Temperature and Dissolved Oxygen under the Ice

Introduction

Lakes in the temperate zone are great environments for examining the implications of the movement of energy and materials. Lakes show interesting patterns in variation in temperature, both vertically and horizontally, and those thermal patterns change with the seasons. Patterns of dissolved oxygen in lakes also show profound seasonal variation. In this lab you will use simple stock and flow models to develop hypotheses about what patterns you might expect to see in dissolved oxygen and in temperature under the ice of Lewiston's only "great pond", No Name Pond, located about 3 miles from the Bates Campus. Next week, in the continuation of this lab, we will head out to No Name Pond, cut holes in the ice, and take measurements to test your hypotheses.

Background

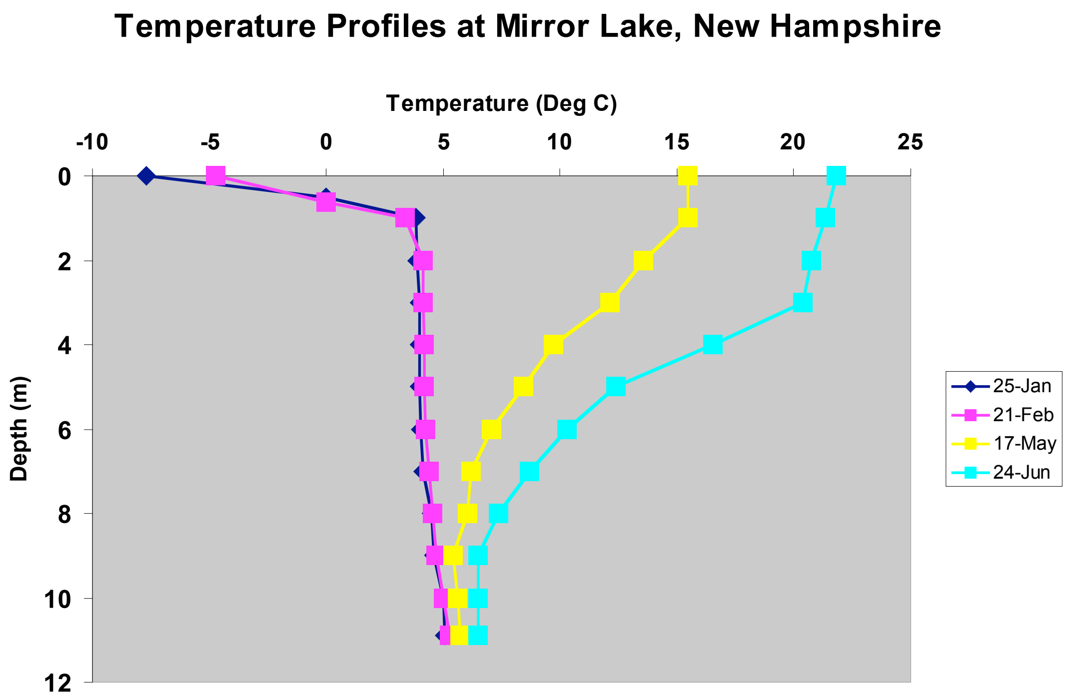
Temperature in Lakes in Winter

Many people have gone swimming in a Maine Lake, especially early in the summer and been surprised at how cold the water was just a few meters below the surface, even when surface water temperatures were quite comfortable. The sudden transition from warm surface waters to cool waters a few meters down is the result of density stratification. The sun warms the surface of the lake. At summer temperatures, warm water is substantially less dense than cold water, so the sun-warmed water floats on top of the underlying cooler water. In the absence of a strong wind, the two layers barely mix, producing a strong temperature gradient near the surface of the lake. In deep lakes, this process can produce in summer a stable temperature pattern characterized by a broad layer of warm water, relatively well mixed by the wind (termed the "epilimnion" in the argot of limnologists), overlying a much colder layer (the "hypolimnion"). The narrow band of water between, often only a meter or so thick, in which water temperatures may climb from 4 or 5 degrees C to 20 degrees C, is termed the "metalimnion". The specific depth at which temperature changes most rapidly with depth is called the thermocline.

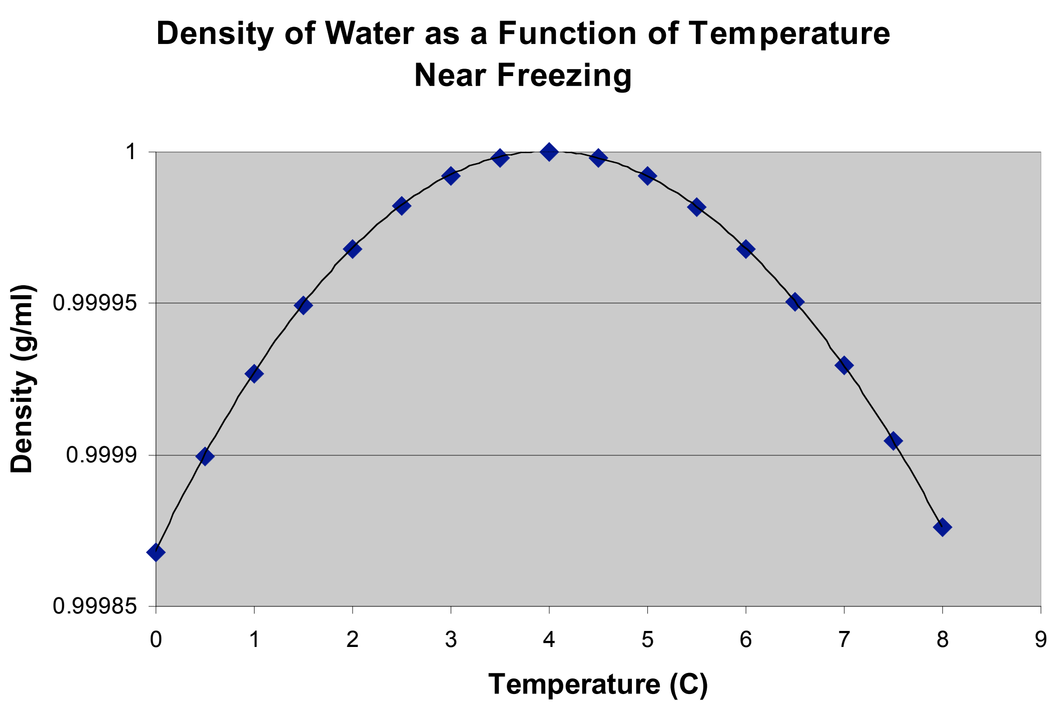
Perhaps because nobody sane goes swimming in the middle of deep lakes in the winter, a similar winter phenomenon is less well known, except by limnologists. In the winter, we also see a form of density stratification in many lakes. However, because of the unusual properties of water near the freezing point, the density stratification takes a counterintuitive form.

Water at low temperatures does not behave as we would expect based on our experience of water at higher temperatures (See the figure on the next page). It turns out that as water cools below a certain point around 4 degrees C, instead of getting more dense, it gets less dense. In other words, between freezing and 4 degrees C, water does not expand as you heat it, in contracts.

As a lake cools in the fall, it cools primarily via emission of infrared radiation from its surface. This process is predominately a surface phenomenon, like the summer warming of lakes by solar radiation. As surface waters cool from their summer maxima, they become more dense than the (now warmer) waters below them. The dense waters sink through the less dense waters beneath them, mixing the lake. In cold climates like Maine, the lake will generally mix from top to bottom and continue to cool until the entire lake is very close to 4 degrees C from top to bottom. This is commonly called the "fall overturn" and is very important in the ecology of temperate lakes. Not only does this event mix warm water with cold, it also equalizes the concentration of nutrients and oxygen between the biologically active surface waters and the deeper waters of the lake. In Maine, the fall overturn typically happens around the middle of November.



Data from Wetzel and Likens, 1991. Limnological Analyses, Second Edition. Springer-Verlag, New York.



Data from Hutchinson, 1957, A Treatise on Limnology, Volume 1:Geography, Physics and Chemistry. John Wiley and Sons, New York.

As the lake continues to cool, however, the surface waters begin to get LESS dense than the deeper water, and a very subtle -- but very important -- "inverse temperature stratification" begins to develop. As fall continues into winter, the surface waters cool further, but because the density differences between water at

0 degrees C and at 4 degrees C are so small, this surface density stratification can be easily disrupted. All it takes is a moderate wind to generate wind-induced surface currents and turbulence sufficient to mix the surface water into the depths, and break the early winter density stratification apart.

This process helps explain why lakes tend to freeze on clear, windless nights. On clear nights, the atmosphere radiates less infrared radiation back towards the lake, increasing the net loss of heat from the lake surface. On windless nights, the cold surface waters of the lake "float" above the deeper, warmer waters without mixing, so surface waters can freeze without having to cool the waters below them first. Once the surface of the lake does freeze, the ice prevents further wind driven mixing, thus stabilizing the delicate winter density stratification.

Creating Your Hypotheses

Traditional limnology has focused much attention on the vertical patterns of stratification in temperature and oxygen in the deep waters near the center of temperate lakes. However, many lakes are dominated not by deep waters, but by shallow waters just a few meters deep. Even many lakes that do contain deep-water areas are dominated in terms of absolute area by the shallower waters around the lake margins. Your job is to develop one or more hypotheses concerning spatial patterns of oxygen and temperature in No Name Pond. As you can see from the map of No Name Pond, something on the order of a third of the lake has depths of under 2 meters, so the traditional limnological understanding of stratification processes will only get you so far.

To generate testable hypotheses about spatial distribution of temperature and oxygen, you will need to construct at least conceptual models of the processes that are controlling the distribution of heat and the distribution of oxygen in No Name Pond. I suspect that you will find it valuable to make explicit, formal use of your back of the envelope calculation skills and your abilities to think in terms of stocks and flows.

You will find it helpful to make stock and flow models of a unit volume of lake water this time, instead of trying to model the entire lake. That way, you can apply the same model to waters in various parts of the lake, and think through how different sources and sinks of oxygen and heat may affect local conditions.

Modeling Temperature

To develop specific hypotheses about water temperature, you will need to construct a simple stock and flow model that incorporates your understanding of processes that can add or remove heat from lake water, and consider where in the lake each are likely to be most significant during the winter.

Sources of heat to the lake can include direct and indirect solar radiation, flow of water into the lake, and conduction of heat from the sediments into the lake. Processes that remove heat from the lake include net thermal (infrared) radiation away from the lake, flow of water out of the lake, and conduction of heat to the overlying air (if the air is colder than the ice surface). It is also worth remembering that freezing of water releases a considerable amount of energy, while melting of ice consumes a lot of energy.

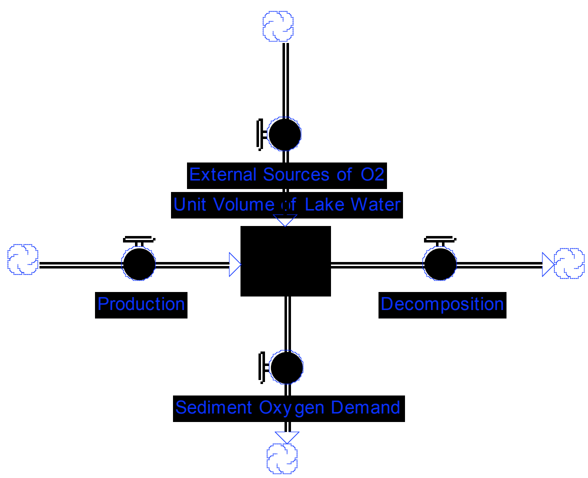
A note of caution: Temperature does not measure the amount of heat present in the water. Heat is measured in units of energy, either calories or Joules. The heat energy stored in a volume of water is found by taking the product of the water body's MASS, TEMPERATURE, and SPECIFIC HEAT. Specific heat is an empirically-derived property of different materials. For our purposes, it is measured in units of cal g^{-1} deg C^{-1}, and for fresh water has a value quite close to 1. As a practical matter, what this means is that to predict the effect of any heat flow into a lake on temperatures, you must consider the volume of water to which the flow of energy is directed. In other words, it takes more energy to warm a lot of water to a specific temperature than it does to warm a small amount of water to the same temperature.

Modeling Oxygen

The fall overturn equalizes the concentration of dissolved oxygen between the surface waters and the deep waters of the lake. The development of ice cover, and the establishment of density stratification tends to leave the lake with few internal currents except those generated by water entering the lake from surface water and groundwater sources. Lake waters don't mix much, except near inlets and outlets.

So, an understanding of dissolved oxygen in winter lakes can be understood in terms of simple box models, in which you explicitly consider the sources and sinks of oxygen within representative volumes of lake water. A number of features of the winter lake environment further simplify the analysis:

1. Winter lakes are cold, and thus both photosynthesis and decomposition are slow, except in warm microsites such as near springs or where other sources of heat are present (but note that the deep waters of the lake are cold during the summer as well).
2. Turbulent water movement helps many phytoplankton stay within the "photic zone" of the lake where light is most abundant. The lack of much water movement in winter lakes limits turbulence under the ice, so most larger phytoplankton sink to the bottom, where they are left in the dark.
3. Snow cover, and to a lesser extent, ice cover reduces the light reaching the top of the water column by more than half, and sometimes by as much as 90%. Most of this light is reflected by the snow, not absorbed. This further reduces any warming effects of the already low winter solar radiation on lake temperatures.



A simple stock and flow model of dissolved oxygen in a representative volume of lake water

Diffusion

You may notice that I have spoken not at all about the role of diffusion in distributing either heat or oxygen within a lake. That is largely a question of spatial and temporal scale. Diffusion is a slow process over distances of more than a few meters. At the larger scales relevant for most limnology, wind driven mixing and convection tend to kick in before diffusion becomes significant. However, this is not true if you are interested in phenomena that occur on smaller spatial scales, such as those that occur surrounding the leaves of aquatic plants.

Solubility

Oxygen, like most gasses, is significantly more soluble in cold water than in warm water. While the physics and chemistry of the process are beyond the scope of this class, what this means is that that if two bodies of water are in contact with one another but at different temperatures, the equilibrium distribution of oxygen will be such that the concentration of oxygen will be greater in the cold water.

Your Task

This week, your task is to build a simple stock and flow model of temperature and oxygen in a representative volume of lake water, and use that model and your back of the envelope calculation skills to develop a prediction about how oxygen and heat are distributed in space within No Name Pond. You might want to ask whether dissolved oxygen should be highest in the deep waters of the lake or in the surface waters. You may want to ask whether the shallow waters around the edges of this lake show different temperature or oxygen profiles than do the waters in the center of the lake. You may want to determine whether stream inflows in the lake affect temperature or oxygen conditions. Better yet, dream up your own hypotheses. Then figure out how to test those hypotheses. Please recall what you learned in the last laboratory about replication of measurements and representative sampling procedures. You will need to plan several measurements from within each part of the lake you chose to study.

So, your task can be summarized as follows:

(1) Build Models of oxygen and heat in representative volumes of lake water
(2) Construct hypotheses about how flows of oxygen and heat will vary from place to place
(3) Design a Study that tests those hypotheses, by taking measurements at different locations.

Tools

For this lab, we are somewhat limited with respect to the tools we have available. We have two dissolved oxygen meters (that also measure temperature) and one multiparameter water quality meter that measures pH, redox potential and depth as well as oxygen and temperature. We have several picks and iron digging bars to cut holes in the ice. Groups are likelyto have to share equipment.

I have prepared maps of No-Name Pond and its watershed based on USGS topographic map data. I have added data on depth of the lake based on "Fishing Depth Maps" available from the State of Maine Geological Survey.

Some facts about no-Name Pond that you may find of interest:

1. The lake has a maximum depth of slightly less than 10 meters.
2. It develops strong summertime thermal stratification.
3. It is a highly productive (eutrophic) lake during the summer. Concentrations of nutrients such as nitrogen and phosphorus are unlikely to limit winter productivity.
4. Decomposition in the deep water of the lake and on the bottom sediments, coupled with sediment oxygen demand is sufficient to deplete the bottom waters of the lake of oxygen in most summers.
5. Generally, this is a fairly typical Maine Lake, with a substantial shallow fringe around the lake (especially at the north end), and a gradually sloping bottom to the deepest point.
6. The ice can get pretty thin near the outlet to the lake. I would not plan to collect any data very close to the outlet.