
ICE COVERED LAKES

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Ice formation

Lakes at high latitudes or high altitudes are ice covered part of the year; typically from November to April and in the very north sometimes from October to early June. Arctic lakes may be ice covered throughout the year. When there is a regular ice cover for several months, the ice thickness reaches more than ½ meter. At mid latitudes occasional ice cover may appear for short periods several times during a winter. Where there is a stable ice cover, ice roads are prepared. Fishing is done also at commercial scale. Ice covered lakes are used for recreation.

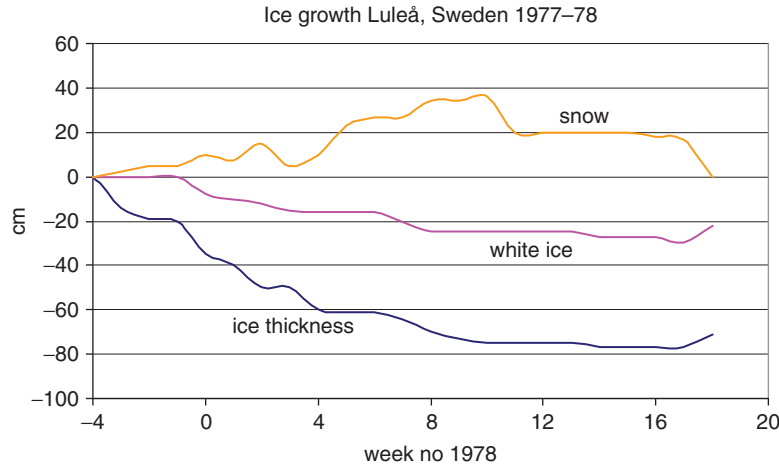
Ice on a small lake is formed rather quickly after the surface water is cooled down to the freezing point – most often after a cold night with no wind. It takes much longer time for a large lake to freeze-over than a small lake, since relatively warm water is brought to the surface during the more intense mixing in a large lake. Ice on lakes grows in a static way; there is no horizontal transfer of ice but the ice grows in the vertical. Ice is produced as black ice, when heat is lost to the cold atmosphere from the water underneath the ice, or as snow ice, when the ice is suppressed under the water surface by heavy snow and water freezes in the slush layer in the snow on top of the ice. Once ice is formed it grows rather quickly in the first weeks until the ice cover and snow on the ice insulate the water from the atmosphere; the rate of ice growth is slowed down. The heat lost from the water to the atmosphere must be taken from the latent heat released when ice is formed, since the water just below the ice is at the freezing point.

Ice formed from the underside of the ice sheet has crystals with columnar structure; it is possible to see through the ice. Such ice is called black ice. Ice can also be formed in a slush layer between the snow and the top of the ice. When the weight of the snow is more than the lifting force from the ice, the ice cover is forced under the water surface and water enters into the snow which becomes saturated with water. When this slush layer freezes, snow ice or white ice is formed. The crystals in this kind of ice are randomly distributed. This ice is not transparent but looks somewhat like milk. An example of ice growth is shown in Figure 1 from a bay in the Luleå archipelago (almost fresh water).

The ice on a lake has ecological consequences. Since there is no exchange with the atmosphere, the oxygen content of the water decreases and the bottom layers may be completely depleted of oxygen. Man's impact on lake ice is mainly from release of oxygen consumption substances, which increases the rate at which the lake water is depleted in oxygen. All releases from industries and waste water treatment plants and also the increased winter flows in regulated rivers have local effects on the ice cover.

Thermal regime

The thermal regime of ice covered lakes considers the heat fluxes to and from a water body without direct contact with the atmosphere, the temperature distribution over the depth, and how it changes during the ice covered period. In the autumn after the surface water is cooled to 4°C and the water has turned over, the warmest water in a lake is that of the highest density. The surface water is colder than the bottom water. If there is a very cold period shortly after the turnover, a wind-sheltered lake may freeze-over when the water not far from the surface and downward is still 4°C. In another year the turnover may be followed by an extended windy period with air



Ice Covered Lakes, Figure 1 Observed ice growth in the inner archipelago in Luleå, Sweden. Snow depth on the ice is shown and separately the snow ice growth. The dotted line is the computed ice thickness using a degree-day approach. Measurements by the author.

temperatures fluctuating around 0°C resulting in a reduction of the lake water temperature down to considerable depths. The initial temperature profile after freeze-over is quite different for the two situations.

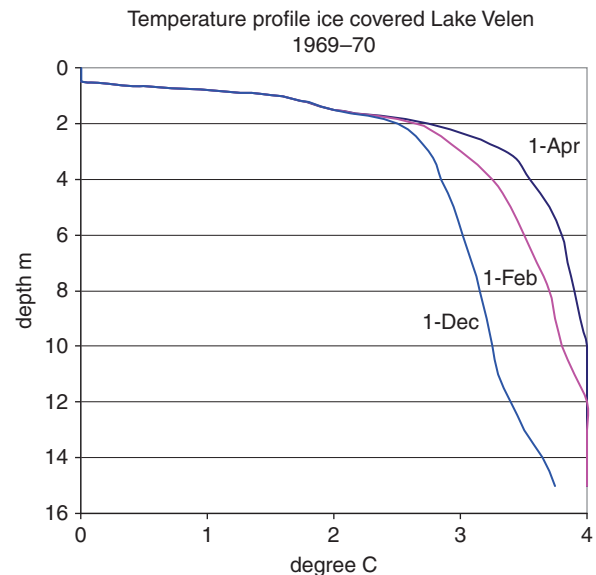
Once a lake has a stable ice cover the lake water is more or less insulated from the atmosphere. The heat lost to the cold atmosphere is taken from the latent heat released from the ice growth. There is a small sensible heat flux from the water to the underside of the ice. The major heat flux in an ice covered lake is that from the sediments to the lake water. Heat stored in the sediment from summer to winter is released. The lake water temperature increases in the course of the winter, see Figure 2 from Lake Velen in Sweden. Lakes in cold long winter climate tend to be warmer than lakes in milder climate with less stable winters. In the milder climate the lakes freeze-over later, when they have cooled down throughout the vertical, and also in the milder climate the lake ice may break up several times during winter allowing wind mixing and heat losses directly to the atmosphere. The bottom temperature is often 4°C already at the time of freeze-up; if not, because of the contribution of heat from the sediments this temperature is approached in the course of the winter. The bottom temperature may even be slightly higher than 4°C , due to diffusion of solutes from muddy sediments.

The change of the heat content, dH/dt in an ice covered lake is

$$\begin{aligned} \frac{dH}{dt} &= \rho c_p \int A(z) \frac{\delta T}{\delta t} dz \\ &= (H_{\text{sed}} + R_{\text{netsol}} - H_{\text{ice}})A_{\text{surface}} + H_Q \end{aligned}$$

where T is temperature, z vertical distance, t time, c_p specific heat capacity, and ρ is density of water and $A(z)$ is area at depth z .

The sediment heat flux per unit area, H_{sed} , is the most important heat flux. The sediment heat flux at shallow



Ice Covered Lakes, Figure 2 Temperature in ice covered Lake Velen, mean depth 6.5 m, max depth 17 m, lake area 2.8 km^2 .

water may be in the range $4\text{--}10 \text{ W/m}^2$ in early winter and reduce to $1\text{--}3 \text{ W/m}^2$ in late winter. At the deep part of a lake it is smaller, $2\text{--}3 \text{ W/m}^2$ in early winter and less than 1 W/m^2 prior to breakup.

The heat advection, H_Q , with the through-flow is very small in most lakes, since the river through-flow per unit lake area is small and the temperature of the inflowing river water is very close to 0°C . In narrow fjord lakes the flow per unit area may be substantial. However, in such lakes a thermocline develops so that the river runs through the lake within a top layer of 0°C temperature. The heat loss, apart from that of the heat loss with outflowing water,

is the sensible heat flux from the water to the underside of the ice, H_{ice} . A pronounced temperature gradient develops close to the underside of the ice. A viscous sublayer develops. The heat flux is $1\text{--}2\text{ W/m}^2$ in most lakes but can be rather much higher in late spring, when solar radiation penetrates the ice. The intensity of the solar radiation, which penetrates the ice is denoted $R_{net\text{sol}}$.

In spring when the snow on the ice melts, solar radiation can penetrate the ice and heat the water below. Although only a small fraction of the solar radiation reaches the lake water, the flux is higher than the other fluxes in an ice covered lake. Depending on the ice character and the ice thickness and time of year the solar radiation penetrating the ice is $10\text{--}40\text{ W/m}^2$, partly compensated for by increased heat transfer from the water to the ice.

Circulation and mixing in ice covered lakes

Knowledge about circulation processes in lakes is essential when planning for the use of a lake for water supply or receiving waters. The conditions controlling the dynamics of ice covered lakes are different from those of an ice-free lake. The ice cover prevents direct generation of wind mixing. The water movements are much determined by thermal processes and by the vertical movement of the ice cover. There are also oscillations caused by the setup of the ice surface by the wind. River inflows induce some circulation close to the inlet. While the currents in ice-free lakes are typically 2% of the wind speed, that is, 20 cm/s when the wind is 10 m/s, the currents in an ice covered lake are very much lower. The oscillation movements may be 1 cm/s back and forth. The currents caused by thermal processes are of the order mm/s or even less. Still these movements result in vertical mixing and changed temperature conditions in the course of the winter.

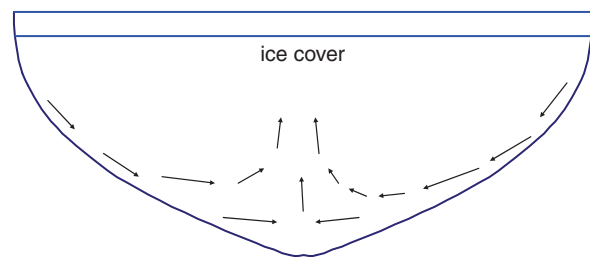
The thermal conditions and the heat fluxes are responsible for convection and mixing of different character. Heat accumulated in the sediments during summer is released to the water in ice covered lakes. When the water gains heat from the sediment it becomes warmer and denser and the water slides downward generating a large convection cell. A different form of more local convection is generated for a short period in the late spring, when solar radiation can penetrate snow-free ice. Density instabilities arise and a top mixing layer develops.

Water which gains heat from the sediment near the shores moves slowly along the bottom toward the deeper parts of the lake, generating large convective circulation cells as shown in Figure 3. The velocities involved seem to be well below 1 mm/s. It is possible to determine a vertical mixing coefficient from the change over time of the vertical temperature profile. The thermal vertical diffusivity is well below $0.1\text{ cm}^2/\text{s}$. The bottom water is mixed due to the convection induced by the heat flow from the sediments. However, once the water has reached the temperature of maximum density, 4°C , the water does not take part in the mixing process; the convection takes

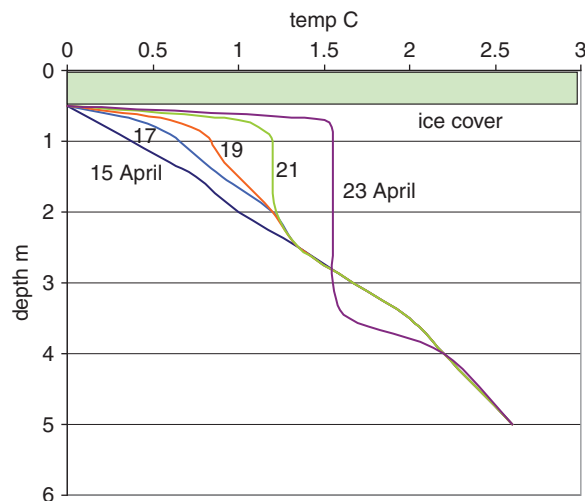
place above this 4°C water. The bottom water in subbasins of a lake may be isolated from the water in the main basin and remain stagnant for many months.

When the solar radiation is able to penetrate through the ice, the water below the ice gains heat and becomes denser than the water further down. Convective mixing is initiated as the warm water sinks. A mixed layer may develop down to considerable depths depending on how far the shortwave radiation reaches, thus depending on the extinction coefficient of the lake water and how much solar radiation penetrates the ice. The mixed layer deepens rather fast, maybe 0.5 m/day . An example of deepening of the mixed layer is shown in Figure 4.

When a wind acts on the ice of a lake, the ice cover is tilted and oscillates. The water particles underneath are forced to move back and forth over short distances, in the order of meters. The maximum velocities in lakes $1\text{--}10\text{ km}^2$ seems to be $1\text{--}3\text{ cm/s}$. The net movement is close to nil, but mixing occurs and particles are dispersed. Some kind of oscillatory currents are always present in ice covered lakes and they significantly contribute to the



Ice Covered Lakes, Figure 3 The principle of large-scale convective circulation generated by heat flux from sediment to water.



Ice Covered Lakes, Figure 4 Convective mixing in Lake Vendyurskoe due to penetration of solar radiation through the ice. Ice thickness 0.5 m.

horizontal mixing. Dye experiments in Swedish lakes, where the oscillation period is about 20 min, have shown that the horizontal dispersion coefficient is in the range 10–200 cm²/s.

A river which runs through a lake generates currents, but after initial mixing near the inlet the river water can be traced only if the river is large. In ice covered lakes, thinner ice on the right-hand side indicating upwelling of warm bottom water with secondary currents induced as an effect of the Earth's rotation has been observed, but most studies show that the current is rather uniformly directed in the upper part of a cross section. When the river flow is large and the lake elongated like a fjord lake, a cold top layer, where the flow takes place, develops over a pronounced thermocline separating the cold layer from a warmer bottom layer.

Summary

Although a lake is ice covered there is mixing and slow currents below the ice. Currents are generated by river through-flow, by oscillation of the ice cover, and by heat released from the sediments. The net currents are of the order mm/s, but still important for the vertical mixing and the development of the temperature profile. The knowledge of the thermal conditions in lakes is essential when planning for water intakes, so that desirable water is provided, or planning for discharge of effluents, so that recirculation is avoided. Withdrawal and release of water may affect the thermal conditions and generate mixing. Regulation of rivers causing winter flows to be higher than the natural ones may influence the temperature in an ice covered lake.

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Cross-references

Arctic Lakes
Circulation Processes in Lakes
Ice Formation on Lakes and Ice Growth
Lake Ice
Mixing in Lakes
Surface Seiches
Thermal Regime of Lakes

ICE FORMATION ON LAKES AND ICE GROWTH

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Description

Ice forms when the surface water temperature drops to the freezing point. In calm water, the ice grows fast from the shore outward. A small lake becomes ice covered overnight. As long as the ice is thin, it may be broken by strong winds. Lake ice grows in a *static way*, which means that the ice production is only within a vertical and a consequence of vertical heat losses to the atmosphere. The ice is not progressing in any horizontal direction due to currents or floating ice.

When there is no or little snow on the ice, the ice grows from the bottom of the ice cover. *Black ice* or columnar ice is produced. The ice is transparent with the molecules oriented vertically. Heat lost through conduction through

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