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Lake in a Bottle

A Laboratory Demonstration of the Unusual Stability Properties of Freshwater

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PURPOSE OF ACTIVITY

Using simple laboratory gear, students can simulate the stratification properties of a freshwater lake and the impact of salt on the relationship between temperature and density. Because some students have little or no intuition for different thermal stratification regimes, this activity is designed to focus on this fundamental behavior of freshwater lakes. The experiment exposes students to basic data collection, analysis, and visualization techniques using an inexpensive, commercially available data logger and sensors. It can be used as motivation for a discussion of sampling techniques, such as sampling density and sampling rate, and how choosing among them can influence the reliability of an experiment's results.

AUDIENCE

This experiment is designed for undergraduate and graduate students taking courses in lake ecology, limnology, or oceanography.

INTRODUCTION

Freshwater has the interesting property that, at atmospheric pressure, it has a maximum density of approximately 999.975 kg m^{-3} at 3.98°C (which will be referred to as T_{MD}, the temperature of maximum density; Figure 1), a temperature well above its freezing point of 0°C. This property leads to a variety of different annual thermal stratification cycles in a lake, depending on the lake's geography, geometry, and local climate (Lewis, 1983). Because of this unusual relationship between temperature and density, freshwater lakes have two primary types of thermal stratification: if the water temperature of a lake is above T_{MD}, then a layer of warmer water can form on top of cooler water below, known as positive thermal stratification. However, if the water temperature is below T_{MD}, then a layer of cooler water can form on top of warmer water below (negative thermal stratification). Depending on the regional climate of a lake, it can exhibit one or both of these structures over the course of a year. In between these periods of thermal stratification, lakes can overturn or mix vertically from surface to bottom, oxygenating water and redistributing nutrients and other properties throughout the water column. The annual cycle of overturns and stratification fundamentally determines the ecosystem structure of a lake (Wetzel, 2001). This phenomenon is unique to freshwater ecosystems because for water of salinity greater than 24 ppt (parts per thousand; most of the world ocean has salinity in the range 34–35 ppt), density decreases monotonically with temperature (i.e., no T_{MD} exists). The density differences involved, however, are very small. For instance, the density difference between 0°C and T_{MD}, with densities of 999.84 kg m^{-3} and 999.97 kg m^{-3}, respectively, is 0.13 kg m^{-3}, a difference of roughly 1 part in 10^4. Regardless of this small density difference, the vital

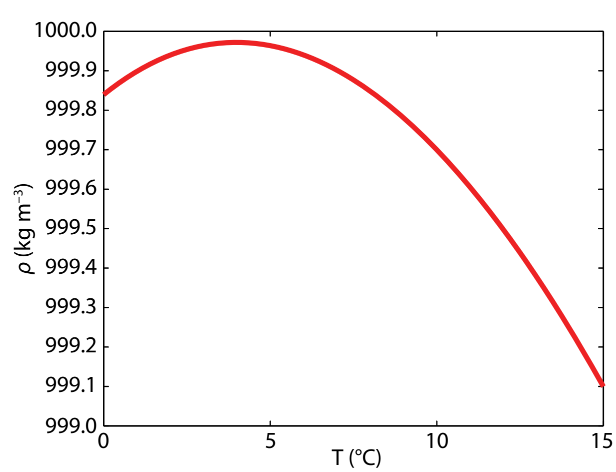

Figure 1. The density of freshwater as a function of temperature, at atmospheric pressure.

role of the T_{MD} density maximum in the overturning behavior of a freshwater lake can be demonstrated using a tabletop apparatus.

RESEARCH QUESTIONS

1. How will the vertical structure of temperature in a container develop over time as it is cooled or warmed?
2. How will insulating the sides of the container affect the response?
3. How will the addition of salt affect the development of the thermal structure?
4. What are the real-world analogues to these behaviors?

HYPOTHESIS

The existence of the temperature of maximum density for freshwater fundamentally determines the development of thermal stratification during both cooling and warming.

MATERIALS

The following materials (Figure 2) are necessary for the experiment:

- A plastic tube, capped and sealed at one end, open at the other. We use a 40 cm long tube with a diameter of 10 cm, and a wall thickness of 0.1 cm.
- Some form of removable insulation for the tube. We use a piece of polyurethane foam (i.e., Styrofoam) into which the tube fits snugly. The insulation we use is approximately 2 cm thick on the sides and bottom. The container remains open to the air at the top.
- A freezer large enough to accommodate the container, insulation, and data logger.
- A set of small temperature sensors (thermistors) and a data logger. There are many products on the market that fill this requirement. We use four Onset TMC6-HD thermistors connected to a 12 bit, four-channel data logger (Onset HOBO U-12-008). The data logger, thermistors, and logging software can be purchased for less than $300, and are useful in a wide variety of applications in addition to this one.
- A thin wooden dowel on which to mount the thermistors. Wood has a relatively low thermal conductivity so the dowel does not have a significant impact on the development of temperature structure within the vessel.

Figure 2. The experimental apparatus. From left: the thermistor array, insulated container, and data logger.

ACTIVITIES

The class can conduct several different experiments using this equipment. In each experiment, the water is either (1) cooled from room temperature to freezing, or (2) warmed from near 0°C to room temperature. The water is either (1) fresh (tap) water, or (2) saltwater. An additional degree of freedom involves (1) an uninsulated tube, or (2) a tube placed in its insulating jacket. Optimally, at least one freshwater uninsulated experiment and one freshwater insulated experiment should be run for each of the heating and cooling scenarios for the best student understanding. As the cooling/warming of the water takes several hours, the best way to run this experiment may be over the course of several lab periods, where students set up each experiment at the end of the lab session, then it is stopped several hours later by a student or instructor. To conserve time, the instructor could set up the experiment in advance, leaving the interpretation of the data to take place during the lab session; however, actively participating in the experiment's data collection is more engaging (as with any experiment). Likewise, the experiment would make a good class project for a small group of students who could work on it outside of class time.

Construction of the apparatus: Students should attach the four thermistors evenly along the length of the wooden dowel. Because our tube is 40 cm tall, we place the thermistors at depths of 5, 15, 25, and 35 cm to equally cover the extent of the tube. We make the assumption that the data from each thermistor is representative of the temperature in roughly one-quarter of the container. This is a good opportunity to discuss "data density"—how would this experiment

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be different with two thermistors? With one? With ten? Should the thermistors be evenly spaced, or is there a better way to distribute them? How do we know when we are fully resolving a phenomenon?

Preparation of saltwater solution: Add 35 g of table salt for each liter of water used. This salinity roughly approximates seawater.

Preparation of 0°C water: Form a slurry of ice and water by adding crushed ice to water and let it melt until only water remains.

Students should prepare the water and the apparatus as necessary for the experiment (i.e., salt or fresh? room temperature or 0°C? insulated or not?). If using insulation, place the tube in the insulating container. Fill the tube up to the rim with the water (it is important that there be little if any headspace in the container—in some cases, the air at the top can itself act as an insulator, dramatically slowing down the experiment). At this stage, the logger needs to be started, presenting another opportunity to talk about data sampling. Students will need to choose a sampling interval (i.e., how frequently data are recorded)—fast enough to resolve events, but not so fast that the logger runs out of memory, for example. It could also be pointed out that the sensors have a finite response time (i.e., how quickly they respond to changes in temperature) and that sampling at a rate faster than the response time is not useful. (As a helpful side experiment, students can determine the response time of the sensors by setting the logger to a rapid sampling interval, plunging a sensor into ice water, and observing how long it takes for the sensor to reach 0°C.) We use a logging interval of ten seconds. This is a good time for students to develop hypotheses about what they expect to happen in each of the scenarios they decide to test.

Once the experiment is over (students can periodically check to see when ice forms at the surface in the cooling runs), the data should be downloaded from the logger to a computer using the logger software. The software provided with the Onset equipment we use allows for some basic data visualization, and also allows the data to be exported to other formats, such as a .csv (comma separated value) file. The files can then be read by commercial analysis software such as Excel or MATLAB.

DATA ANALYSIS

The thoroughness of the data analysis will depend on the mathematics and physics backgrounds of the students, as well as their computer skills. For the following steps, we assume at least some basic mathematical background, as well as familiarity with concepts like heat content and heat flux, which are usually covered in a first semester physics course. Heat content refers to the *amount* of thermal energy needed to change the temperature of an object by a certain amount, whereas heat flux refers to the *rate* at which thermal energy is being transferred to (or from) an object. In this case, we do not directly measure the heat flux, but estimate it by observing the rate of change of the heat content of the vessel. Oceanographers and limnologists spend a great deal of effort measuring both of these parameters in the real world, and this experiment is an excellent opportunity to make the same sorts of estimates on a much more manageable scale.

At the conclusion of each experiment, either as an in-class exercise or as homework:

- Students display the temperature data from the thermistors as a function of time to see, qualitatively, how the system responds in the different scenarios.
- Students calculate the density of the water at each of the locations within the tube as a function of time using the equation of state for freshwater (Chen and Millero, 1986). Alternately, the equation $\rho(T) = 999.96 - 6.97 \times 10^{-3}(T - 3.985)^2$, where T is temperature in °C and the density ρ has units of kg m^{-3}, is a very good approximation for freshwater.
- Students estimate the change in heat content of the water relative to a reference temperature T_0 using
$$H = \sum_i \rho c_p (T_i - T_0) V_i,$$
where H is the heat content in Joules, ρ is the density of water in kg m^{-3}, c_p = 4,186 J kg^{-1} K^{-1} is the specific heat, T_i is the temperature of each of the thermistors, T_0 is a reference temperature (commonly set to 0°C), and V_i is the volume of the container represented by each thermistor.
- Given the heat content H, students estimate the heat flux Q between the water and its surroundings using
$$Q = \frac{\Delta H}{\Delta t},$$
where Q is the heat flux in Watts and Δt is the time interval between samples, in seconds. Q represents the rate of transfer of thermal energy between the water and its surroundings.

Students will find that the heat flux and thermal structure are substantially different in the different experimental scenarios, and that the T_{MD} density maximum plays a fundamental role in the development of stratification in all of the freshwater cases.

RESULTS

A description and explanation of the results that should be obtained from four of the potential experiments is provided below. Before each of these experiments is performed, students should form hypotheses about the behavior of the water column during heating or cooling. You can lead them on by asking about where the heating/cooling is likely to take place, what the resulting density-driven circulation might be, and how this will redistribute the heat within the container.

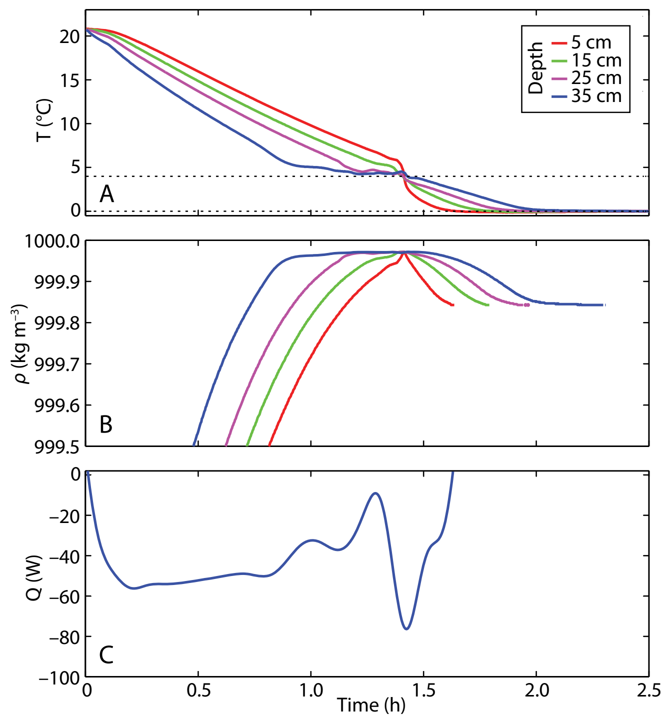

Figure 3. (A) Temperature at 5 cm, 15 cm, 25 cm, and 35 cm depth for the uninsulated cooling case. Dashed lines are at 0°C and 3.98°C for reference. (B) Calculated density for the uninsulated cooling case. Densities were not calculated for water cooler than 0.1°C. (C) Rate of change of heat content. Not calculated once ice starts to form at the surface. The data are low-pass filtered for legibility.

Activity 1: Freshwater Cooling in an Uninsulated Container

Immediately after the container is placed in the freezer, the water inside the container stratifies (Figure 3A), with the temperature at the lowest thermistor dropping most rapidly. In this case, most of the heat loss is occurring at the walls of the container and the cooled, denser water sinks to the bottom. Once the bottom water approaches T_{MD}, its temperature plateaus, and any cooling of this T_{MD} water produces positively buoyant water that rises and mixes with warmer water above. Soon thereafter, the second-lowest thermistor plateaus at T_{MD} as the water continues to cool. Eventually, the surface thermistor reaches T_{MD}, at which point the water becomes negatively stratified. At this stage, further cooling produces less-dense water, and water cooled along the sides of the container becomes positively buoyant and rises to the surface. Once it reaches 0°C, ice forms on the surface, while the rest of the water column continues to cool. Students should note that even though the character of the thermal stratification changes (from positively stratified to negatively stratified), the density (Figure 3B) is always positively stratified.

The heat flux Q (Figure 3C) decreases during the experiment because the rate of heat loss is proportional to the difference between the air and water temperatures, which decreases throughout the experiment. The fluctuation in the rate of heat loss when the temperature passes through T_{MD} is likely due to the limited spatial resolution of the temperature measurements.

Activity 2: Freshwater Cooling in an Insulated Container

Because the exposed surface area is significantly reduced when using an insulated tube, the experiment takes much longer and is perhaps best left to run overnight. Prior to the experiment, students can use geometrical arguments to estimate how long cooling will take. Students can also use simple rules of heat conduction to estimate what the heat flux through the insulation will be, given the air and water temperatures; the heat flux through foam walls will be

$$Q_{walls} = \frac{Ak(T_w - T_A)}{d},$$

where A is the area of the insulated sides of the container, $k \approx 0.02$ W m^{-1} K^{-1} is the thermal conductivity of insulation, T_w and T_A are the water and air temperatures, respectively, and d is the thickness of the foam walls. Students can estimate this rate for the geometry they are using, and should compare this rate to the heat loss they observe. (For our geometry, we found it to be on the order of 1 W, while the observed rate of heat loss was roughly 10 W; Figure 4C). The difference between these rates represents the rate of heat loss at the surface. In this case, this result suggests that nearly all of the cooling is taking place at the surface, not through the sides of the container.

Above T_{MD}, water cooled at the surface produces a momentarily unstable water column (Figure 4A), with slightly colder (denser) water sitting atop warmer, lighter water below. This situation drives a process called penetrative convection, in which the water column is continuously slightly unstable, and convective (i.e., density-driven) flows redistribute heat throughout the entire water column. Because this source of cooling dominates, the water column cools off roughly uniformly, as observed. The character of the cooling in this case is distinct from that observed in the uninsulated case. Once the entire water column reaches T_{MD}, negative stratification forms. At this stage, the surface reaches 0°C relatively quickly because the heat loss impacts a smaller portion of the water column, and ice forms. Once ice begins to form (after approximately 10 hours), the rate of cooling of the rest of the water column is consistent with estimates of heat flux through the sides of the container because the surface ice acts as an insulator.

Activity 3: Saltwater Cooling in an Insulated Container

For this experiment, use an insulated container and add enough salt (35 g of table salt to each liter of water) so the water has salinity analogous to the world ocean. In this case (Figure 5), the water column remains uniform in temperature as it cools, suggesting that penetrative convection is responsible for the redistribution of heat throughout the entire experiment, similar to the freshwater case except the no overturn occurs at 4°C. Note that it cools below 0°C, since the addition of salt lowers the freezing point.

Activity 4: Freshwater Warming in an Insulated Container

For the insulated freshwater warming case (Figure 6), the water column initially warms up uniformly, as warming at the surface drives penetrative convection. Once reaching T_{MD}, the system stratifies, with the surface waters heating up quickly, the lower waters much more slowly. The rate of warming decreases as the water temperature approaches the ambient air temperature.

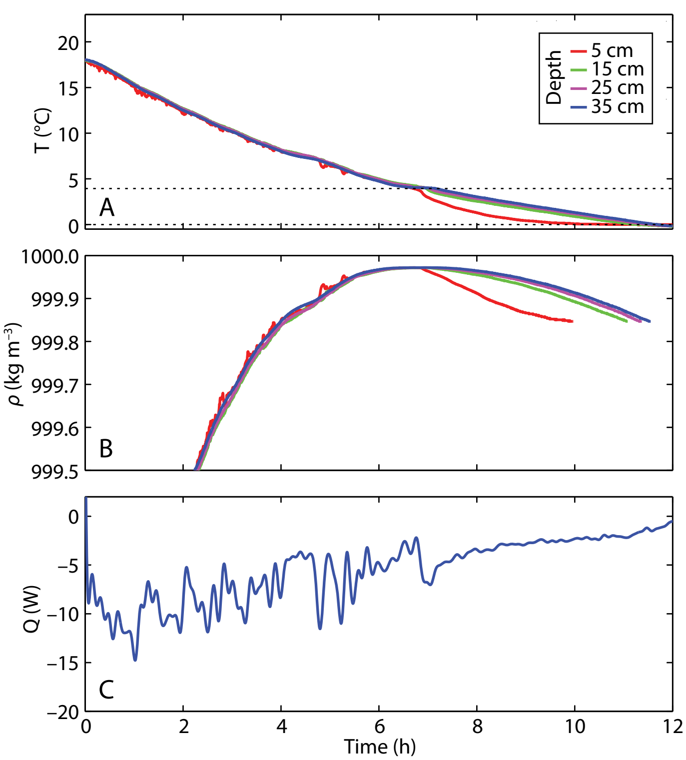

Figure 4. As in Figure 3, but for the insulated cooling case. Note the significantly longer time scale. Data from some of the thermistors is obscured prior to reaching 4°C because the water column is uniform in temperature.

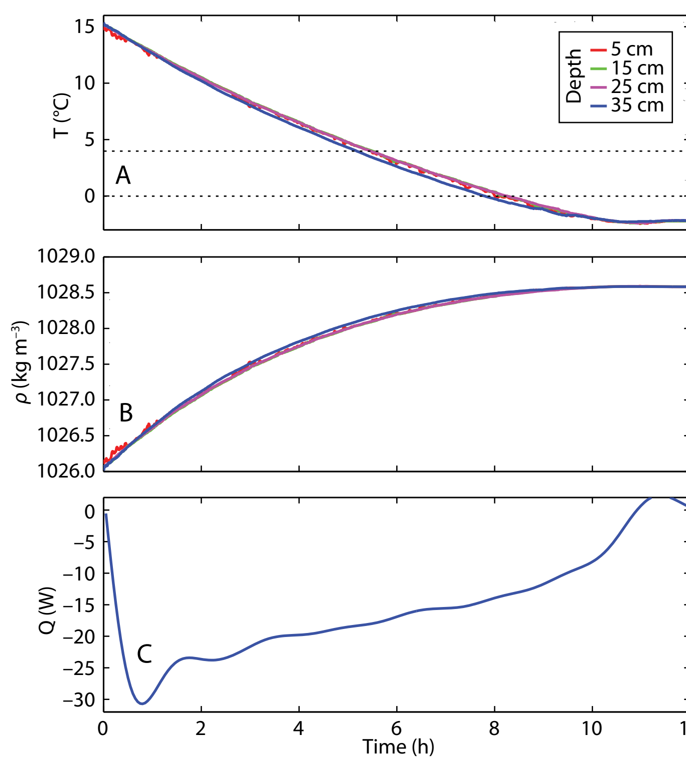

Figure 5. As in Figure 3, but for the insulated cooling saltwater case. Density is calculated assuming a salinity of 35 ppt.

As an interesting aside, when we initially performed the warming experiment, we used a 50 cm long tube and filled the container to 40 cm, so that there was a 10 cm "head space" of air above the water. In this case, the air in the head space became stably stratified (with a layer of cool air in contact with the water lying below a layer of warm air from the room), and the heat flux into the water was very small, occurring almost entirely through the insulated walls of the vessel. Because still air has roughly the same thermal conductivity as polyurethane foam ($k \approx 0.02$ W m^{-1} K^{-1}), this was roughly equivalent to placing a 10 cm block of foam insulation on top of the water. In the cooling case, however, the air in this head space was unstable (being cooled from the surface) and could transfer heat effectively through turbulent processes. This experimental setup is a useful demonstration of the impact of atmospheric stability on the rate of turbulent heat flux, the insulating properties of still air, and, ultimately, the distinction between convective and conductive heat transfer.

WHAT DO THESE EXPERIMENTS HAVE TO DO WITH LAKES?

The case in which the vessel is insulated on the sides and at the bottom is analogous to the dynamics experienced by the open waters of a large freshwater lake, where lateral variability is weak. In the absence of horizontal advection and strong horizontal gradients, the thermal structure of a lake behaves in a largely one-dimensional sense, with strong gradients in the vertical only. Indeed, many, if not most, of the features observed in the insulated case have direct analogies in the annual development of a dimictic lake, that is, a lake that experiences both positive and negative stratification over the course of a year (Lewis, 1983). As an example, temperature data from a mooring in Lake Superior (Figure 7) shows distinct periods of positive and negative stratification, with periods of penetrative convection in between, at which point the lake is being thoroughly vertically mixed. In the period starting in mid-November, the temperature at 12 m and 50 m is the same, and surface cooling is driving penetrative convection, similar to the behavior of the cooled insulated vessel before it reaches T_{MD}. Likewise, at

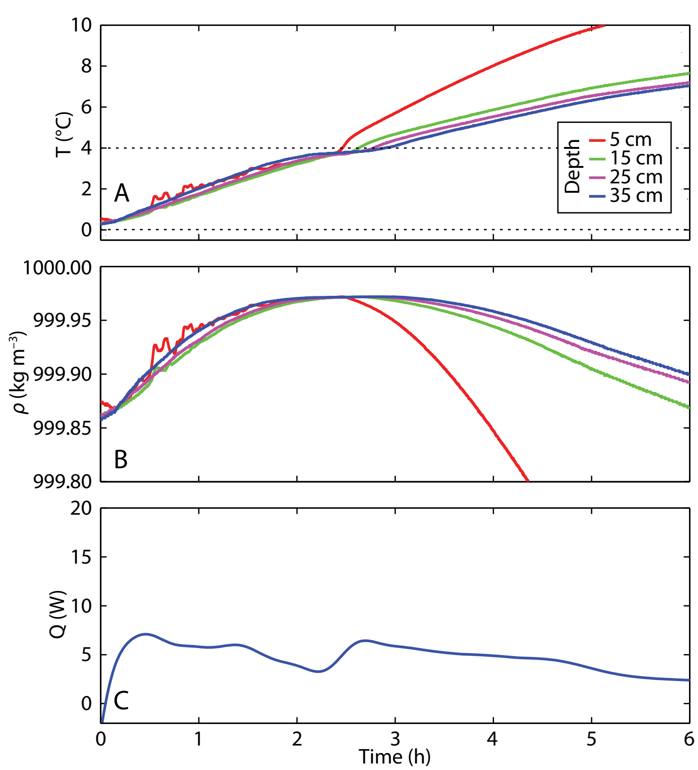

Figure 6. As in Figure 3, but for the insulated warming case.

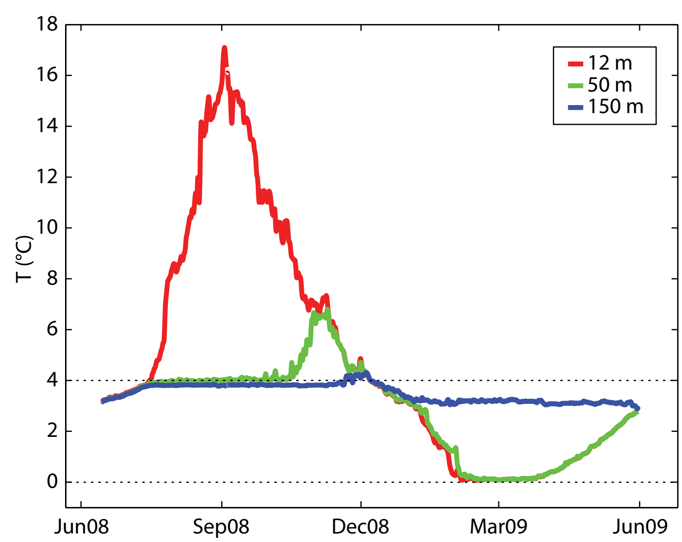

Figure 7. Low-pass filtered temperature data from approximately 12 m, 50 m, and 150 m depth in Lake Superior. Mooring location was approximately 48°04'N, 87°47'W. Dashed lines are placed at 0°C and 3.98°C for reference.

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the beginning of December, the entire water column reaches its temperature of maximum density, cools slightly, and then establishes strong negative thermal stratification. While the actual mechanics of the heat transfer are different between these two cases, the resulting thermal stratification development is remarkably similar. Other lakes, in different climates, may experience only one of these phases, or may remain stratified all year long.

The uninsulated cooling case is analogous to a freshwater lake in which the cooling rate has significant lateral heterogeneity, as in a lake with shallow regions around the edge. In a mechanism known as deepwater renewal, water can cool off quickly in localized regions, become negatively buoyant, and sink to an equilibrium level. Lakes such as Lake Malawi, on the borders of Malawi, Mozambique, and Tanzania (Halfman, 1993; Vollmer et al., 2005) or Lake Issyk-Kul in Kyrgyzstan (Peeters et al., 2003) are thought to have their deep waters occasionally refreshed by this lateral cooling mechanism. This mechanism is especially important in lakes that do not fully mix on an annual basis so that deeper waters are excluded from ventilation with the atmosphere.

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