms used to house instrumentation: subsurface moorings, surface buoys, and WireWalkers.

Subsurface moorings typically consist of a concrete anchor or pair of anchors, an acoustic release, flotation immediately above the release, a jacketed steel cable, and a steel subsurface float to keep the mooring taut and vertical. Thermistors are attached to the mooring line at premeasured locations. If ADCPs are included, they are typically in stainless steel inline cages. One or more pressure sensors are attached to the cable at premeasured locations, and are used to determine, post-recovery, the true deployment depth of the mooring, as opposed to the designed depth of the mooring. Moorings are designed so that the subsurface float is 10 m below the surface, due to U.S. Coast Guard regulations concerning subsurface obstructions. The lack of data in the top 10 m of the water column is offset partially by co-locating moorings with surface buoys in the summer, and in the winter the upper portion of the water column is sufficiently well mixed that there is no real need for measurements shallower than 10 m. Moorings are deployed by initially deploying the subsurface float, then assembling the mooring as cable is paid out. Once the mooring is fully assembled, it is dragged behind the boat until water of the appropriate depth is located using a precision depth recorder, at which point the anchors are dropped overboard, sinking quickly to the bottom of the lake, carrying the rest of the mooring with it, and the exact deployment position recorded. For retrieval, the acoustic release is activated using an acoustic release deckbox, and the mooring, except for the anchor, floats to the surface and is retrieved.

Surface meteorology buoys consist of a heavy anchor, typically multiple concrete blocks or railcar wheels, a $\sim$100-m-long ground line, a depressor weight made of heavy chain, a 40-m-long tether, and a buoyant surface buoy to which meteorology equipment is attached. A thermistor string is attached to the 40-m tether with thermistors at predetermined depths. All meteorological sensors and the thermistor string are interfaced with a data logger which in turn communicates with a shore-side computer to provide near real-time data. Surface buoys are deployed in a similar manner to subsurface moorings, with the surface float being deployed first, water of appropriate depth located, and anchors deployed. Surface buoys can only be deployed in the ice-free season (approximately May–November), and were often replaced with an over-winter sub-surface mooring to ensure continuity of the dataset. Meteorological data from these buoys are not included in this archive, but is available at ndbc.noaa.gov.

WireWalkers use the surface wave field to operate a cam that allows an instrumented platform to repeatedly profile through the water column, providing nearly continuous profiles of water properties. A month-long deployment can

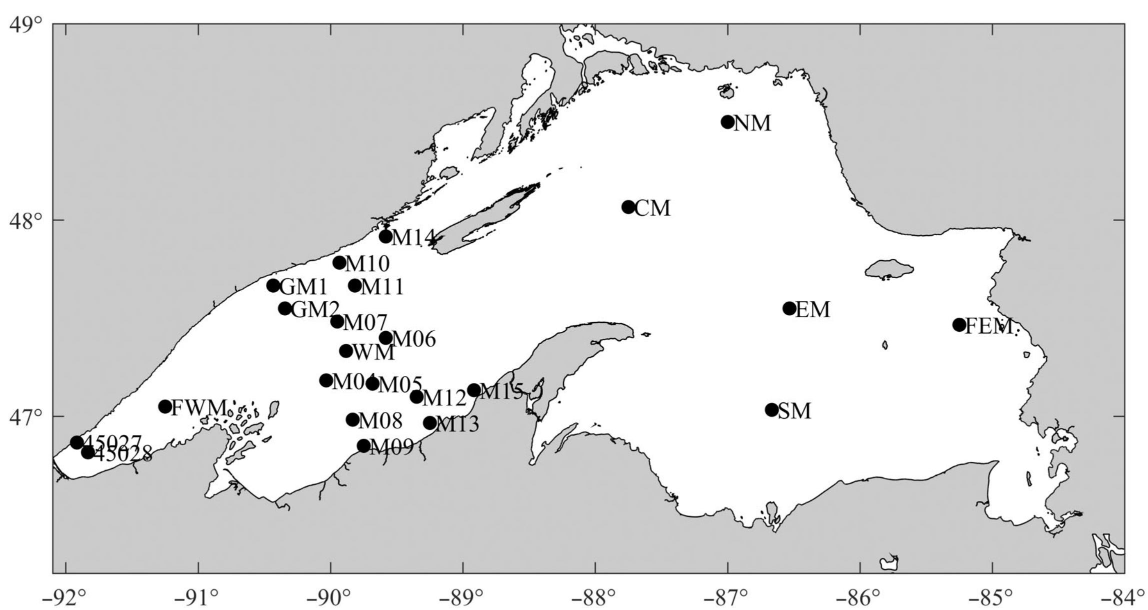

Fig. 1. Mooring locations in Lake Superior, 2005–2020.

Table 5. Mooring locations. Positions and depths are nominal, and vary slightly from deployment to deployment.

Mooring	Description	Latitude (dd°mm.m′)	Longitude (dd°mm.m′)	Depth (m)	Comment
45027	McQuade onshore	46°51.9′	91°55.6′	50	
45028	McQuade offshore	46°48.7′	91°50.1′	50	
FWM	Far Western Mooring	47°2.9′	91°14.9′	170	
GM1	Grand Marais 1	47°40.0′	90°26.0′	155	
GM2	Grand Marais 2	47°33.4′	90°20.7′	165	
WM	Western Mooring	47°19.3′	89°48.1′	185	Near NDBC 45006
CM	Central Mooring	48°1.3′	87°46.1′	257	Near NDBC 45001
NM	Northern Mooring	48°30.0′	87°3.0′	200	Near ECCC 45136
EM	Eastern Mooring	47°32.2′	86°34.3′	212	Near NDBC 45004
SM	Southern Mooring	47°2.0′	86°40.0′	384	
FEM	Far Eastern Mooring	47°28.5′	85°14.9′	247	
M04	NICE mooring 4	47°11.4′	90°1.7′	155	
M05	NICE mooring 5	47°10.4′	89°41.3′	200	
M06	NICE mooring 6	47°24.3′	89°35.0′	200	
M07	NICE mooring 7	47°28.7′	89°56.6′	150	
M08	NICE mooring 8	46°59.4′	89°50.1′	200	
M09	NICE mooring 9	46°50.7′	89°45.2′	50	
M10	NICE mooring 10	47°47.1′	89°55.8′	200	
M11	NICE mooring 11	47°40.0′	89°49.5′	185	
M12	NICE mooring 12	47°5.6′	89°21.1′	130	
M13	NICE mooring 13	46°58.2′	89°14.9′	40	
M14	NICE mooring 14	47°55.4′	89°34.8′	240	
M15	NICE mooring 15	47°8.2′	88°55.4′	40	

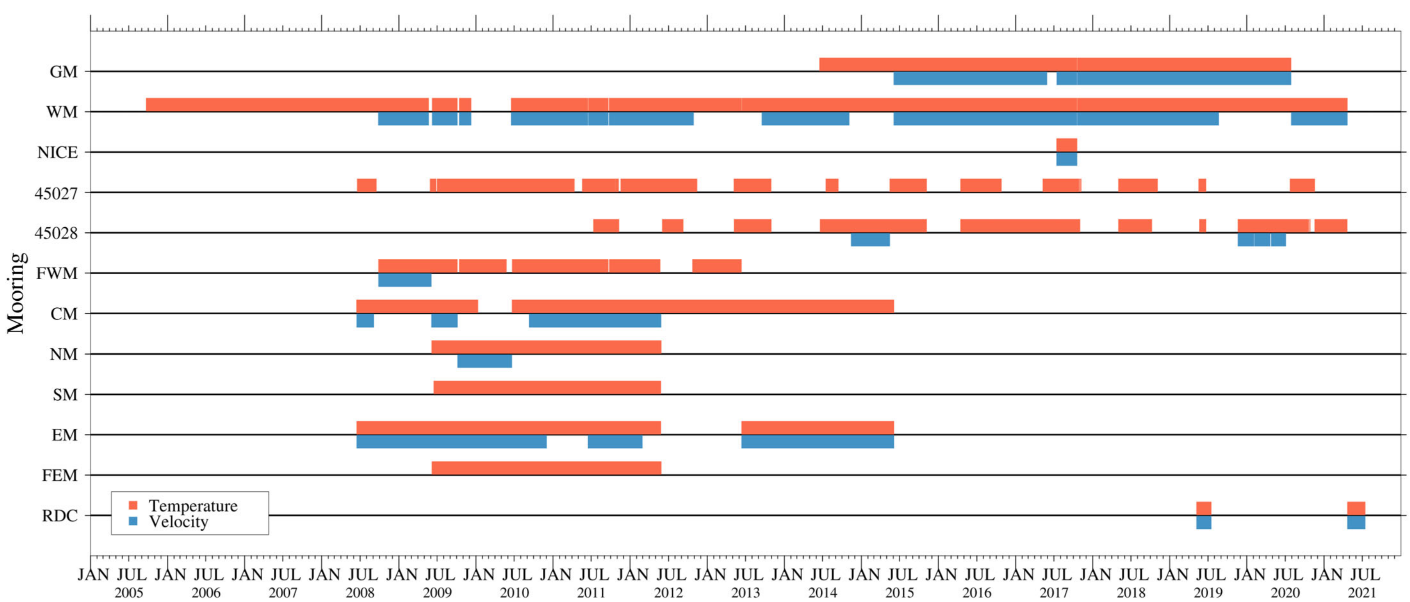

Fig. 2. Gantt chart of deployments. “GM” refers to both GM1 and GM2; “NICE” refers to moorings M4-M15. “RDC” refers to deployments associated with radiatively driven convection experiments in 2019 and 2021, the data for which are available separately from the archival material described here.

consist of thousands of individual profiles. More detail regarding the operation of these platforms can be found in Lucas et al. (2017). WireWalkers were deployed in Lake Superior only during the intensive field program of 2017.

Sensors

The moorings carried primarily thermistors and ADCPs, though some early deployments carried other equipment, such as sequential sediment traps, and surface meteorology buoys measured meteorology. In this archive, we focus solely on thermistor and ADCP data.

Thermistor technology evolved significantly during the duration of these deployments. Early moorings used primarily Seabird SBE-39 and RBR TR-1000 thermistors. These have relatively limited memory compared to modern instrumentation, and sampling periods were typically 10 to 30 min, depending on the expected length of deployment. Several generations of thermistors have been used, primarily RBR TR-1050 and TR-1060, before the adoption of the RBR TR-SOLO T and TR-SOLO3, which are used exclusively now, and are typically set to a 1 Hz sampling rate. Pressure sensors are a progression of SBE-39, TR-2050, TR-SOLO D, and TR-DUET sensors, which, again, are only used to validate the deployment depth.

We have used primarily RDI WH-300 and WH-600 ADCPs throughout the extent of our deployments. These are older units, and typically configured to record data at 20 min intervals. The major deployment in 2017 also included a Nortek Aquadopp and a Nortek Signature 500 ADCP.

Major deployments

The data collected and presented in this archive have never been part of a long-term, sustainable effort to collect physical data; rather, it is an amalgamation of several sequential projects, bridged with cruises of opportunity. That said, there are five primary efforts that contribute to the archive.

The earliest deployments (2005–2007) were overseen by Josef Werne as part NSF OCE-0452927 to study the depth and seasonality of the growth of Thaumarchaeota, in order to improve our understanding of the TEX86 temperature proxy (Woltering et al. 2012). This consisted solely of a mooring at WM, which included sediment traps at two depths.

From 2008 to 2013, an NSF grant (NSF OCE-0825633) to characterize winter conditions in a deep lake expanded the array significantly to seven different sites (FWM, WM, CM, NM, EM, FEM, and SM) for 3 yr, three of which were occupied beyond that (WM, CM, and EM, which are the sites adjacent to NDBC buoys in the lake). An NSF RAPID grant (NSF OCE-1445567) allowed the extension of the deployment for a year after the unprecedented cold winter of 2013–2014.

From 2016 to 2018, an NSF grant (NSF OCE-1635560, OCE-1635163, OCE-1635166, PIs Samuel Kelly, Andrew Lucas, and Jonathan Nash) to study to coastal generation of internal waves (the Near Inertial Coastal Experiment [NICE]) provided multiyear support for three moorings (GM1, GM2, and WM), and an intensive field season in summer 2017, which included several traditional moorings as well as 10 WireWalkers.

From 2019 to the present, an NSF grant (NSF OCE-1829895) to study radiatively-driven convection in a deep freshwater lake further extended the dataset, including the deployment of innovative mooring designs, such as moorings with high lateral resolution (2019 and 2021) and a mooring with unprecedented vertical resolution (2021).

Finally, from 2011 to 2021, the GLOS funded the deployment of two surface meteorology buoys (45027 and 45028), both of which carried subsurface thermistor strings to characterize thermal structure in the coastal waters of western Lake Superior. On several occasions, over-winter moorings were deployed at one of these sites on the buoy recovery cruise and recovered on next year's deployment cruise, in order to provide continuity from 1 yr to the next. In the archival files, we treat the thermistor string nodes, which are technically parts of a single instrument, as separate thermistors in order to facilitate ease of analysis.

Technical validation

Thermistors are returned to the manufacturer every several years for calibration. ADCPs undergo a compass calibration each time a battery is replaced. These calibrations occur on dry land away from structures, while installed in their stainless-steel cage. The returned signal strength intensity (RSSI) from ADCPs is uncalibrated and caution should be used when comparing absolute RSSI levels between deployments.

Data use and recommendations for reuse

The data have been used in a number of manuscripts to explore a range of physical phenomena: winter conditions (Bai et al. 2014; Titze and Austin 2014, 2016; Yang et al. 2020; Ozersky et al. 2021), Near-inertial oscillations (Austin 2013), springtime convection (Austin 2019; Austin et al. 2022*b*), upwelling (Li et al. 2021), zooplankton behavior (Austin et al. 2022*a*), stratification formation (Piccolroaz et al. 2015; Woolway et al. 2021), biochemical temperature proxies (Woltering et al. 2012), and a classroom teaching demonstration (Austin et al. 2011).

There are a broad range of additional use cases for these data. Foremost perhaps is model validation. In addition, topics such as interannual variability, seasonal connectivity, thermobaric stability, seasonal formation and destruction of stratification, and internal wave generation and propagation are all areas for which the dataset has significant potential.

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Conflict of Interest

None stated.

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