SEASONAL LAKE ICE

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Contents

Summary

In cold regions, lakes are covered by ice for several months of the year. Seasonally freezing lakes occur in a large zone from latitudes 40–45° to the high-polar regions, with ice thicknesses reaching ½ – 2 m. Perennially ice-covered lakes are rare, occurring mainly in northern North America and in the dry valleys of Antarctica. When present, lake ice forms a stable lid and grows as congelation ice and snow-ice. Frazil ice formation is very rare, and in freshwater lakes the concentration of impurities is very low. At the other extreme, saline lakes form ice similar to sea ice, and in very large lakes ice drift is important. Research of lake ice has largely evolved from practical needs. Safety questions related to traveling on ice have been the key issue. The bearing capacity depends both on the thickness and strength of the ice, and ice thickness models have been widely used. The ice cover stabilizes the temperature structure of lakes in winter. In spring, solar radiation melts ice across its thickness, and any impurities contained in the ice are released into the water column. Ice phenology data have been collected due to the general interest in this natural phenomenon with its variations and due to the importance of the ice season to local communities. For lake ecology, solid ice cover cuts off the renewal of oxygen, and when covered by snow, light penetration is very limited. Winter fish kills may take place when the ice season is long. The influence of climate changes on lake ice duration is of major interest to understand the impact to practical winter conditions and ecology. Future research efforts are needed in the physics and modeling of ice melting, mechanical breakage of ice, and the full two-dimensional ice–water interaction.

1. Introduction

Most lakes contain fresh water with their sizes ranging from small ponds to large intra-continental basins with areas of more than 10^4 km^2. In the boreal zone, tundra, and high mountain regions, lakes freeze over in winter. The ice season may last more than half a year, and the thickness of the ice can reach over one meter. In high polar zones and at very high altitudes, there are perennially ice-covered lakes, with ice cover several meters thick. Frozen lakes have belonged to people’s normal life in the cold regions (Figure 1). Solid ice cover has been an excellent base for traffic across lakes and to transport cargo, provided the ice is thick enough. Until about mid-20th century, when refrigerators were not common, the cold content of lake ice sheets was utilized. Ice blocks were cut in winter, and used as a cooler for food in summer.

Figure 1. Winter in Lahti harbor at Lake Vesijärvi, Finland.

Seasonal lake ice is normally thin compared with the lake depth. Its physical properties show variability due to the high homologous temperature (The ratio of the actual absolute temperature to the melting point.), the large size of individual crystals, and the presence of impurities. Lake ice stratification pattern consists mainly of congelation ice and snow-ice. Snow accumulation on lake ice is a common, essential feature both for strong insulation and for snow-ice production. Even a thin layer of snow significantly lessens both the heat exchange between the lake water body and the atmosphere and the transfer of sunlight into the ice and water. When ice is thick enough, it can stay as a stable cover across the lake. In very large lakes ice breakage and mechanical displacements can take place. The decay of lake ice cover is a thermo-mechanical process, starting from the shoreline. Melting of near-shore ice releases the ice from land boundaries, and the ice cover may shift due to winds and currents.

In a lake, physical phenomena and processes are very different under ice cover compared to open water conditions. The ice cover cuts the transfer of momentum from the wind to the water body, thereby damping turbulence and mixing. The surface water temperature is at the freezing point, and there is very little vertical transfer of heat, apart from geothermal lakes. Release of heat and gas from the lake bottom makes a contribution into the circulation in the water body and the structure of the ice cover. In spring, solar radiation provides a strong downward flux of heat, and the ice melt water with its impurities is released into the water column. Primary production is paused when the level of sunlight becomes too low. Another critical factor is that the ice cover ceases the renewal of dissolved oxygen in the water body. Land-ice interactions due to thermal expansion and onshore ride-up or piling-up are an important environmental and practical issue. Lake ice deforms shore areas, rises loads on structures, and in shallow areas bottom scouring by ice and freezing give rise to bottom erosion.

This chapter on *Seasonal lake ice* presents an up-to-date, as of 2014, on the status of knowledge of the physics of lake ice with applications. The focus is on freshwater lakes. Much of the research history in lake ice is based on earlier results of sea ice and river ice to lake environment. Section 2 presents lakes, their classification, and the geographical zones of ice-covered lakes. Ice formation and the structure and properties of lake ice are treated in Section 3, and Section 4 contains lake ice thermodynamics from the freezing of lakes to ice melting. Section 5 focuses on the water body beneath lake ice cover with stratification and circulation, environmental questions, and ecology. Section 6 gives a closing discussion with the bibliography follows thereafter.

2. Freezing of Lakes

2.1. Lake Types and Characteristics

Lakes are found in all climate zones (Figure 2). The low-latitude edge of potentially freezing freshwater lakes can be taken as the January (Northern Hemisphere) or July (Southern Hemisphere) 0°C isotherm of atmospheric surface temperature. This zone covers most of Eurasia and North America down to around 40°N at sea level. In the central Asian mountains the boundary is more to the south, while in the Western Europe it is more to the north. Apart from Antarctica, in the Southern Hemisphere only some mountain areas contain frozen lakes. In the high Andes ice covered lakes occur even at the Equator. In the cold climate zone there are lakes, which do not freeze. For example, very deep lakes can have thermal time scales longer than the winter and therefore the surface water may stay above the freezing point, geothermal heating can compensate for surface heat losses, and salinity can depress the freezing point. Proglacial lakes are found at the margins of existing glaciers and ice sheets, and glacial melt water forms the main part of their water balance.

The physical classification of the lake basins is based on their size and shape. A simple approach is to consider the magnitudes of the geometric size, both horizontal and vertical. The following system corresponds to the present terminology as well as the common language:

Lateral	Very large 1000 km	Large 100 km	Medium 10 km	Small 1 km	Very small 100 m
Vertical	Very deep 1000 m	Deep 100 m		Shallow 10 m	Very shallow 1 m

Figure 2**.** Examples of freezing lakes in Finland. (a) Boreal zone, Lake Pääjärvi. (b) Tundra, Lake Kilpisjärvi

Deeper lakes can store more heat and their temperature changes more slowly than in shallow lakes. Freshwater lakes are vertically mixed at the temperature of maximum density (4°C), and therefore the depth of a lake is one of the principal characteristics to influencing the timing of the initial ice formation. The horizontal size influences the mixing conditions, since long wind fetches create more turbulence and higher waves. In brackish and saline lakes, the temperature of maximum density depends on the salinity, and mixing by cooling reaches the halocline.

A fundamental property of lake water is its density, denoted by ρ. This is provided by the equation of state, which is written in general form as

$$\rho = \rho(T, S, p) \tag{1}$$

where T is temperature, S is salinity, and p is pressure. Salinity is usually ignored in the case of freshwater bodies ($S < 0.5$ ‰). Results from marine research are conducted to obtain the properties of water in brackish and saline lakes. The influence of pressure on density is significant only in very deep lakes. Salinity and pressure also influence the temperature of maximum density and the freezing point.

In freshwater lakes, free convection or turnover events take place at the temperature of maximum density. The annual frequency of these events is the primary basis of the limnological classification of lakes. Most seasonally frozen lakes have two turnover events – in spring and fall – and thus are dimictic. The summer stratification shows warm upper layer and cold lower layer, and in winter, the stratification is inversed. The time between spring and fall mixing becomes shorter in colder climate. When cold enough, they merge together – the lakes are then referred to as cold monomictic.

2.2 Ice-covered Lakes

With regards to ice, lakes can be divided into three main zones (Figure 3): ice-free, seasonal, and perennial. Between the perennial and seasonal zones there is a quasi-perennial zone, where lakes sometimes have an ice-free summer, and between the seasonal and ice-free zones there is an ephemeral zone where ice occurs during some years but other years are ice-free. In Eastern Europe such lakes are found south of about 55°N, e.g., in Northern Germany and Hungary. Nature as well as people needs to adapt life for both ice winters and ice-free winters in the ephemeral zone. Winter 1963 was the latest very cold winter in Central Europe, when even the deep Lake Constance (Bodensee) bordering Austria, Germany and Switzerland froze over.

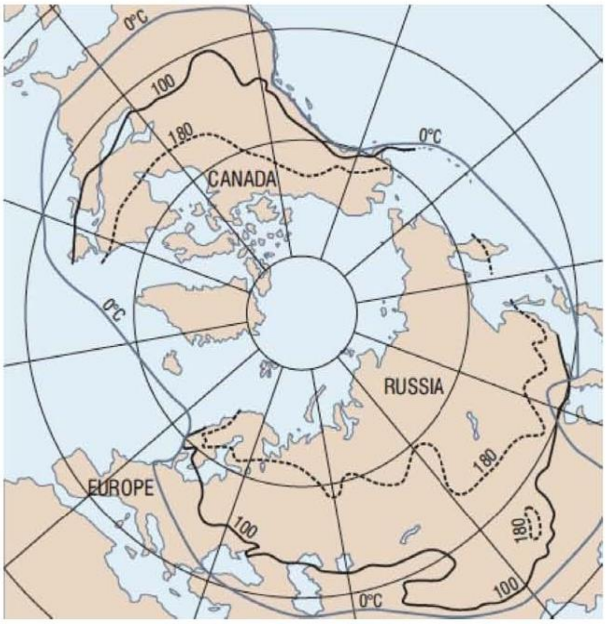

Figure 3**.** The zone of seasonally frozen lakes in the northern hemisphere. The contours 100 and 180 refer to the mean length of the ice season (days). The January 0°C isotherm is also shown.

Apart from the ephemeral zone, the mean annual maximum ice thickness in seasonally frozen lakes ranges within 20–200 cm. No reliable data exist on the maximum possible thickness; based on the sea ice data from the Siberian shelf, it can be estimated that the seasonal ice in Siberian lakes can grow to approximately 2 m during one winter. There are two categories of lakes with perennial ice. In very cold climate it is possible that at least some of the ice grown in winter survives over summer. In Nunavut and Alaska there are such lakes. Another possibility is in very cold climate when the ice cover is snow-free and consists of clear ice, e.g. in the McMurdo Dry Valleys of Antarctica (Priscu and Foreman, 2009). The ice cover in these lakes has been observed to be several meters thick. The second category is glacial-bound lakes at ice sheets and glaciers around the world: epiglacial lakes on the bare ground close to the boundary of the land ice mass, subglacial lakes at the base of ice sheet, and supraglacial lakes on the top of the lakes in blue ice regions.

2.3. Lake Ice Climatology

Lake ice phenology studies the dates of freezing and ice breakup. Timing of such events has been recorded for long periods in a large number of lakes due to both practical reasons and a general interest in such phenomena. Also lake ice phenology is a good climatic indicator due to its sensitivity to climate conditions. The freezing date is defined as the first day in an ice season when the lake area under observation has frozen over. The ice break-up date, in turn, is the last ice day in a given winter season. An example of a phenomenological time series of a boreal lake is given in Figure 4. The variability of the freezing date is 2 ½ months, and for the breakup date it is 1 month. For the last 100 years most lake ice time series show slow trends toward milder winters with high random variability. Toward the climatological ice margin the variability of the freezing and breakup date increases and ice-free winters are becoming more common.

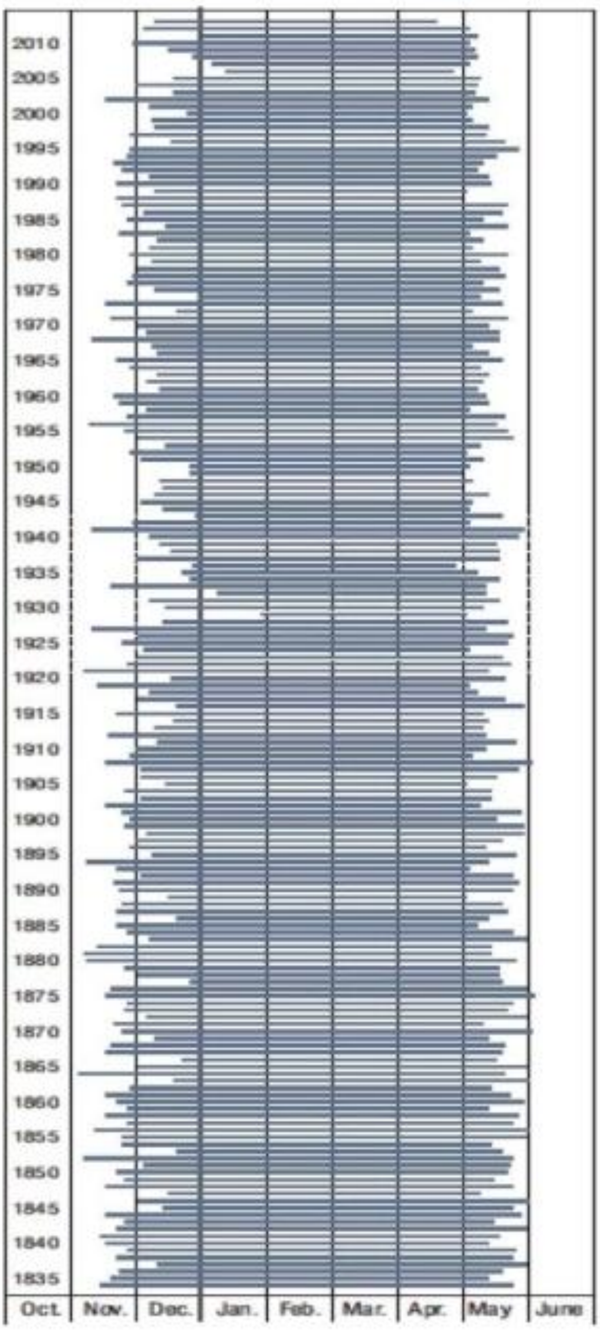

Figure 4**.** Lake ice phenology time series for Lake Kallavesi, Finland (63°N 28°E), 1835–2013. The data are from SYKE (Finnish Environment Institute) database. The thick lines (grey and black) show the annual ice season from freezing to ice breakup.

Ice formation is generally governed by intense radiative and turbulent heat losses from the warmer lake surface to the colder atmosphere. Unstable stratification of the atmospheric surface layer strengthens the turbulent losses. Due to mechanically forced mixing, convection can continue below 4°C. When heat transport from the warm deeper layers to the lake surface is reduced, the surface cooling rate increases, and the surface temperature achieves the freezing point. Hence, the timing of freezing is strongly dependent on synoptic conditions over the lake. Ice growth continues as long as the released latent heat can be conducted through the ice to the atmosphere. The main factors controlling the ice growth are the heat fluxes at the upper and lower boundaries of the ice cover together with the thermal properties of ice and snow. An early appearance of snow cover can play a crucial role in decelerating the ice growth due to the very low heat conductivity of snow. The thicknesses of congelation ice and snow-ice layers are primarily controlled by the air temperature and snowfall time history. Evolution of ice coverage is related to ice thickness in that thicker ice has more lateral strength and a thick enough ice cover typically remains intact until melting sets in.

The severity of winters can be quantified with the maximum annual ice thickness. In large lakes, the period of lateral ice growth may be long, and therefore the quantity of ice coverage, equal to the ice area divided by the total lake area, is another characteristic of the severity of the ice season. For example, in Lake Ladoga the probability of complete ice coverage is about 50%, although ice forms in the lake every year. The surface heat balance during ice melting is fundamentally different from that during ice growth. Then stable stratification of atmospheric surface layer strongly reduces the turbulent heat exchange, and solar radiation is the dominant source of heat for snow and ice melting. Albedo (The ratio of outgoing to incoming solar radiation, $\alpha (0 \leq \alpha \leq 1)$) and transparency of the ice have a strong influence on melting. The key role of solar radiation also explains the fact that ice breakup dates are coherent at spatial scales of hundreds of kilometers. Liquid precipitation is another major factor that accelerates ice melting.

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Biographical Sketch

Matti Leppäranta was born 1950 in Helsinki, Finland. He received MSc degree in mathematics in 1976 and PhD degree in geophysics (sea ice) in 1981 in the University of Helsinki. He has worked as a research physicist in the Finnish Institute of Marine Research in 1975-1991 and as a professor in geophysics in the University of Helsinki since 1992. His science career has been around geophysics of sea ice and lake ice, covering their structure and morphology, remote sensing, thermodynamics, dynamics and environmental and climate questions. He has given sea ice dynamics lectures in several advanced study institutes and published the books *The drift of sea ice* (2005) and *Physical oceanography of the Baltic Sea* (2009, with Kai Myrberg) and *Freezing of lakes and physics of their ice cover* (2014). Matti Leppäranta has acted as a post doc physicist in Cold Regions Research and Engineering Laboratory, Hanover, NH, visiting teacher in Universitetstudiene i Svalbard (UNIS), and visiting scientist in Hokkaido University, Japan, and Dalian University of Technology, China. He is an adjunct professor in University of Sherbrooke, Québec, Canada and Polar Research Institute of China, Shanghai.