Novel Observations of Full-Depth Advection in Late Summer Lake Superior

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Introduction

Within the study of physical processes in large lakes, much focus is given to dynamics at or near the surface of lakes. These shallow processes are relatively easy to observe when compared to deep-lake, or hypolimnion, processes. Near-surface dynamics are also generally regarded as more energetic, more important for particle transport, and more impactful on human communities than their deep-lake counterparts. Therefore, shallow dynamics represent a significant portion of literature on physical processes in large lakes. Lake Superior, the largest of the Laurentian Great Lakes, is no exception to this trend. To help address the limited research on hypolimnion processes, this paper presents observations of rapid and drastic changes throughout the full water column in Lake Superior during late summer based on moored observations of temperature and pressure. These drastic changes occurred annually to varying degrees at a site in the southeastern basin of the lake over the duration of the 2009-2012 mooring deployment. Although similar dynamics are observed annually, the 2009 record is given primary focus due to its greater rapidity of changes to the water column compared to other years. The observations suggest that the deepest parts of the lake (>300 m) can see large fluctuations in temperature and thermal structure during stable stratification regimes and are generally more active than assumed.

There is no clear set of dynamics which can easily explain the observations, which underscores a lack of understanding of how water moves in Lake Superior. This ignorance has broader ramifications. Understanding the transport of water, and thus heat, is fundamental to understanding how large lakes will respond to changing climate. Surface temperatures of Lake Superior have been shown to be warming faster than regional air temperatures, and the duration of ice cover is likewise shrinking (Austin and Colman 2007; Zhong et al. 2016). Growing surface temperatures and shorter winters have both increased primary productivity in the lake (O'Beirne et al. 2017). To understand how anthropogenic climate change will affect Lake Superior further, more must be known about how heat is distributed and moves across and within the lake.

Although shallow dynamics are heavily studied over hypolimnion dynamics, studies concerning the latter are present and represent a wide array of physical processes that cause water motion in the deep regions of lakes. In 2002, Ralph showed that eddies, or circular currents, are present in Lake Superior. Usually on the scale of 10-100 km across, these currents exist at all depths and contribute to horizontal variability of lake surface temperature (Ralph 2002). In addition to circular currents, studies of general patterns of circulation in Lake Superior show that coastal water can propagate offshore, mixing and interacting with the water in the open lake. These studies were conducted by observation (Beletsky et al. 1999) and through numerical modeling (Bai et al. 2013; McKinney et al. 2018). The study of cold intrusions, or cold water swiftly descending from the lake surface to the bottom, has been applied to large lakes as well, namely Crater Lake (Crawford and Collier 2007) and Lake Baikal (Wüest et al. 2005). However, these phenomena occur during winter in lakes much deeper and steeper than Lake Superior. The changes in temperature due to cold intrusions are also quite small, generally on the order of a tenth of a degree Celsius.

Another dominant process in the interior of large lakes is internal waves, or waves that propagate between layers of different density (i.e. different temperature). Internal waves are either linear or nonlinear. In a study of Lake Biwa, Japan, Shimizu et al. (2007) showed that, while linear internal waves appear in the hypolimnion, they generally do not change the characteristics of the water column except for mixing along density layers. On the other hand, nonlinear internal waves can theoretically trap masses of water in their interior while they travel and therefore cause advection—or horizontal transport—of water (Ostrovsky and Stepanyants 1989). A later study by Preusse et al. (2012) showed that fully developed stable cores likely do not exist in nature.

In addition to circulation and internal waves, vertical mixing due to turbulence can also affect the hypolimnion. Michalski and Lemmin (1995) showed that, while vertical mixing plays a large role in the upper hypolimnion (<90 m), it plays a lesser role in the deep hypolimnion. While many mechanisms that affect the deepest parts of large lakes have been explored and revealed by years of research, the set of observations presented here represent natural phenomena that are not readily attributed to any single mechanism within the list above.

Methods

From the summer of 2009 to the summer of 2012, seven full-depth temperature moorings were deployed across the extent of Lake Superior (Figure 1). The depths of the mooring locations ranged from 170 m at the Far Western Mooring (FWM) to 380 m at the Southern Mooring (SM). The moorings were equipped with 10-16 thermistors (i.e. temperature sensors) spaced closely near the surface and farther apart toward the bottom. Since the moorings have no surface signature, Coast Guard regulations stipulate that the top of the mooring—and therefore shallowest thermistor—be located 10 m below the surface of the lake. The deepest thermistor on each mooring was located just above the release mechanism at about 5 m above the lakebed.

Since a variety of thermistor models were used across mooring deployments, not all data were measured at the same frequency. To account for individual instrument storage capacity, some

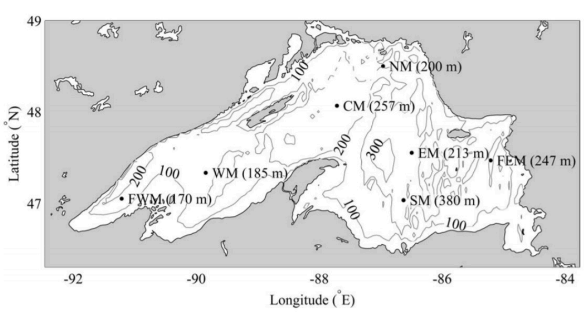

Figure 1: Lake-wide mooring locations (from Titze and Austin 2014).

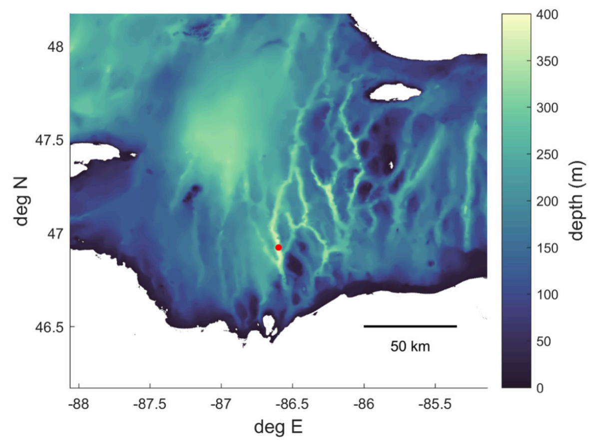

Figure 2: Bathymetry surrounding the SM site (red dot). The southeast region of Lake Superior is characterized by highly irregular bathymetry. Data from National Centers for Environmental Information.

thermistors took measurements every 10 min while others took measurements every 1 min. In both cases, the measurement period was greater than the response time of the sensor to ensure maximal accuracy of ~ 5 mK. The mooring at the SM site was equipped with Brancker Research (RBR) TR-1000 sensors that measured temperature every 30 min and TR-1050 sensors that measured temperature every 10 min. Two TR-2050 pressure and temperature sensors were also included at the 10 m and 40 m depths. Pressure was measured to determine the actual depth of the mooring once it was deployed which, upon review of the pressure record, was about 10 m deeper than originally intended.

The seven moorings were deployed in regions of Lake Superior characterized by different basin size, depth, distance from shore, and surrounding bathymetry (underwater topography). Bathymetric data were taken from the National Centers for Environmental Information (NCEI) Great Lakes Bathymetry repository. A three arc-second (~90 m) grid was available for Lake Superior from this source at the time of this study. Notably, the SM site is located in a region of intense bathymetric irregularity; the deepest point of the lake (~400 m) is located directly to the north, and a seamount that extends upward to 25 m below the lake surface is positioned directly to the southeast. The mooring was also deployed in a deep submarine trench that runs north-south (Figure 2). Compared to the other mooring sites, the SM site is surrounded by areas with more variable bathymetry.

During most of the ice-free season, meteorological conditions over the surface of Lake Superior are recorded by three National Data Buoy Center (NDBC) buoys. Buoy 45004 is the nearest to the SM site and is located within 2 km of the EM site (see Figure 1). For the purposes of this analysis, hourly wind speed and direction from this buoy were taken to describe the wind field at the SM location 74 km to the south.

The relative heat content at mooring locations was found by modeling the water column as a sequence of vertically stacked, discrete layers of water centered on each thermistor, and then summing the heat content of all layers. Accordingly, heat content was estimated as

$$H = \sum_{i=1}^{n} \rho_w c_P (T_i - T_{MD}) \Delta z_i$$

where H is the heat content per unit area of the water column in J m^{-2}, ρ_w is the density of water assumed to be a constant 1000 kg m^{-3}, c_P is the specific heat of water taken as 4180 J kg^{-1} C^{-1}, T_i is the measured temperature of the ith layer in C, T_{MD} is the temperature of maximum density of fresh water, and Δz_i is the thickness of the ith layer in m. By defining the heat content relative to the temperature of maximum density, the zero-crossing becomes a phenological indicator for switching between positive (summer) and negative (winter) thermal stratification regimes (Titze and Austin 2014). Although the temperature of maximum density is a function of pressure (and therefore depth), it is assumed to be constant, and assigned an approximate value of 4°C (Chen and Millero 1986). The constant approximation is valid because this study is concerned with changes in relative heat content on the order of 10^9 J m^{-2}, and a nonconstant temperature of maximum density engenders fluctuations two orders of magnitude smaller (Chen and Millero 1986).

In addition to relative heat content, the stability of the water column as a function of depth was calculated as a proxy for strength of stratification. The definition for stability (Boehrer and Schultze 2008)

$$N^2 = -\frac{g}{\rho_0}\frac{d\rho_{pot}}{dz}$$

was discretized for calculation using the moored data such that

$$(N^2)_i = -\frac{g}{\rho_0}\frac{(\rho_{pot})_{i+1} - (\rho_{pot})_i}{z_{i+1} - z_i}$$

where g is the local gravitational acceleration (10 m s^{-2}), ρ_0 is a reference density (1000 kg m^{-3}), ρ_{pot} is the potential density—a function of temperature—in kg m^{-3} (Chen and Millero 1986), and z is depth in m. During periods of sufficient stratification, the thermocline depth is taken to be the depth of maximum stability.

Results

Leading up to September 29, 2009, the southern mooring thermistor record exemplifies characteristic late summer thermal structure (Boehrer and Schultze 2008; Titze and Austin 2014). Figure 3a shows the SM temperature at depth from August through December 2009. The thermocline is situated at or above the shallowest thermistor, so most (if not all) of the mooring is in the hypolimnion. The hypolimnion makes up a majority of the water column and ranges

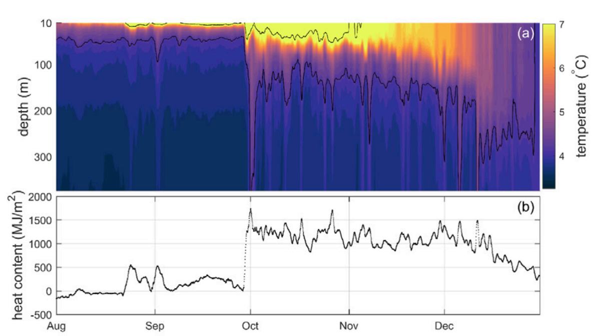

Figure 3: (a) Water temperature as a function of depth and time at the SM site during the second half of 2009. The 4.25°C and 8°C isotherms are plotted in black. (b) Heat content per unit area relative to 4°C at the SM site. The sudden spike in heat content and plunging of both isotherms marks the onset of the advective event. A 16-hr running average filter was applied in order to remove the inertial signal. Both plots share the same time axis.

in temperature from 10°C down to 4°C at the bottom, with only a 0.5°C change occurring from 50 m to 380 m. The 4.25°C and 8°C isotherms are plotted (Figure 3a), and the former remains stable at 50 m depth except for a small deflection at the beginning of September. During the month of September, the maximal stability of the water column was generally between $2x10^{-4}$ and $8x10^{-4}$ m^2 s^{-2}. Since the shallowest two thermistors were likely at or below the base of the thermocline, these values probably represent an underestimation of the actual stability.

From September 29 to 30, the water column at the SM site underwent a significant change in character. The 10 thermistors in the top 100 m reported increases in temperature ranging from 0.5°C to 5°C, with larger changes corresponding roughly linearly with less depth. The five thermistors located 150 m to 374 m below the surface all recorded increases in temperature of about 0.5°C as well. Within the period of one day, the entire 380 m water column shifted upward in temperature by at least a half a degree Celsius, with greater shifts near the surface. During this same time, the thermocline steadily deepened to a maximal depth of 60 m before rebounding upward to 20 m. The deepening of the thermocline was matched with a slight decrease in maximal stability from about $1.5x10^{-4}$ to $1x10^{-4}$ m^2 s^{-2}, suggesting a general weakening of stratification and increase in mixed-layer depth.

By October 1, the temperature of the entire water column peaked above 4.25°C, and temperature at all depths continued to fluctuate both positively and negatively over the course of the next two days. Notably, there were roughly day-long periods when the shallowest 100 m experienced thermal changes in direct opposition to changes below 100 m. By October 3, the depth of the 4.25°C isotherm climbed and then remained generally between 100 m and 200 m depth, and no significant changes in maximal stability occurred. Following the rapid temperature changes at all depths between September 29 and October 3, 2009, the water column at the SM site entered an altered, but semi-stable stratification regime for the remainder of the year. As the lake moved toward winter homogenization, or "overturn," maximal stability and surface temperatures continued to decrease as expected from seasonal changes.

Concurrent with the large temperature fluctuations was a strong wind event over Lake Superior: a northerly wind peaked at 18 m s^{-1} at midnight on September 29 and gradually backed off over the course of the next three days (Figure 4). When the meridional (north-south) wind component is compared to the temperature at 250 m (chosen as an indicator for signals propagating into the deep lake), a striking relationship is revealed. Figure 4a shows the meridional wind component and the water temperature at 250 m advanced forward in time by 48 hr. After the initial event, there is a strong correspondence between episodes of increased windspeed from the north and temperature variability in the deep part of the SM site. For comparison, the same temperature signal is plotted similarly against the zonal (east-west) wind component in Figure 4b. The temperature variability during such events is always of the same nature: a warming at depth that is proportional to windspeed and then subsequent cooling after the wind ceases. High wind episodes before the September 29 event do not appear in the deep-water signal, and similarly, winds blowing from the south have little to no effect either. The thermal response at the SM site is highly asymmetric in regard to wind forcing.

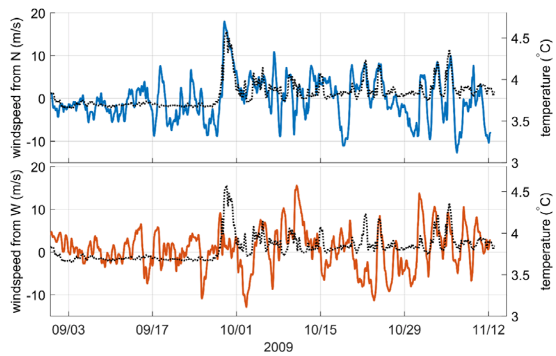

Figure 4: (a) The magnitude of the meridional (north-south) wind component is plotted in blue on the left vertical axis. The temperature at 250 m depth from the SM site advanced in time by 48 hr is plotted in dotted-black on the right vertical axis. (b) The same as above, but for the zonal (east-west) wind component in orange. A 4-hr running average filter was applied to all data and both plots share the same time axis.

The moored pressure record also provides insight into the dynamics of the SM event (Figure 5). Directly preceding October 1, the pressure quickly jumped by 1-1.5 dbar with an hour-long maximal excursion upwards of 2.5 dbar. After two days of heightened values, the pressure at both sensors returned to pre-

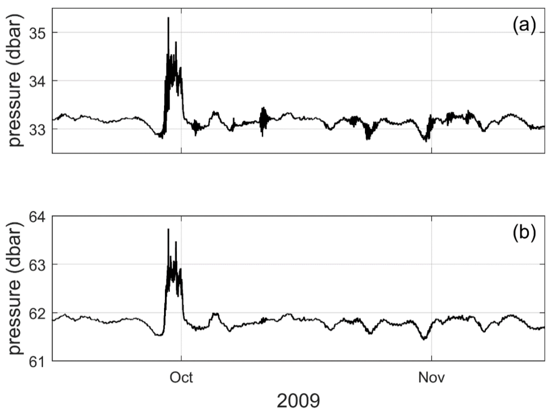

Figure 5: (a) Pressure as a function of time from the shallower pressure sensor at the SM site. The advective event is apparent in the large spike in pressure directly preceding October 1st. The ambient pressure suggests the mooring was deployed about 10 m deeper than originally intended. (b) The same as above, but for the deeper pressure sensor. Both plots share the same time axis.

event ambient levels. The jump in pressure could be the result of a strong current "blowing" the mooring over slightly and causing the sensors to descend in the water column. For every meter of depth, pressure increases approximately 1 dbar, so it's possible that the current blew the mooring over enough to lower the sensors 1.5 m in the water column. While nothing can be said about the direction of the current and very little can be determined about its magnitude, the pressure signals suggest that the large temperature fluctuations during the event were accompanied by a rapid increase in local circulation.

This energetic period at the SM site can be viewed from a lake-wide perspective as well. At the time of the event, seven total moorings were deployed and recorded the evolution of the temperature field across the extent of Lake Superior. Intriguingly, no other mooring site showed significant changes in the deep part of the lake following the storm. Changes in thermal structure at the other sites are apparent but limited to the upper water column. The response is isolated at the SM location, suggesting that a specific set of parameters, perhaps a combination of local circulation and lakebed geometry, caused northerly winds to stir up the deep lake.

Yet another description of the event is provided by the heat content at the SM location. Figure 3b shows that the heat content remained relatively stable within 300 MJ m^{-2} of the zero-crossing with a few excursions upward to 500 MJ m^{-2} during August and September leading up to the event. Then on September 29, the heat content increased rapidly by over 1500 MJ m^{-2} in about two days before settling to a new average value of 1250 MJ m^{-2}. This rapid increase in heat content is equivalent to the entire water column warming by 1°C and happened as a result of the full-depth upward temperature shift described above. A maximal heating rate of 2500 W m^{-2} was observed over a four-hour period during the event. Given that heat flux from the lakebed is negligible and the heat flux at the lake surface is bounded above by about 1000 W m^{-2} at Lake Superior's latitude, the observed heating cannot be explained by energy being absorbed at the lake surface alone. Instead, the rapid change in heat content suggests that the event is advective in nature. In other words, a region of water substantially warmer than its surroundings was transported onto the mooring location. For the advection of thermal energy on this scale to occur in the relatively short time frame of four hours, a combination of two things likely occurred: a strong current persistent throughout the water column and the existence of a sharp front between water masses of significantly differing thermal character. It is also worthy of note that the SM location did not begin to lose heat until well into December.

Although the results presented above occurred in 2009, qualitatively similar observations of full-depth temperature variability were also recorded in 2010 and 2011 at the SM site. However, the changes observed in the water column during 2009 represent a more drastic and rapid transition out of summer stratification than the observations from the two subsequent years.

Discussion

From the available observations, a general picture of dynamics affecting the full water column captured at the Southern Mooring can be drawn. Perhaps most noticeably, a rapid, drastic, and full-depth change in thermal structure at the site is apparent. The event occurred during stable late-summer stratification and marked the start of a period with persistent increased heat content, a deeper mixed layer, and lower stability. The event followed sustained northerly winds, and afterwards, similar northerly winds were seen propagating into the temperature observations throughout the deepest portion of the water column. This relationship between wind and deep-lake temperature persisted until winter homogenization. Notably, the magnitude of increased temperature at depth corresponds well with northerly and northwesterly winds but does not seem to be related to winds from any other direction. The pressure record suggests that the mooring was "blown" over for two days following the high winds, presumably by a significant current. Unfortunately, neither direction nor magnitude of the current can be determined with the given observations. This argument for increased circulation is echoed by the large and rapid increase in local heat content, the only reasonable explanation for which is the advection of a mass of warmer water onto the mooring. Additionally, the event was isolated at the SM site; similar events were not recorded at any of the other six mooring locations across the lake. The Southern Mooring site is located 40 km offshore which is sufficiently far to be removed from coastal downwelling, or warm surface water "piling up" along the coast. The site is also marked by highly irregular bathymetry. Trenches, pits, and seamounts all contribute to the high variability around the site. Lastly, these types of events that happen during late summer stratification and drastically change the character of the water column at this specific location appear to happen annually to varying degrees.

Despite the diverse set of observations, the underlying mechanisms that cause these events in Lake Superior are unknown. General assumptions tend to mark the hypolimnion of large lakes as rather quiescent during summer stratification, especially when compared to the upper layer of the lake. However, these findings suggest that the hypolimnion is more energetic than is generally thought. This highlights an incomplete understanding of the dynamics governing the deepest regions of large lakes and the interactions and boundaries between shallow and deep layers.

It is likely that these types of events are caused by a combination of known dynamics rather than an entirely novel mechanism. The localization of the observed event at the SM site suggests that a set of parameters unique to that location are at play. The most notable difference between the SM site and the other mooring sites is the highly irregular bathymetry. Additionally, the coincidence of high windspeed and deep-lake temperature variability points to wind forcing as a principal cause. Sustained periods of wind drive currents, the presence of which is strongly suggested by the pressure and heat content observations. Therefore, a possible explanation for the rapid change in thermal structure is that circulation caused specifically by northerly winds encountered unique bathymetric features at the SM site, and a concentration of warm water cascaded into the deep layer of the lake. The specifics of such an event are unknown and beyond the scope of this study.

Since the set of observations made at the SM site in 2009 suggests that the event was advective in nature, two circumstances must have been true within the lake: horizontal currents were present, and regions of water with differing thermal character (i.e. heat content) existed in close proximity. The rapid change in character of the water column can be explained by a transition between the two different water masses being transported over the stationary mooring by local circulation. Although these conditions may be assumed from the observations, neither were directly observed due to the limitations of the mooring. Velocity is not known because only temperature and pressure were recorded, and the spatial variability of temperature is not known because there was only one mooring at the location. The observations are also limited by slow recording speed; most thermistors logged every 30 min.

To amend these shortcomings and further characterize the events at the SM site, a new set of moorings could be deployed. By adding an acoustic doppler current profiler (ADCP) to each mooring, water velocity at different depths in the water column would be recorded in addition to temperature and pressure. In many applications, ADCPs are placed near the top of the mooring to provide high vertical resolution to the horizontal velocity data. However, this deployment would require full-depth velocity measurements since the observed events occur throughout the entire water column. Therefore, the ADCP would be placed near the bottom of the lake. In the years since 2009, instrumentation has become faster and able to store significantly more data, so a temperature and pressure sampling rate of at least once per second could be achieved. This represents an 1800x increase in temporal resolution, meaning the precise transition between thermal regimes could be determined during an event. Finally, at least one additional mooring could be deployed in close proximity to the SM site to form a cluster of moorings. Preferably, two additional moorings would be deployed. One would be placed 5 km to the south of the SM site in the same trench and at a similar depth. The second mooring would be placed 5 km to the east of the SM site outside of the trench at a depth of 100-200 m. This second mooring location is on a steeper slope and nearer to the seamount that sits to the southeast of the SM site. By deploying the three moorings orthogonally and at different depths, one could determine the horizontal scales that support drastic differences in thermal character and the interactions that water masses have with bathymetric features in the region.

In addition to a more advanced deployment, more analysis must be conducted on the data that is already available. Although the deep advective events occur to a lesser degree in 2010 and 2011, these years still offer insight into the dynamics that govern the SM site. Specifically, interannual variability of the relationship between northerly wind and deep-lake temperature fluctuation could be examined.

This set of moored temperature and pressure observations is a salient example of how little is known about the deep-water dynamics of large lakes despite the body of research dedicated to their study. Through further observations and analysis of the previously unwitnessed events recorded in the southeastern basin of Lake Superior, important governing mechanisms may come into focus. The world's large lakes hold much of the planet's available fresh water, and understanding how these resources continue to respond to a changing climate has the potential for broad physical, ecological, and human implications.

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