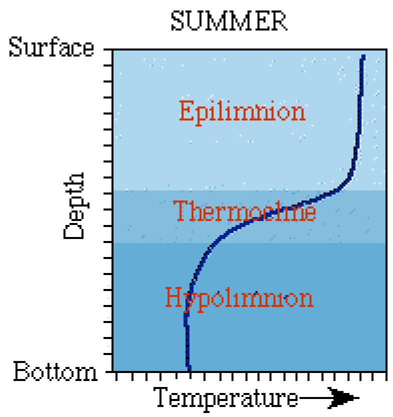
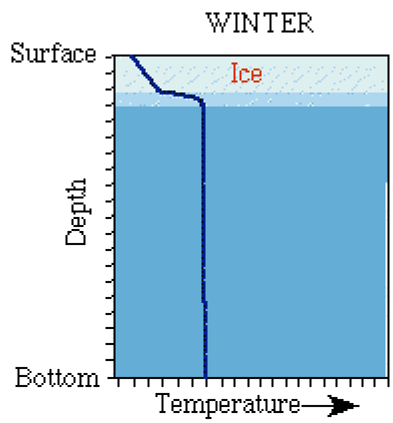
DENSITY, LAYERING AND STABILITY

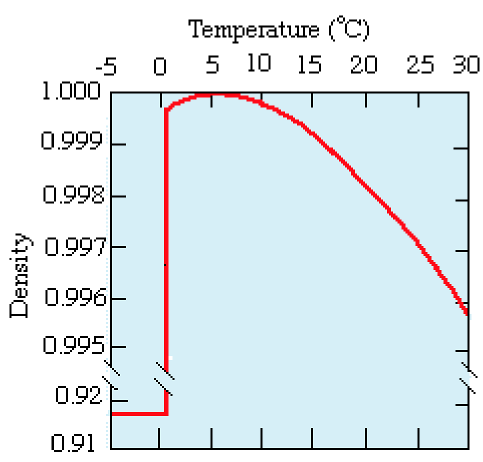
Stability of the water column -
First, a more detailed review of stratification:
Lakes in temperate regions, particularly deep ones, stratify during at least part of the year.
Typical stratification thermal profile:

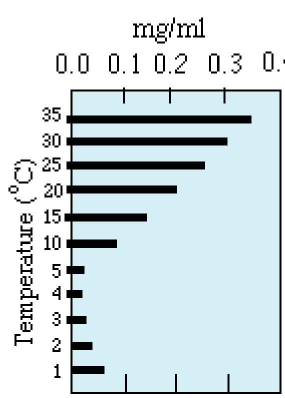




Three principles govern thermal, density stratification of lakes:

1. Heat enters and leaves the lake primarily from surface.
2. The density of water varies with temperature.
   a. The temperature of maximum density is 3.98°C
   b. Water is less dense at temperatures both below and above 3.98°C.
3. Warmer water has greater difference in density per degree temperature change than water between 0 and 4 °C.





Density Difference Resulting From a 1°C Change

Heating wavelengths absorbed rapidly, so surface warms. Density change between 29-30 °C is 36.77 times higher than the change between 4 and 5 °C. Therefore, energy required to mix a lake that has a surface temp significantly above 4-5 ^{o}C is going to be large because the density differences are large.

Other factors modify the density of water, and therefore density differences in a water column.
1. **Pressure** lowers temp of max density such that in a deep lake, bottom waters may be below 4 ^{o}C. At sea level, pressure is equivalent to a water column of 1.032 kg x 1cm^2 and approx every 10 m is additional atmospheric pressure. The temp of max density lowered approx 0.1^{o}C per 100m.

Temp of max density below 500 m = 3.39^{o}C and below 1000 m = 2.91 C.

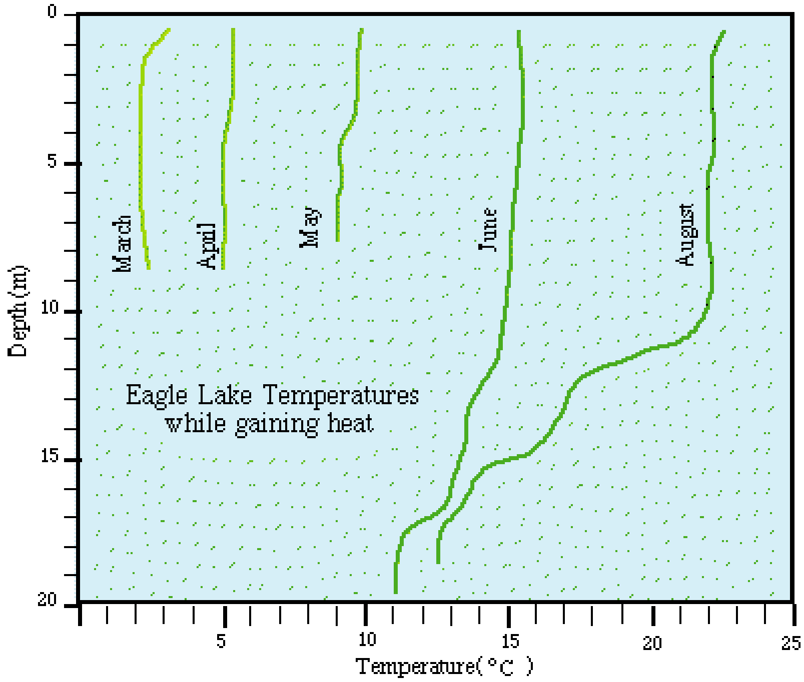
2. **Solutes** can cause anomalies: the temp of greatest density is depressed and hypolimnion temperatures can fall below 0 ^{o}C. Manito Lake in Saskatchewan the freezing pt is -1.1 and the max density is -0.3 .

Specific gravities are increased by solutes (salts). Lakes where stratification is salt related, the temp induced density relations can be reversed. Can get a shallow pool of brine due to evap that is overlain by dilute layer from rain, runoff. Solar radiation penetrates dilute layer and saline layer accumulates heat.

3. **Suspended particles:** effective in increasing density of a water. A **density current** of turbid, muddy water can enter lake, cut thru the colder water and continue downward until it reaches a level where it hits water of equal or greater density.

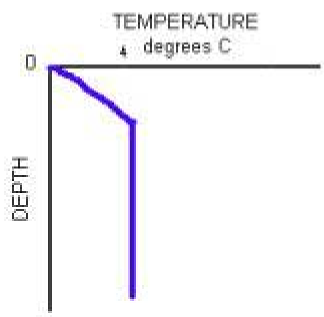
Ex: Colorado River where it enters Lake Mead after Grand Canyon. During the summer, there was flow along the lake bottom of sediment laden river water. In later years, salinity played a role.

Density differences cause a resistance to vertical mixing. The work necessary to mix is dependent on the difference in weight of the strata being mixed. A difference of 10 ^{o} Celsius conveys much more stability between 15 and 25 degrees than between 5 and 15 degrees. Partly because of this difference, a lake like Eagle Lake will warm isothermally to some level before beginning to stratify.



Monthly temperature curves can be followed from left to right. Eagle Lake does not begin to stratify until late May or Early June by which time the entire water column is at least 10^{o}C.
winter

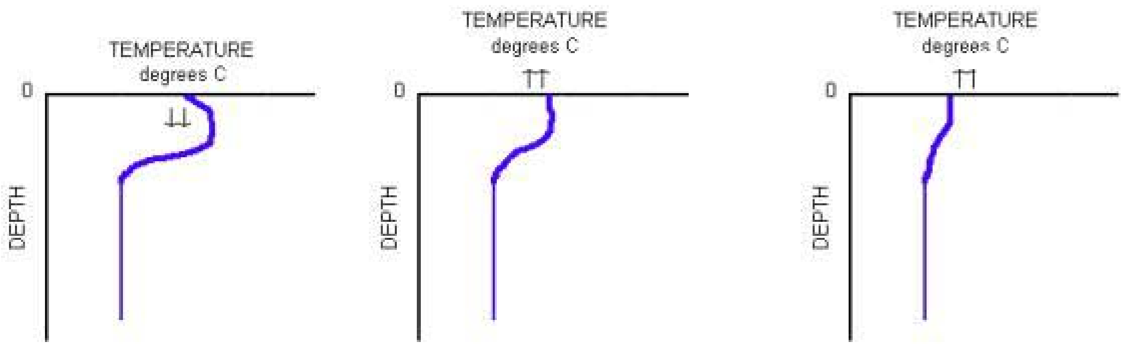
Seasonal cycles
Temperate zone, winter



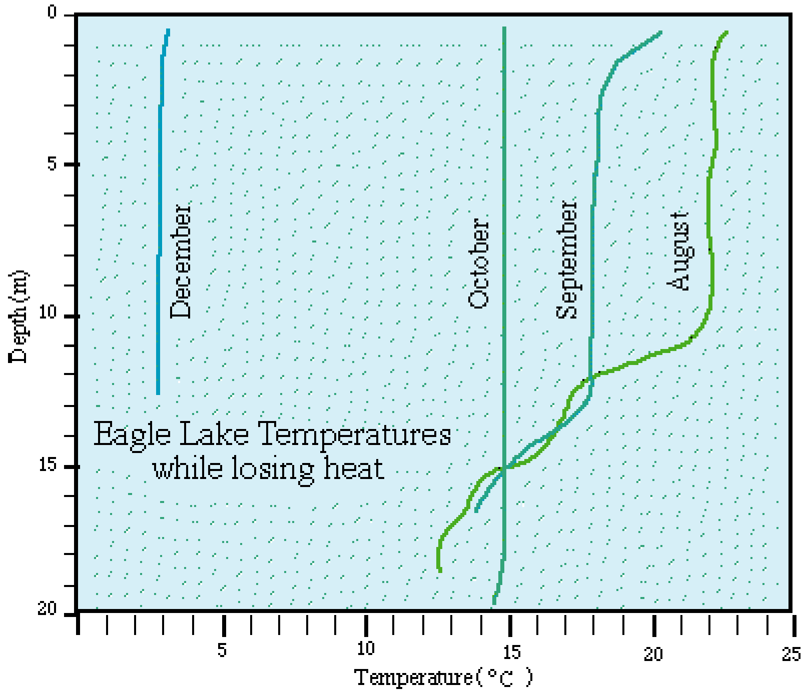
Reverse or inverse stratification cold water is on top of warmer water

Seasonal cycles

Temperate zone, fall



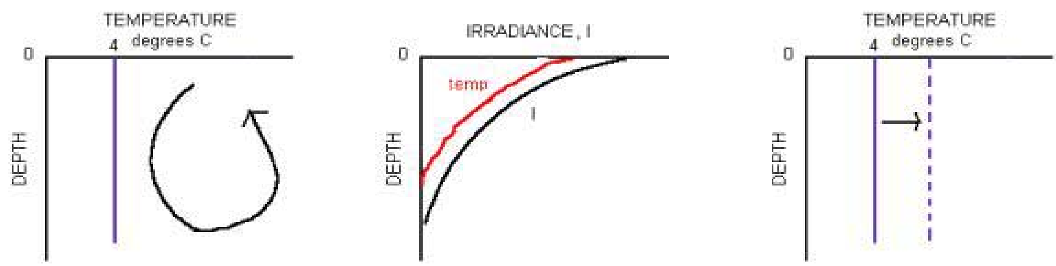
After water column reaches 4°C, further cooling produces less dense water which floats on surface, losing further heat to become ice. A clear, calm night results in a thin layer of ice which prevents wind mixing. Additional heat loss results in thickening the ice rather than further cooling the water. However, because thermal stability is so slight at those temperatures, as long as the water is open, a small breeze will keep it mixing and prevent ice formation until whole body of water has been cooled to near zero °C.



Ice thawing is complex. Solar energy is absorbed by ice, it begins to thaw around trapped salt crystals, thereby becoming weaker without becoming thinner. The same thickness of ice which supported a truck in January may not support a human in March. Any springs entering the lake may be adding water at the average annual temperature of the area. If the average annual temperature is above 4°C, the spring water will stay on top, melting ice. Also shallow areas may be warmed by light passing through ice and being absorbed by the substrate. One way or another, a hole will open, usually somewhere along shore.

Seasonal cycles

Temperate zone, early spring



Isothermal spring overturn or turnover

Energy from light

Isothermal warming

Mixing determines pattern of ion and gas transport
Can mix organisms (meroplankton) and resting eggs

A bit of open water lets the wind work on the water, causing two effects:

- Surface water is blown across the opening and against the ice - brings up deeper, usually warmer water to replace it, which in turn is blown against ice, melting some and enlarging the opening.
- Waves begin to propagate and as the hole gets large enough, the wave action begins to crack the weak adjacent ice.

The entire ice cover can go off in a day. In the process the lake water is completely mixed, bringing warmer water in contact with the ice and melting much of it, in the process dropping the temperature of the water body several degrees.

Wind

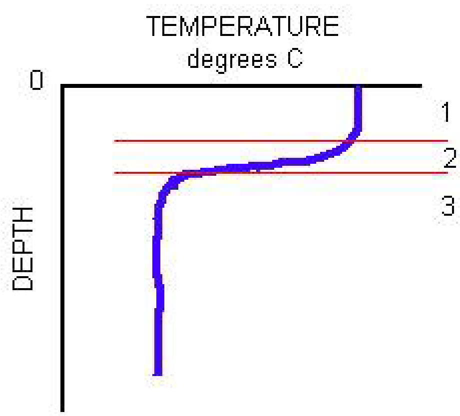
Big factor in lake stratifying and mixing is wind. Wind mixes the surface heat down into the water. **Wind fetch:** effective distance over the surface of the lake that the wind can blow unimpeded. This is mostly a function of lake size but also relates to shape and orientation of long axis relative to prevailing storm winds. A lake with small wind fetch will stratify earlier and remain stratified longer than a larger lake. Table compares features of large and small lakes for which elevation, latitude and climate are equal:

feature	larger lake	smaller lake

periods of stratificalion	shorter	longer
depth of thermocline	deep	shallow
summer epilimnion temperature	colder	warmer
summer hypolimnion temperature	warmer	colder
winter ice cover	shorter	longer
winter ice	thinner or absent	thicker

A small lake next to Lake Superior would have 3 feet of ice on it while Superior was still open. By contrast, in the summer, the surface temperature of the small lake might approach 30 ^{o}C while Superior was still 10 ^{o}C. The depth and timing of stratification also have a profound influence on other aspects of the lake's chemical and biological characteristics.

Some commonly used vocabulary Layers:



1. Epilimnion: The surface layer of a lake during the period of summer stratification.

2. Thermocline: A horizontal layer of water in a lake with a particularly steep temperature gradient. During the summer stratification it is the intervening layer between the epilimnion and the hypolimnion. (A more general term for a stratified layer is *pycnocline*, for density stratification, whether caused by temperature or salinity. Other terms in use are: *Sprungschicht* and *discontinuity layer*.)

2.a. Metalimnion: The thermal transition layer below the epilimnion. Commonly used interchangeably with thermocline. Some authors have defined the thermocline as the depth at which the temperature changes most rapidly and the metalimnion as the entire zone over which the temperature is changing rapidly.

3. Hypolimnion: The deep water region in a lake below the thermocline or metalimnion.

Reference: J. Imberger and J.C.Patterson, 1989, "Physical Limnology", pp303-475 in Advances in applied mechanics, vol 27. TA 350 .A4

TYPES OF MIXING AND LAKE CLASSIFICATION

Noun **Mixis** and adjective **Mictic** use to categorize lakes according to stratification and mixing patterns.

AMIXIS

Some lakes never circulate: ice covered and protected against win shear. Usually above 80^o in North. About ten in Greenland. Anduissaq Lake has ice 1.8 to 4 m thick over water 187 m deep. Temps are 0.1 at top to 0.7 on bottom. Several Antarctic lakes are perenially frozen..

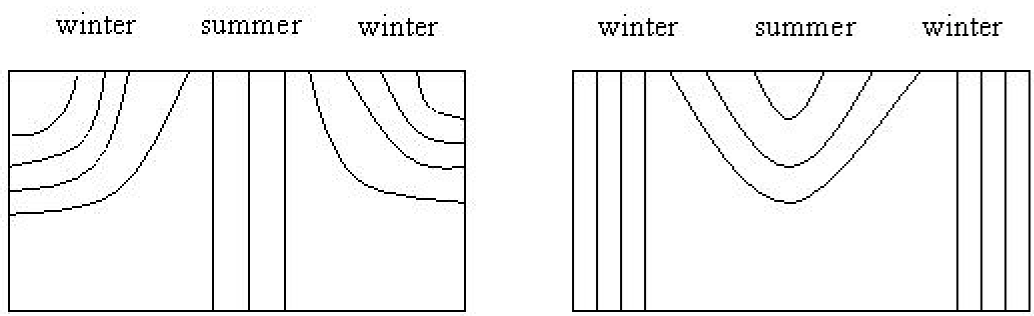
Some of these lakes at high altitudes - Andes Mts.

HOLOMIXIS Lake mixes completely by wind driven circulation.

Oligomictic: typically in warm climates that have relatively warm water at all depths. Very stably stratified due to warming of surface creating large density differences between strata. Occasional cooling of surface allow occasional mixing. Ex: Lake in Cameroon that exploded with CO_2. Lake Tahoe due to great depth and volume, 501 m, 156 m^3, may not mix every autumn. Mixed once 1964-1968 and briefly in 1973.

. <u>Monomictic</u> -- One regular period of mixing sometime within the year.

Monomictic lakes



Cold monomictic

Inversely stratified most of year
Do not stratify in summer
Usually high latitude or altitude
Oneida Lake

Warm monomictic

Stratified during summer
Mix all winter – no ice
Often in S. U.S. or in Pacific Northwest
Cayuga and Seneca Lakes

1. cold monomictic – are inversely stratified through most of the year and do not stratify in summer. Frozen over during winter and shielded from wind. Usually 0^{o}C just below ice to 4^{o} at depth. During summer they can be almost isothermal, mixing with every wind, but never strongly stratified. EX: Oneida Lake, NY - poorly stratified during ice free season, sometimes isothermal at 24^{o}C.

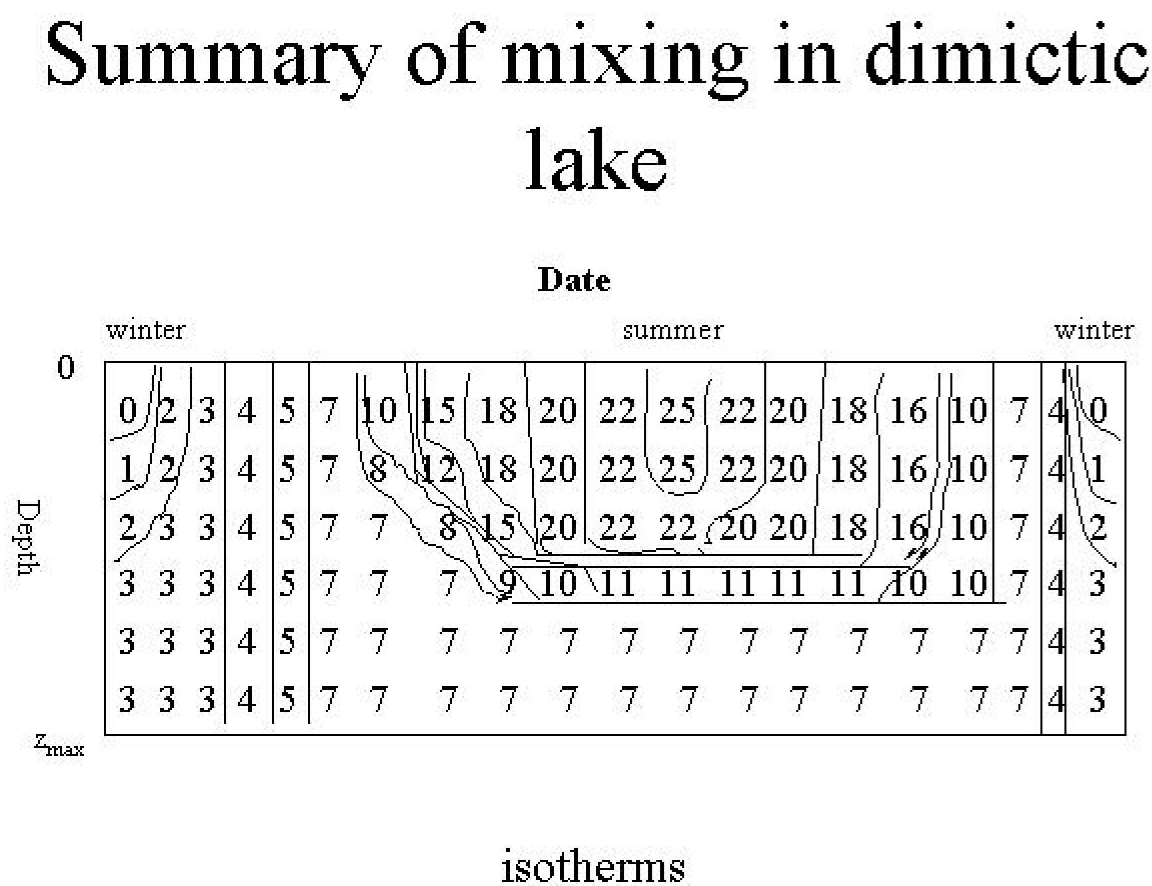
Some shallow lakes in windy areas will stratify somewhat but get continually mixed by wind: Winnibigoshish in Minnesota.

Some sub-Arctic lakes that never get above $4\text{-}8^{o}$, and therefore can stratify only weakly due to small density differences.

2. warm monomictic -- stratified most of the year but mixes all winter because it doesn't become ice-covered Old classification. Subtropical lakes that circulate during winter months but are stratified other times. Problem: many of these lakes are not subtropical. English lake district and NY Finger Lakes. Probably better to describe warm monomictic as lakes that lack ice cover and mix in winter. Get direct stratification in spring-summer that lasts until winter. EX: Elephant Butte Reservoir, NM on the Rio Grande, circulates at about 8^{o} C in winter.

Tropical lakes

Dimictic: These are the type we talked about earlier, with vernal and autumnal overturns each year. These are typically presented as Typical temperate lakes. There are temperate areas that do not have dimixis - Australia has none.



In some temperate zones, there are shallow lakes or lakes exposed to very strong winds that stratify during warm months and are mixed throughout the rest of the year - they are **cold monomictic**.

Some factors to add to previous discussion:

1. During the fall overturn, cooling of the entire water mass occurs until the water column is a uniform 4^o or so. On some cold, calm night, the surface loses enough heat to the atmosphere to cool the surface to the freezing pt. Ice then starts the winter stagnation period.

During the fall circulation period, loss of heat at the air water interface creates dense water that sinks downward, aiding the wind in mixing.

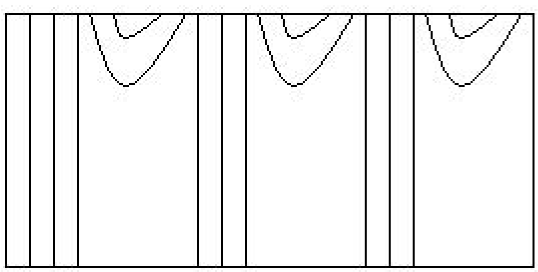
2. During spring overturn, wind can prolong mixing period and the entire lake becomes warmer. Or several calm days during overturn can quickly create large density differences before the bottom waters have had a chance to warm, resulting in a hypolimnion near 4^{o} C. Hypolimnion temp can tell a lot about the past vernal weather conditions.

Ex. Tom Wallace Lake Kentucky: 8.7m deep, max length 0.33 km, protected by steep wooded hills, doesn't freeze during mild winters. June Hypolimnion no more than $7\text{-}8^{o}$. Protected from wind, stratifies quickly, isolating hypolimnion. I expect some light penetration to bottom might gradually warm hypo.

Contrast Lake Itaska, Minn; 9^{o} further north, expect cold hypolimnion? Max depth 14 m, 4 km long and exposed to wind. June hypolimnion $11\text{-}15^{o}$.

POLYMICTIC: mix many times a year; often influenced by diel cycles

Polymictic lakes



Cold – are 4 degrees top to bottom; stratify briefly in summer

Warm – stratification breaks down often

Can mix daily or with storms

Oligomictic – mix every few years – unusual, irregular, short circulation

Lake Ohrid, Yugoslavia; some deep tropical lakes

Amictic – always frozen

1. cold polymictic -- are 4 degrees C top to bottom; stratify occasionally for a brief periods
2. warm polymictic -- stratify and that stratification breaks down many times a year

Many mixing periods or continually mixed. Often affected more by diel temp changes than by seasonal. Ex. Some Andean lakes at fairly high altitudes have their surfaces gain heat during the day and stratify diurnally. Cool nights cool the surface to cause downwelling convection currents and destroy stability.

Arizona desert ponds cool by evaporation during the day and night. Heat of vaporization of water is 580 cal/g. Cooling a 1mm thick layer of water beneath 1 cm^2 of pond surface would cause a loss of heat of 58 cal. Solar radiation supplied heat during the day exceeds the heat loss of evap. Pond stratifies. Evap cooling at night destroys stratification.

MEROMIXIS

Lakes circulate at times, but incompletely. Contrast to **Holomixis**. Usually dense stratum of bottom water remains stagnant. (The term describing a density gradient is **PYCNOCLINE**.)

Big Soda Lake, Nevada is **Meromictic.**

BIOGENIC MEROMICTIC: solutes from bacterial decomposition of organics and photosynthetic precip of carbonates. **Biology determines physical system.** There are lakes in Austria where anthropogenic processes induced **biogenic meromixis**. Cutting of forests released nutrients, clay. Clay increased bottom water density; nutrients caused **Eutrophication** - algae produced bicarbonate and biomass and settle to bottom.

ECTOGENIC MEROMIXIS: Density gradient caused by delivery of water from outside sources. Either dilute water that stratifies surface or saline water that sinks to the bottom of a lake.
Salt to deice roads have been known to cause this. Zuni Salt Maar in New Mexico is fed very saline water derived from springs within the Maar (a cinder cone)

CRENOGENIC MEROMIXIS: Subsurface flows of saline water into a basin. Sometimes classification is not clear cut between Ectogenic and Crenogenic.

Several unusual conditions not classified above.
EX: The thermal bar: Large cold lakes, shallow water near shore warms and deeper water continues to circulate isothermally as it had through the winter. The two regions are separated by a narrow band of downwelling water - the most dense in the lake. There is a warm surface layer, a 4^o isothermal layer called the **thermal bar**, and a cooler, less dense bottom layer. Often nutrients from runoff are trapped in the **thermal bar** and spring blooms of phytoplankton occur there. May happen in Lake Tahoe.

Lake Type Summary

1. DIMICTIC LAKES (temperate lakes) have two periods of mixing, stratification, and inverse stratification. With winter ice cover.

2. WARM MONOMICTIC LAKES (subtropical lakes) lower latitudes in which the temperature never drops to 4 C at any depth. No ice cover. Never gets cold enough for inverse stratification. Stratified in summer, mix for the rest of the year.

3. **COLD MONOMICTIC LAKES** Ice-covered polar lakes in which waters at any depth never get warmer than 4 C. Never get warm enough for summer stratification but loose ice cover in summer. They are inversely stratified in winter and period of mixing in summer, but with water at or lower than 4 C. These get warm enough to mix, but not stratify, in the summer.

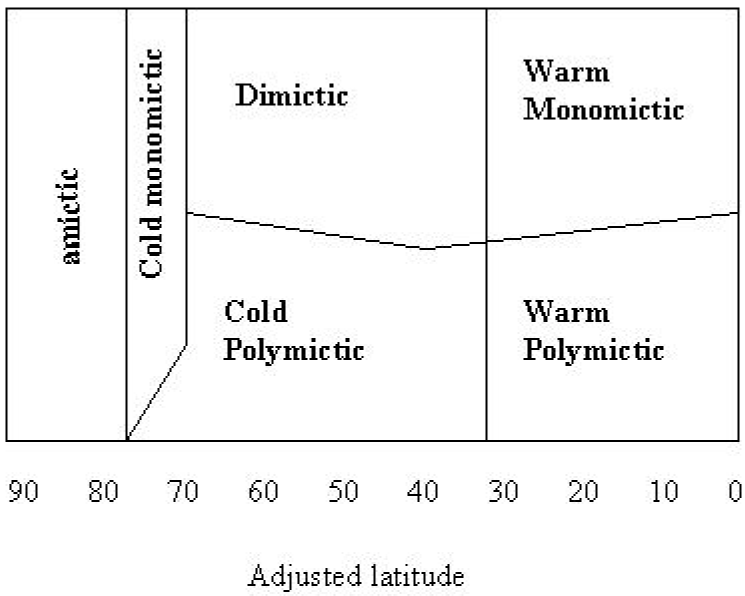
4. **AMICTIC LAKES** ("cold amictic") insulated and isolated by a permanent layer of ice. Characteristic of the Antarctic and high alpine regions. They don't get warm enough to mix and are further isolated from the wind. Lake Vanda is amictic. They are always inversely stratified. There may be an ice-free moat of liquid water around the shore in summer.

5. **OLIGOMICTIC LAKES** (warm amictic or tropical lakes) Lakes which for various reasons do not mix annually but rather only rarely (oligomictic) or never (amictic). These lakes are more or less permanently stratified but may mix under rare conditions. These are usually deep, low elevation, warm tropical lakes with water temperature much higher than 4 C. The epilimnion does not cool enough to mix with the hypolimnion. Mixing occurs rarely and at irregular periods.

6. **WARM POLYMICTIC LAKES** (unstable stratification). Exhibit frequent mixing. These are shallow lakes in which the wind may destroy summer stratification only to have it reform later when the wind dies. This may happen several times during the summer.

7. **COLD POLYMICTIC LAKES** mixing and stratification alternate continuously on a 24 hour cycle. Characteristic of high elevation tropical lakes where nighttime temperatures are low (elevation) but there is intense insolation during the day (low latitude). The lake is uniformly 4 C at night but surface waters warm and stratify weakly during the day. At night the temperature drops back to 4 C.

Distribution of mixing types



After Lewis (1983)

from Hutchinson and Loffler, 1956

STABILITY

Stability **S** is the amount of work required to mix an entire lake to uniform density throughout the vertical without adding or subtracting heat. If the density in the lake is uniform, 0 work is required.

Some quantitative aspects of stratification.

The dynamics of heat flux and temperature stratification are intricate and the subject extended treatment by Imberger and others.

Nevertheless, some aspects of temperature stratification may be given quantitative treatment.

1. Stability of a parcel of water.

<u>Richardson's stability</u> – determines whether or not two fluids will mix

a. $Ri = (g \times d\rho/dz) / \rho_{average} (du/dz)^2$ Where

g = acceleration of gravity
ρ= density
u = horizontal velocity

b. Ri > 0.25 then no mixing -- numerator dominates

c. Ri < 0.25 then will mix -- denominator dominates (energy of mixing)

When the Richardson number is less than 0.25, internal waves spontaneously appear, and break. Mixing ensues until gradients are reduced and the system stabilizes.

2. Simple stratification and stability pattern.

The stratification of thermocline is a very effective barrier to vertical transport of heat and dissolved ions and gases. "RTR", or *relative thermal resistance* is defined by Wetzel: ratio of the density difference between the top and bottom of a 0.5 meter segment divided by the density difference between water of temperature 5 degrees and water of temperature of 4 degrees, i.e. the density difference between water of 5 degrees and water of 4 degrees is one unit of RTR.

$$RTR = \frac{\text{density of top of } \tfrac{1}{2} \text{ meter layer - density of bottom of } \tfrac{1}{2} \text{ meter layer}}{\text{density of } 4^{o} \text{ water} - \text{density of } 5^{o} \text{ water}}$$

3. Stability of a lake; S.

S = amount of work required to mix the heat in the lake uniformly over depth. Calculation of stability of a lake is based on a comparison between the vertical location of the center of mass of the stratified lake compared to the vertical location of the center of mass of the same lake after complete mixing (and with the same total heat content).

In the lake is a point representing the center of gravity $\mathbf{z_g}$: above this point the water mass equals the water mass below. Vertical density contrasts due to temp, solute and suspended particle lower the center of gravity from when density was homogeneous. **S** increases as the center of gravity is lowered.

S = the amount of work necessary to lift the entire lake from the actual $\mathbf{z_g}$ to the level of $\mathbf{z_g}$ that would exist at uniform density.

The work, force times the distance through which mass is moved, is in ergs (the absolute unit for work in the cms system) and is related to lake surface area (cm^2). Stability should be expressed as dyne-cm per cm^2. Customarily, acceleration is omitted from the dyne (a force that gives a 1 g mass an acceleration of 1 cm/sec/sec) and stability is represented as g-cm/cm^2 . Result: a relative indicator of stability rather than a real measure of work. Limnological engineers do calculate a real work to estimate the pumps required to mix an aeration pond or small reservoir.

Idso (1973) proposed the following formula for stability:

$$S = \frac{1}{A_0} \int_{Z_0}^{Z_m} A_z (z_{avg} - z_g)(\rho_z - \rho_{avg}) dz$$

A_z = area at depth z

A_0 = area of surface
ρ_{avg}= density at complete mixing (unstratified lake) which can be approximated as the mean density that would result from mixing to uniformity.
ρ_z= density at depth z, actually an average density for a layer or stratum.
z_{avg}= depth (average for mixed water column)
z_0= zero or surface depth
z_m= max depth in cm
z_g= depth of center of gravity of unstratified lake.

Calculate the average density or density after complete mixing: multiply density in each stratum by its volume and by summing over all strata and dividing by total volume:

$$\rho_{avg} = \frac{1}{V} \sum_{z_0}^{z_m} \rho_z A_z \Delta z$$

If you set up a table of density with depth, calculate as above the mean density from stirring the lake, can then interpolate to get the depth of the center of gravity.

I z, cm	II T_z , °C	III A_z 10^8 cm^2	IV ρ_z , g cm^{-3}	V A_z/A_0	VI $A_z\Delta z$ 10^8 cm^3	VII $\rho_z A_z \Delta z$ 10^8 g	VIII ρ_z - ρ_{avg} g/cm^3	IX z-z_g cm	X VxVIIIxIX g cm^{-2}
50	27.7	2.15	.99634	.9134	215	214.21	-0.00165	-196.5	.29789
150	26.7	1.80	.99662	.7692	180	179.39	-0.00137	-96.5	.10169
250	20.9	1.50	.99804	.6410	150	149.71	0.00005	3.5	.00112
350	14.0	1.235	.99927	.5278	123.5	123.41	0.00128	103.5	.06992
450	10.3	.980	.99970	.4188	98	97.97	0.00171	203.5	.14574
550	8.1	.725	.99987	.3098	72.5	72.49	0.00188	303.5	.17676
650	7.3	.470	.99992	.2009	47	47	0.00193	403.5	.15645
750	7.0	.220	.99993	.0940	22	22	0.00194	503.5	.09182
850	6.9	.010	.99993	.0043	1	1	0.00194	603.5	.00503
Totals					909	907.18			1.04642

Tom Wallace Lake, Kentucky, June 26

Practical method of calculation:

1. Plot graph of g/cm^2 against depth and use grid or planimeter or digitizer to calculate area under curve - that gives you **S** in g-cm/cm^2 .

2. Calculate ρ_m as average ρ:

$$\rho_{avg} = \frac{1}{V} \sum_{z_0}^{z_m} \rho_z A_z \Delta z$$

= 907.18/909 = 0.99799 g/cm^3

Thus, the actual center of gravity is not needed and the mean density is established by multiplying the density in each stratum by its volume and summing and dividing by total volume.
The depth at which the mean density is present during the existing stratification is found by examining the data in column IV and interpolating.

The interpolation gives z_{avg} from above table as 246.5 cm.
The final calculation for **S** is:

$$S = \sum_{z_0}^{z_m} (z_{avg} - z_g)(p_z - p_{avg}) \frac{A_z}{A_0} \Delta z$$

= 1.04642 g/cm^2 x 100 cm = 104.6 g-cm/cm^2

Lake number, L_N

Robertson and Imberger describe the derivation of Lake Number and its application to several lakes and reservoirs in North America and Australia. Lake Number serves as a quantitative parameter that predicts lake mixing by considering both temperature stratification and wind mixing in a single index. The index has the advantages of (1) being relatively simple and (2) serving as a predictor of stability or mixing.

Lake Number Reference: Robertson, D.M. & J. Imberger, 1994 "Lake Number, A Quantitiative Indicator of Mixing used to Estimate Changes in Dissolved Oxygen." Int. Rev. ges. Hydrobiol. **79**:159-176

"Lake number is a quantitative index of the *dynamic* [emphasis added] stability of the water column; it is defined as the ratio of the moments about the water body's center of volume, of the stabilizing force of gravity (resulting from density stratification) to the destabilizing forces from wind, cooling, inflow, outflow, and artificial destratification devices." ..."If we can assume that the wind is the dominating force for mixing...L_N can be defined by:..."

$L_N = [g \times S_t \times (1 - Z_t/Z_m)]/[p_m \times v_*^2 \times A_m^{1.5} \times (1 - Z_g/Z_m)]$ where: g = accelleration of gravity (980 cm/sec^2)

z_t = thermocline height above the bottom

p_m = water density at the surface (g/cm3)

u_* = water friction velocity (cm/sec) due to wind stress, approximated by:

$$u_*^2 = p_a/p_m \times C_D \times U_{10}^2$$

where: U_{10} = wind velocity 10 M above the water surface (cm/sec)

C_D = drag coefficient = 1.3×10^{-3} (dimensionless)

p_a/p_m = ratio of air/water density = 1.2×10^{-3} (dimensionless)

"A L_N = 1 indicates that the wind is just sufficient to force the seasonal thermocline to be deflected to the surface at the windward end of the lake. For L_N >>1, stratification is strong and dominates the forces introduced by surface wind energy. Under these circumstances, the isopycnals are expected to be primarily horizontal. Little seiching of the seasonal thermocline and little turbulent mixing in the hypolimnion are expected. Above the value of 1.0, increases in L_N represent very little difference in terms of mixing below the seasonal thermocline. For L_N <<1, stratification is weak with respect to wind stress. Under these circumstances, the seasonal thermocline is expected to experience strong seiching and the hypolimnion is expected to experience turbulent mixing due to internal shear ..."

"The period over which the wind should be averaged depends on the length of time required to tilt the thermocline to the surface, which is dependent on the strength of stratification." [Usually 2 or 3 days for lakes in study when lakes were weakly stratified, i.e. $L_N \sim 1$.]

"Deep mixing events can often be detected by a rapid increase in deep DO concentrations... However, even during this weakly stratified period [winter], L_N values are often greater than 1.0 which suggests there are discrete episodes of deep mixing. During this period, which usually has been referred to as holomixis, WAR [one of their study reservoirs] is actually acting as a polymictic system....."

Comment: Use of LN gives an indication of actual mixing events rather than just the time period during which stratification is weak.

Conclusion: "L_N values are superior to S_t values as an indicator of the extent of deep mixing. S_t values represent the strength of stratification and not the extent of mixing; whereas L_N values less than approximately 1.0 directly indicate deep mixing..." (p166)

Comment: In effect, L_N provides a dynamic indicator of mixing under existing wind and stratification conditions, rather than the static concept provided by S_t alone.

Note: Authors apply L_N to a number of well studied North American and Australian lakes and reservoirs. Their results demonstrate the effectiveness of using L_N as an indicator of deep mixing. Their time/depth diagrams of oxygen vs. L_N are revealing. They go on to develop models of oxygen concentration in their lakes based on the prediction of mixing from application of L_N.

Applications

1. Reference: Seasonal Mixing and Catastrophic Degassing in Tropical Lakes, Cameroon, West Africa. by George W. Kling, Science: 237:1022-1024. 1987.

"On 21 August 1986 a massive release of CO_2 from Lake Nyos claimed 1700 lives in northwest Cameroon."

Kling comments on various hypotheses put forward to explain event (and other similar catastrophic lake degassing events in Cameroon crater lakes). Kling's analysis: sudden degassing was probably the result of turnover in an oligomictic lake. CO_2 and other gases accumulate over many years in the hypolimnion. Turnover occurs irregularly every few years or decades when unusually cool weather persists for enough time to cool epilimnion and produce turnover. (Other influential factors, advection of cool water from the watershed to the hypolimnion, cooling the hypolimnion.) Kling's analysis predicts catastrophic degassing expected August or September in this region, when unusually cool weather occurs. Timing would be different in other tropical areas, but similar degassing events could be expected in other oligomictic lakes with sufficient productivity to produce a significant accumulation of hypolimnetic gasses, kept in solution by hydrostatic pressure. Vertical circulation will bring "supersaturated" gases to the surface. Indeed the bubbles could accelerate the circulation.

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