Master's thesis

Development of temperature and oxygen gradients during the formation of ice cover in a deep boreal lake

Heather Mariash

University of Jyväskylä
Department of Biological and Environmental Science

International Aquatic Masters Programme

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University of Jyväskylä, Faculty of Science

Department of Biological and Environmental Science
International Aquatic Masters Programme

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Supervisors: Dr. Kalevi Salonen, Professor of Limnology
Reviewers: Dr. Enn Kaup, Senior Researcher, Institute of Geology, Tallinn University of Technology
Dr. Kalevi Salonen, Professor of Limnology

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ABSTRACT

Due to difficult access to large lakes at the time of freezing their hydrodynamic regime is poorly known. In this study, we investigated the dynamics of temperature during the formation of ice cover in 78 m deep Lake Pääjärvi in southern Finland. Temperature loggers and CTD were the main tools applied. In early winter, the cooling rate was highest in shallow areas and in bays where water exchange with the central basin was lowest. At the deepest point of the lake temperatures remained vertically uniform until 3 ^{o}C, after which temperature was inversely distributed and at times also stratified. When open water area decreased, water mixing by wind was dramatically reduced. In accordance with that, we observed an increase in temperature and a decrease in oxygen below the depth of 50 m before the whole lake was ice covered. This means that heat and possible electrolyte flux from the sediment increased the overlaying water density so that it started to flow along the rather steep sediment slopes. Our results help to understand large scale and dynamic translocations of water masses in early winter. This can help interpretation and modeling of oxygen consumption in deep lake basins in winter.

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TIIVISTELMÄ

Järvien ollessa jäätymisen aikaan vaikeasti saavutettavia on ymmärrettävää, ettei jäätymisvaiheen hydrodynamiikasta ole paljoakaan tietoa. Tässä työssä tutkittiin yksityiskohtaisesti jäätymistä edeltävää lämpötilan kehitystä 78 m syvässä Lammin Pääjärvessä. Havainnot tehtiin CTD-luotaimella ja automaattisesti rekisteröivillä lämpötila-antureilla. Veden jäähtyminen oli voimakkainta matalilla alueilla ja lahtien poukamissa, joissa veden vaihtuminen oli vähäisintä. Järven keskellä syvimmän alueen yläpuolella vesi pysyi pystysuunnassa tasalämpöisenä aina 3 ^{o}C saakka. Sen jälkeen lämpötila oli pinnassa aina alhaisempi kuin syvemmällä ja ajoittain vesipatsaassa oli erotettavissa selvä kylmä päällysvesi ja lämmin alusvesi - eli todellinen käänteinen kerrostuneisuus. Taipumus kerrostuneisuuteen liittyi ilmeisesti vapaan vesipinta-alan pienenemiseen järven jäätyessä rannoilta kohti järven keskustaa. Vesipinta-alan tultua riittävän pieneksi sekoittuminen ei enää yltänyt pohjaan saakka, jolloin happipitoisuus alkoi 50 m:n alapuolella laskea jo ennen koko järven jäätymistä. Tämä selittyy pohjavirtauksilla, jotka syntyivät sedimentin lämmittäessä yläpuolellaan olevaa alle neliasteista vettä. Lämmennyt raskaampi vesi valui kohti järven syvännettä ja matkalla sedimentti kulutti osan veden hapesta. Saadut tulokset auttavat ymmärtämään talven aikaisia vesimassojen liikkeitä ja hapen kulumista järven syvimmissä osissa. Tuloksia voidaan hyödyntää myös järven talvisten lämpö- ja happiolojen mallintamisessa.

Contents

1. INTRODUCTION

Winter limnology "broke through the ice" first in the 1940's with Mortimer (1941), who gave insight into water movements under ice through physical and chemical gradients. Then again in the 1960's, people like Likens and Hasler (1962) ventured out onto ice covered lakes to describe lake heat transfer and circulation using updated techniques. Since Liken's work in the 60's, there have been a few works which mention density currents, latent heat transfer and vertical mixing (Likens and Ragotzkie 1965, Welch and Bergmann 1985, Welch *et al.* 1987, Bengtsson 1996, Wetzel 2001, Kalff 2003). Few of these works have studied a large, deep lake, which is the focus of this paper.

There is a general consensus that under ice dynamics are vastly different from the rest of the year simply due to atmospheric isolation, sharp decrease in solar radiation, and little to no wind turbulence (Welch 1985, Wetzel 2001). Largely due to severe and sometimes dangerous conditions, under-ice water dynamics have largely been avoided for study; regardless, the importance of winter limnology cannot be ignored further. Water movements and physio-chemical gradients have great importance to a lake's overall metabolism (Mortimer 1941). Anoxic conditions that arise in late winter are especially biologically significant (O'Sullivan 2005).

In this paper I have broken down the topic into several sections in order to examine key features of physical and chemical conditions under ice. First, and most importantly, the role of temperature and the gradients that occur will be discussed. Second, I will discuss dissolved oxygen, which has been studied intensively. Then the physical aspects of the under ice forces, such as density differences and stability pressures, will be addressed. In the end, I aim to discuss how these aspects interplay in the formation of early winter gradients in a deep temperate lake during the formation of ice cover.

1.1 Temperature

1.1.1 Cooling/ heating rates

Thermal conditions are the underlying factor driving circulation beneath the ice when the water is isolated from the atmosphere. In the ice free months, the lake's temperature is a result of the heat exchange between the water and atmosphere (Bengtsson 1996). Once ice forms there is relatively little thermal change (Bengtsson 1996). Since underlying water is insulated from freezing temperatures, it generally remains between 0-4 ºC (Meding 2001). Within this range, however, temperature increases throughout the main water mass has been broadly documented (Harrison 1863, Yoshimura 1937, Likens 1965, Billello 1968). Temperature may increase 0.5-2 ºC from freeze to ice break-up (Bengtsson 1996). Temperature changes are found within the vertical profile, leading to the establishment of temperature gradients. The establishiment of thermal gradients is one indication there are some differences in heating and cooling rates within the water column; though gradients are also produced by a combination of cooling at the surface and by gradual reduction of open water area (Mortimer 1941). Hence water movement must be minimal in order not to eliminate these thermal gradients (Bengtsson 1996). Temperature profiles in a deep Canadian lake, showed that bottom water was significantly warmer than rest of the vertical water column (Kenney 1996). When studying heating and cooling rates Bengtsson (1996) recommends a resolution on at least a daily scale and also temperature measurements in different areas of the lake, all of which we have incorporated into this study.

1.1.2 Heat Content

Likens & Hasler (1962) were the first to measure transport of heat under ice with a radioactive tracer in a small lake. Welch and Bergman (1985) did similar studies, followed by Bengtsson (1986) who used a tracer to study a large lake. The three main causes contributing to warming were found to be: solar radiation, heat flow from sediments, and inflow of warm water (Yoshimura 1937). Although Likens & Ragotzie (1965) and Mortimer (1941) speculate that oxidation of organic material may contribute to bottom heating, Billello's (1968) calculations show negligible contribution to bottom warming by oxidation processes. Ice and snow thickness reduces radiation substantially limiting heating effects to only the upper layers of water and may nearly completely isolate the lake. Solar radiation and temperature is at the lowest during winter conditions (Agbeti 1995). Flow through of warm water is also case specific and seasonal, since in mid winter small creeks are typically frozen and no longer contributing to thermal conditions. This leaves latent heat stored in the sediment during the summer months to be the contributing heat source during the months of complete ice cover (Mortimer 1941, Welch and Bergmann 1985, Kalff 2003). This resultant heat is responsible for convective currents which prevent complete stagnation under ice (Mortimer 1941). Basin morphology, degree of summer heating, and a combination of other environmental factors contribute to the quantity of heat held by the sediments (Wetzel 2001).

1.1.3 Stratification

During autumn overturn, there is a loss of thermal stratification and rapid decrease in whole lake water temperature. Prior to freezing, the lake continues to cool below 4 ºC in wind exposed lakes. The littoral regions cool more rapidly than the main body of the lake, due to the smaller water volume and much longer horizontal distances to mix the water as compared to vertical distances at the deepest point. Therefore ice formation begins at the littoral zone moving concentrically inward, increasingly inhibiting wind effects. Inverse stratification occurs when the surface temperatures are at their lowest, wind induced turbulence is prevented from the encroaching ice cover, and the latent heat is contributing to the warming of the lower water layers (Agbeti 1995). In Agbeti's (1995) investigation, both lakes studied became weakly thermally stratified during ice formation, and became isothermal before ice cover and at ice break up, as anticipated. Seasonal mixing and stratification also affect utilization of dissolved organic carbon (Bradely *et al*. 2007).

Broadly, Wetzel (2001) defines inverse stratification as a state in which colder water lies over warmer water. More specifically this paper demarcates between stratification versus a distribution. A period consisting of a cold epilimnion, thermocline, and warm hypolimnion, we define as true inverse stratification. For all other times, when colder water gradually and consistently warms towards the lake bottom, we describe this as an inverse distribution.

1.2 Oxygen

Dissolved oxygen is an effective characteristic that reveals a lot about a lake's metabolism. The balance between the oxygen supply and the metabolic consumption defines the total amount of dissolved oxygen in a lake. The sediment-water interface is the main site of oxygen consumption (Brewer 1977, Bradely 2007) In part, the rate of oxygen consumption is governed by the distance from the sediments and the oxygen concentration within the water (Babin 1985). Similarly, Agbeti (1995) found dissolved oxygen was nearly saturated (11-15 mg l^{-1}) in the top 3 m, but declined to near anoxic levels near the sediment surface. As a general rule of thumb, we can say that the concentration of dissolved oxygen decreases with depth (O'Sullivan 2005, Barica, 1979).

1.2.1 Depletion

During periods of ice cover the lake's oxygen inputs often effectively cease. There is no atmospheric inputs from wind aeration due to ice cover (Agbeti 1995, Bengtsson 1996, O'Sullivan 2005). In addition snow reduces incoming radiation therefore photosynthesis becomes negligible (Schindler and Nighswander 1970, Bengtsson 1996, Kenney 1996). The loss of thermal stratification and decrease in temperature, contribute to increased dissolved oxygen concentration throughout the whole lake before freezing over. Contrary to past studies which show oxygen saturation levels at 80-100% prior to freeze up (Barica and Mathias 1979); Babin (1985) found dissolved oxygen levels surprisingly low at 69% saturation at fall turnover. Timing of winter oxygen depletion in deep water will be an important factor to investigate; this may even begin before final freezing, if water column will become inversely stratified.

1.2.2 Biological effects

Until ice cover, lakes undergo drastic and sometimes rapid temperature changes caused by wind turbulence and decrease in irradiance as well as heat flux thus resulting in the redistribution of nutrients and other elements throughout the water column (Alvarez-Cobelas, 2005). In Finland, photosynthesis is virtually absent in mid winter due to low solar radiation and ice/snow cover, therefore the oxygen change may approximate the lake's respiration, similarly in Canadian Arctic (Welch and Bergmann 1985). A further handicap in winter for autotrophs is the reduced daylight period and the low angle of direct solar radiation (O'Sullivan 2005). Freeze out and photosynthesis produces oxygen during the early winter, which is balanced by the oxygen consumption from biota and decaying organic matter (Meding, 2001).

These combined physical and chemical processes affect the biology of water organisms which are dependent on the distribution of oxygen (Meding 2001). Variation in community structure is related to physical and chemical gradients with depth and time intervals, across seasonal transition from autumn turnover to winter ice cover (Pearce, 2005). There have been several studies looking at bacterioplankton or phytoplankton movements under ice, whose spatial variations effect biological processes (Cloern 1992, Mehner 2005). Heterotrophic bacteria at the sediment water interface in lakes influence organic matter cycling (Bradely *et al.* 2007). Stanzel (2004) found oxygen consumption correlated with increased temperature and noted that sediment surface was generally warmer. O'Sullivan (2005) notes that despite the decreased light, temperature remains the limiting factor controlling the growth rate of algae. Changes in timing and duration of ice cover will lead to marked changes in the structure of the bacterial and plankton communities.

1.3 Physical Conditions

1.3.1 Stability

In the autumn, the water surface cools, reducing the density difference between epi- and hypolimnion, gradually degrading the mixing layer deeper and deeper until finally reaching the bottom (Mortimer 1955).

Due to sediment absorbing and storing heat throughout the summer, the bottom remains warmer than the overlaying water (Welch and Bergmann 1985, Kalff 2003, Bengtsson 1996). In large lakes with water temperature well below four degrees the difference in temperature, which is highest during the fall, results in the warming of near-bottom water and hence makes the warmed water denser compared to the cooler layers above. In winter, cold temperatures and little to no freshwater runoff create conditions for a cold and light surface water layer. This initiates a boundary layer promoting stratification and little oxygen renewal to deeper layers (Holte 2005).

As soon as ice at the lake margins spreads wide enough so that wind induced turbulence no longer is able to destroy the density gradient, a density current along the sediment slopes is created. Consequently, deep, large lakes may begin to stratify inversely even before final freezing. At the same time the secondary currents such as density currents, allow diminutive oxygen redistribution and heat transport (Bengtsson 1996).

1.3.2 Density differences

Density differences are small between 0-4 ºC, therefore there is only a minor density gradient, and this gradient is enough to cause inverse stratification, where cold water is above warmer water (Wetzel 2001). However inverse winter stratification is easily disrupted by small amounts of wind energy (Wetzel 2001). As long as there are cold, calm days during ice formation, inverse stratification can appear even before complete ice cover. Plenty of wind may cause the temperatures to fall below maximum density of 4 ºC; if this is the case then heat flux will increase density of water in contact with the sediments contributing to the sediment surface currents along the bottom.

Freezeout and heat are the driving factors of winter circulation (Welch 1985). In freezeout, the expulsion of gasses, elements, and total dissolved solids during ice formation, causes a concentration of salts which increase water density in turn contributing to both horizontal (Welch 1985) and vertical currents (Schindler 1974). Directed circulation from the littoral zone to the centre of the lake is an important distribution mechanism for nutrients and other chemical and biological constituents (Kenney 1996). Increased density by electrolytes in the water can assist in the flow of water sliding down sediment slope to deeper parts of the lake (O'Sullivan 2005). Salts frozen out during ice formation or from sediment along the descent can be found near bottom and make it possible for bottom water to be warmer than 4 ºC (O'Sullivan 2005, Wetzel 2001). Density instabilities may result from solar radiation penetrating the ice especially nearing late winter (Bengtsson, 1996). Heat transport by current degrades the ice cover in late winter weakening ice cover, rendering it hazardous for surface travel (Kenney 1996).

1.3.3 Flow along sediment surface

Physically, the sediment surface interface is the transition layer from fluid (water) to solid (sediment) (Danovaro *et al.* 1998). Previously established, is how the sediments warmed from the previous summer, release heat to the adjacent water in the winter, making near bottom water warmer than upper water layers. In addition, surface layers are made denser due to freeze out. This provides the platform for the density currents to form. Water just beneath the ice is transported laterally towards the shore, subsequently coming in closer contact to the sediments, which results in the acquisition of heat; water becomes denser, thus continuing to sink along the bottom as it picks up heat (Hutchinson 1938, Likens and Ragotzkie 1965, Welch and Bergmann 1985, Welch et al. 1987, Bengtsson, 1996, Wetzel 2001, Kalff 2003). Chemical exchanges between the sediment and water, for instance oxygen uptake contributes to the density currents along the sediment surface (Wetzel 2001). In this way sediment's heat content contributes to overall lake circulation, mixing a large portion of water under the ice (Mortimer 1941, Agbeti 1995, Bengtsson, 1996, Kenney 1996). The mixing process under ice is a lake wide baroclinic circulation directed from the littoral zone to the deeper parts (Kenney 1996). Through this circulation regime, it is clear that stratification and density gradients, which take into account both temperature and pressure, in the water column affect overall circulation.

1.4 Objectives

Our study incorporates three disciplines, physical (heat flux and water flow), chemical (redistribution oxygen), and biological effects (bacterial population), to investigate the dynamics of the winter freezing phase of inland lakes. The period of ice cover formation (December-January) will be the primary focus of my discussion.

In winter, low concentration of dissolved oxygen in deep areas of large, ice-covered lakes is due to the occurrence of thermal density currents flowing over sediment surface. A significant part of the oxygen uptake of lake sediment is transferred to the deepest part of a large deep lake in the early phase of lake freezing, partially before the final freezing. Thus our primary focus is to investigate temperature gradients and the oxygen dynamics. Directed circulation from the littoral zone to the centre of the lake is an important distribution mechanism for nutrients and other chemical and biological constituents (Kenney 1996). Increased bacterial numbers in deeper waters is hypothesized, due to the sweeping of water along the sediment surface by density gradients.

The extent at which the sediment transfers heat, salts, and bacteria is unknown yet. Also with inverse stratification there may be more complex processes driving winter circulation. Despite the handful of literature that points toward circulation mechanisms there are still discussions about the winter currents, under-ice oxygen consumption, and the dynamics of the sediment surface flow.

2. MATERIAL AND METHODS

2.1 Study Site

The study was conducted at Lake Pääjärvi (Fig.1), an oligomesotrophic lake in southern Finland (61°04´ N, 25°08´ E) during December 2005 through January 2006 and then the following winter starting in January 2007. The lake has an area of 13.4 km^2 and mean depth of 14.4 m (Arvola, 1996). Our sample site was 75 m deep and about 400 m from shore. Helsinki University’s Lammi Biological Field station was our staging post and laboratory during the data collection period.

Table 1. Temperature logger chain locations along both the steep and gentle slope of Lake Pääjärvi. The transects ran from the deepest point towards the shore.

Logger Chain	**Coordinates**	
	North	East
20m steep	61º 03' 617	25º 08' 232
40m steep	61º 03' 457	25º 08' 381
75m	61º 03' 305	25º 07' 700
40m gentle	61º 03' 396	25º 07' 623
20m gentle	61º 03' 429	25º 08' 662
10m gentle	61º 03' 640	25º 09' 160
5m gentle	61º 03' 568	25º 09' 359
2m gentle	61º 03' 622	25º 09' 461

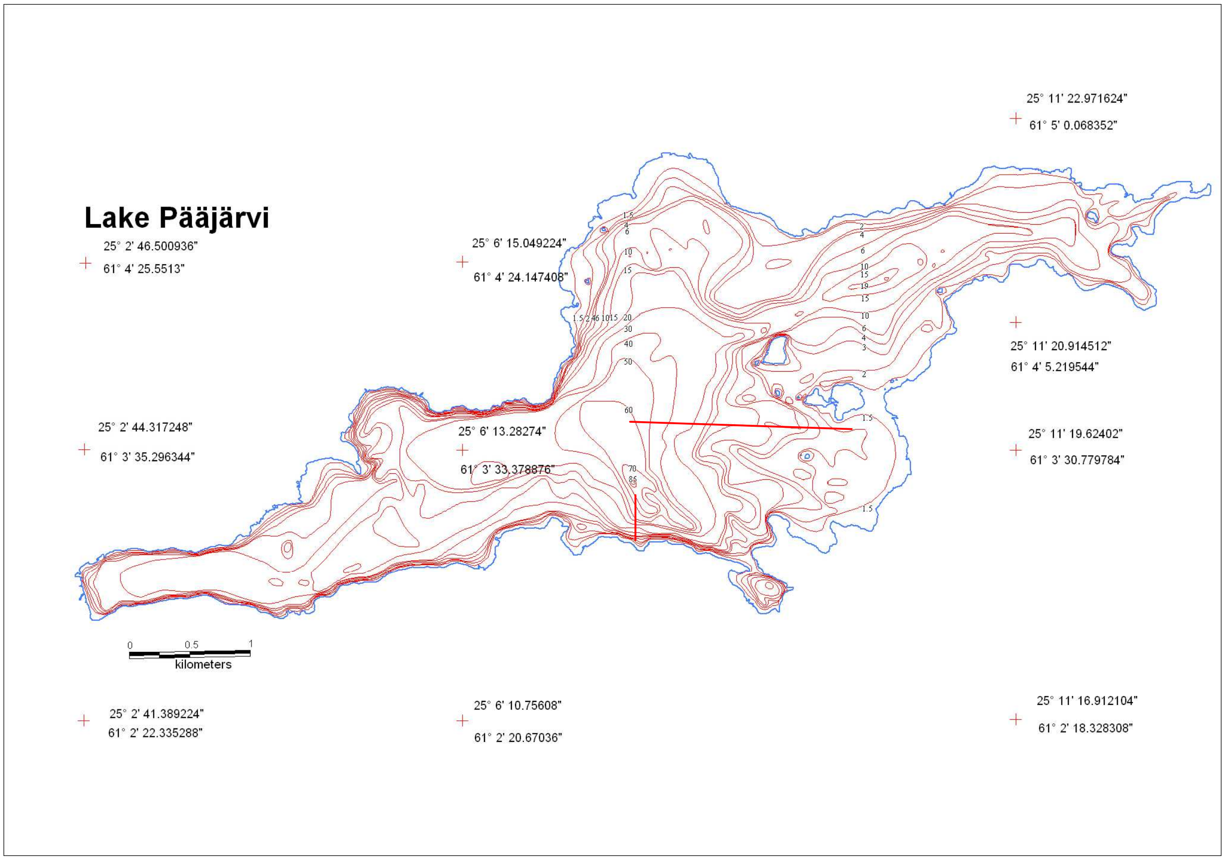


Figure 1. Bathymetric map of Lake Pääjärvi, showing the location of the deepest point and the 2007 temperature logger transects.

2.2 Sampling Regime and Analysis

During the lake freeze over period, chemical and physical parameters were measured, and bacterioplankton samples were collected and analyzed. Lammi Biological field station provided weather station readings.

Samples were taken at the deepest point biweekly during the freeze over period. In addition, temperature logger chains recorded continually throughout the sampling period. There were two temperature transects, during 2007, first one running east following a gradual slope towards the shallow regions near the islands. The second transect ran from the deepest point progressively towards the southern shore which has a very steep slope. Depending on the amount of ice cover, access to the deepest point varied. In the beginning, we sampled via motor boat, and then later as marginal ice was sufficiently thick, we had to push a row boat until it broke through the ice and we continued to the deepest point by rowing. Finally upon complete ice cover, we could sample the deepest point on foot. Water samples were obtained using a Limnos water sampler at 5 meter intervals from the surface. All 100 ml glass bottles were kept in plastic foam boxes immersed in lake water-snow mixture until processed in lab less than two hours later.

Dissolved oxygen determinations were essentially according to the Winkler method with the use of Mettler Toledo DL53 (V2.4) titrator used with LabX computer software (Carpenter, 1965). In 2007, dissolved oxygen was measured by an Aandera oxygen optode and temperature sensor (model 4130) coupled with the CTD. Water temperatures, depth and conductivity were measured using AML MicroCTD 7178, Applied Microsystems. The temperature profiles come from the logger chains using Starmon Mini temperature recorder (manufacturer: Star-Oddi, Iceland), temperature range -2 - +40 ºC, absolute accuracy ± 0.05 ºC, average resolution about 0.014 ºC. Dissolved inorganic carbon was determined according to Salonen (1979). Bacterioplankton were filtered as per Bergström *et al*. (1985) stained with acriflavine, filtering 1ml of sample and 5 ml of Millipore GS filtered water onto a black Nuclepore (0.2 µm) membrane, then using immersion oil to mount them onto microscope slides. Bacteria concentrations were determined from pictures taken from the epifluorescence microscope then transferred into analySIS® 3.0 Soft Imaging System. Due to difficulties with precipitates and general subjectivity, our way of systematically counting the samples was to only change the red threshold in the program, in order to determine which bacteria were to be included in the count. Five random images of the microscope fields were evaluated for total bacterial count then averaged for the analysis.

3. RESULTS

3.1 Temperature

3.1.1 Air temperature

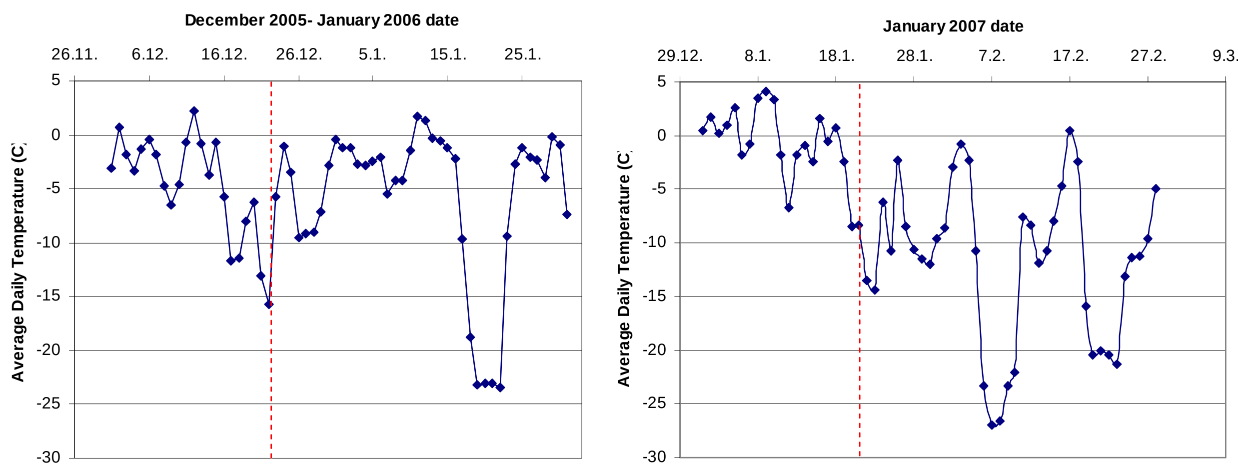


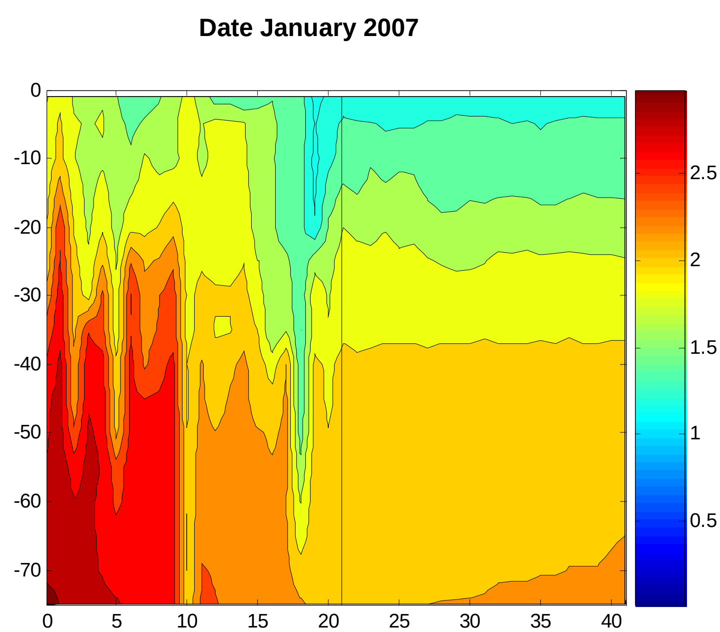
Figure 2. Daily average air temperatures during the early winters of 2006 and 2007. The dashed line indicates the formation of complete ice cover.

During December 10 to the 20th, 2005 ambient air temperatures fluctuated, with no trend lasting longer than 3 days, between 3 ºC to -16 ºC. Likewise in 2007, air temperature fluctuated roughly every three days during the pre-ice cover period. It also took two calm days at below -6 ºC to initiate ice cover. During 3 weeks before the onset of ice, there were 10 days above 0 ºC in 2007 compared to 2 days in 2005 (Fig. 2).

3.1.2 Water temperature

In this deep northern lake, the isotherms showed that in 2005 the complete autumn overturn was becoming incomplete two weeks before the formation of ice. In 2007, when freezing happened much later, that phase was reached already more than 3 weeks earlier. Once ice cover was established there was no longer vertical mixing characterized by the stabilizing temperatures at certain depth intervals (Fig. 3).

In 2005, ice cover development began with thin marginal ice on December 13. By December 20th there was thick shore ice; both arms of the lake were completely covered. There was stacked ice in the centre basin extending about 75 m from shore; 0.5 cm thick ice extended about 50-75 m from the stacked ice before open water. Overnight 30 m more ice had developed, even the buoy marking the deepest point had been frozen in the early morning, but by the time samples were taken the deepest point was again part of the ice free area. December 22, 2005 and January 21, 2007 marked the first day of complete ice cover. By December 28th, 2005 there was 3-5 cm thick ice at the deepest point.



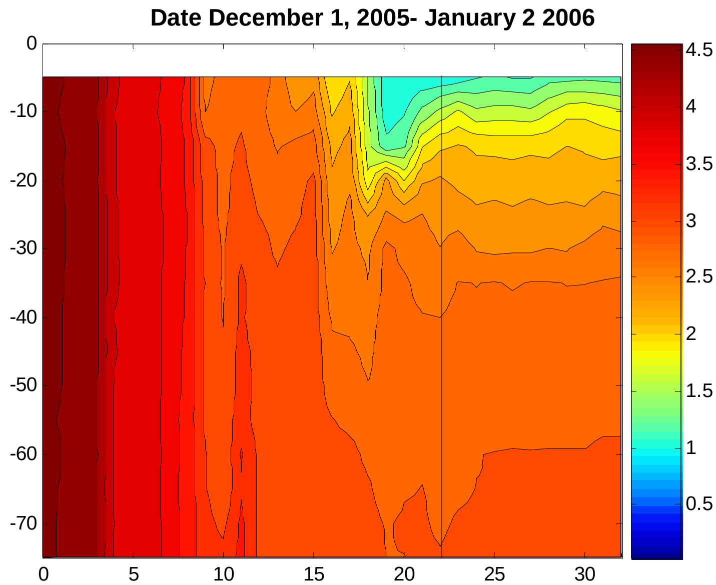


Figure 3. Isotherm plots at the deepest point of Lake Pääjärvi using daily averages at every 5 m intervals. The vertical lines indicate the first days of complete ice cover.

In 2007, marginal ice started to form after January 12th. It took a sharp decline in air temperature to disrupt the uniform temperature distribution, so that a respective decline in surface temperature was noticed just prior to final freezing. Surface temperatures were much cooler in 2007 despite the warmer air temperatures preceding the freezing compared to the 2005-2006 winter; longer cooling time did not require such low temperatures to complete ice cover. Once ice cover was established, in 2007 the mixing layers were fewer, but cooler (1.3 ºC > x < 2.1 ºC), than in 2005-2006 winter (1.5 ºC > x < 2.7 ºC) (Fig. 3).

Vertical temperature profiles were uniform until December 8th . Before the ice started to form the entire lake body had temperatures below 3.5 ºC and 2.1 ºC, for 2006 and 2007, respectively. The surface layer temperatures were hovering at the 1 ºC prior to the onset of ice cover, after which the surface layers had steady marginal increases from 1.05 ºC on December 23, 2005 through to a high of 1.40 ºC January 7th, 2006 (Fig. 4). In both years the upper 20 m stayed between 1-2 ºC, whereas the bottom 25 m stayed above 2.0 ºC (Fig. 3). The isotherms also show the rising of bottom temperature after ice cover (Fig. 3).

With air temperatures fluctuating from 2.3 ºC to -6.4 ºC for 3 weeks, the lake body steadily cooled in 2005 but it took two more cold snaps of days below -10 ºC to finally have complete ice cover (Fig. 3).

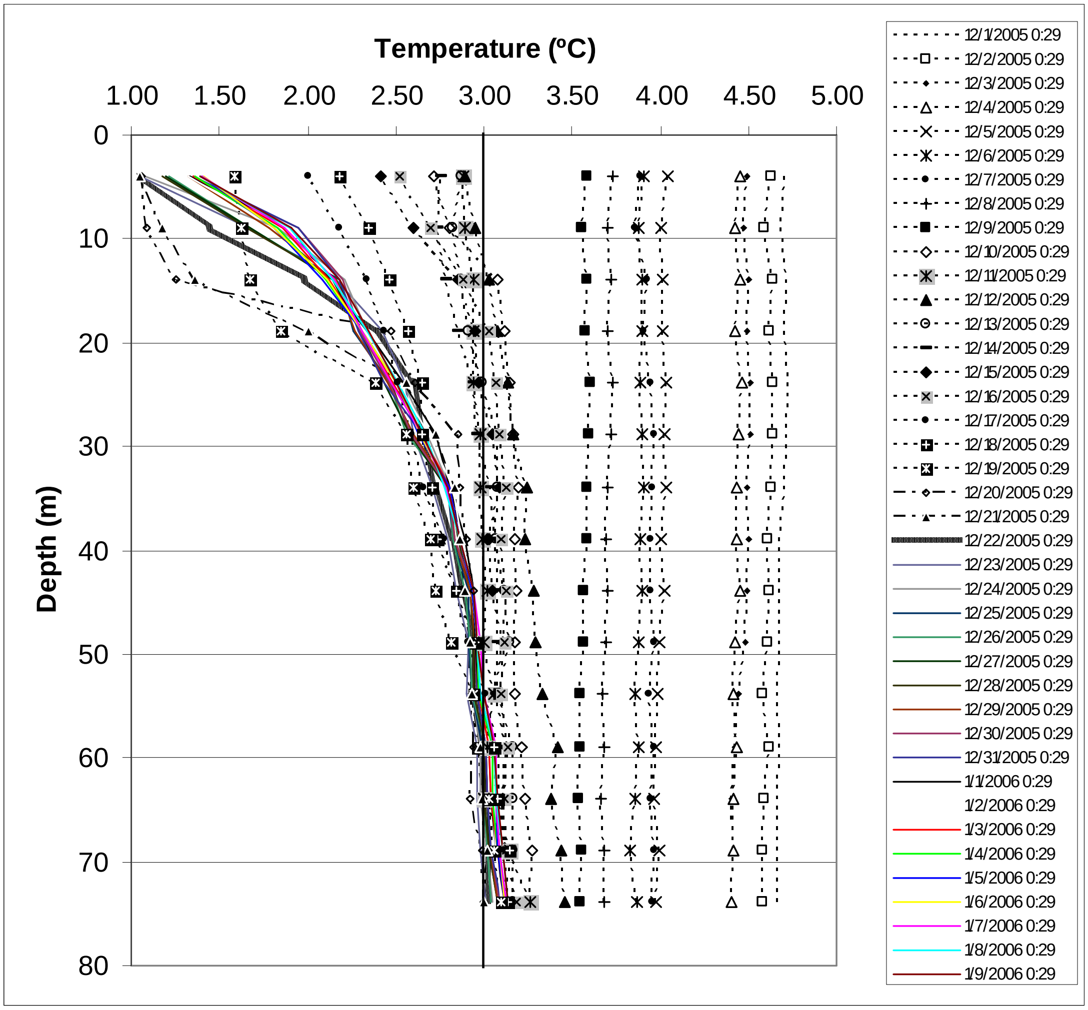
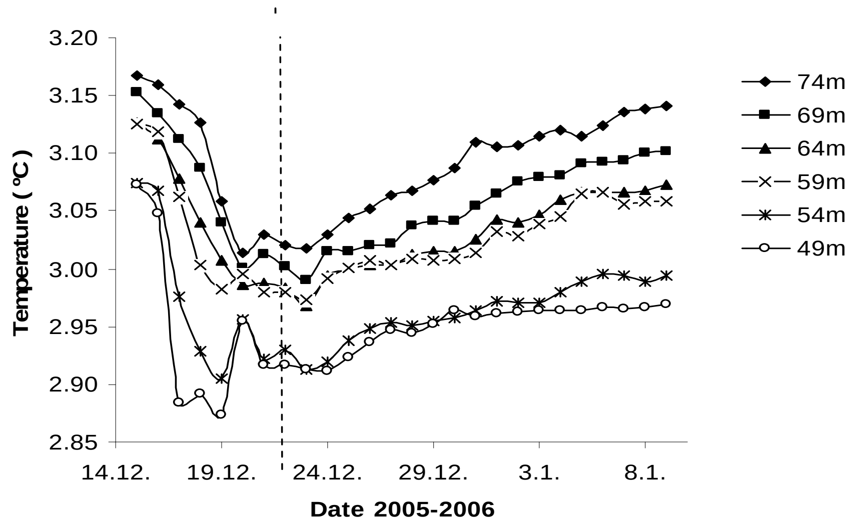


Figure 4. Daily temperature profiles through the water column at the deepest point on Lake Pääjärvi. Temperatures were taken at 23:30 nightly by temperature loggers in early winter 2006. The black vertical line emphasizes temperature below the 3ºC, when a negative gradient towards the surface started to develop. The thick hatched line (22.12.05) is the first day of complete ice cover. All dates prior to ice cover are dotted, after ice cover the inverse temperature gradient is established, all lines are solid.

This temperature profile (Fig. 4) provides an alternative to view temperature dynamics, which are not as clearly seen through the isotherms. It shows the steady reduction of temperature starting from > 4.5 ºC, until the upper layers freeze and bottom layers stay above 3 ºC. First full ice cover was on December 22, 2005 and January 21, 2007; almost immediately after the ice's insulating properties take effect (Fig.4). Initially the whole lake was extensively mixed, thereby having uniform temperature reduction throughout the water column, especially evident in 2005. In both years, with marginal ice beginning to form (about 10 days prior to complete ice cover) the lake body was no longer uniformly mixing. The upper layers cooled from 3.5 ºC to about 2.7 ºC, and then only by December 18 did the water column begin to stratify essentially (Fig. 4).
During the same time, thin but wide spread ice had almost completely covered the east and west arms and air temperatures plunged to -12 ºC, the coldest temperatures at that time (Fig.2). From the 19th -21st there was dramatic real inverse stratification, when the upper layers are colder than the bottom. The metalimnion would be between 10-20 m depths.

These same dates also include the coldest water temperatures; December 21 being the coldest, with bottom (75 m) temperatures dipping to 3.00 ºC and at 5 m as low as 1.1 ºC. However, this inverse stratification soon disappeared after full freezing and normal winter time temperature distribution occurred.



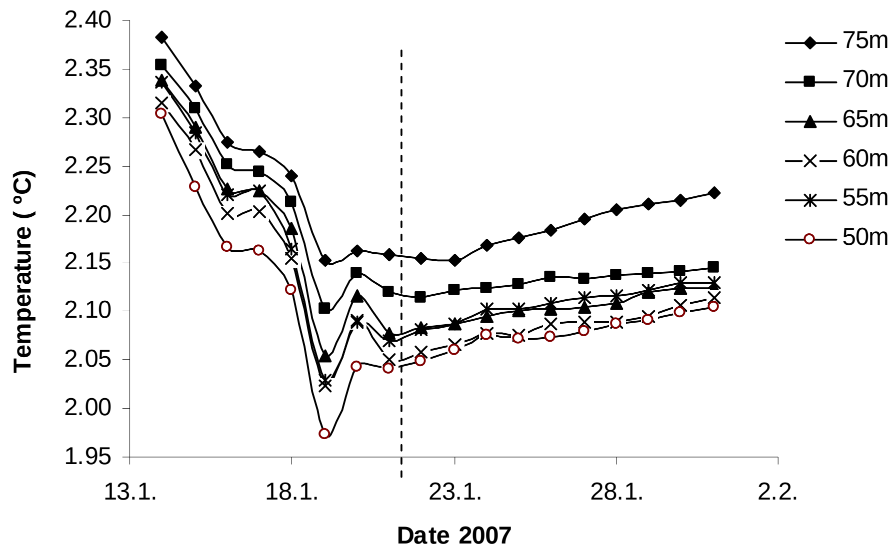


Figure 5. The temperature change below 50m using daily averages in Lake Pääjärvi in 2005 and 2007.

In 2005 there was a rapid decrease in water temperature leading up to the complete freeze period from December 18-20. Then also bottom temperatures decreased by 0.1 degree in two days (Fig. 5), which is a considerable change since the lower depths had less turbulent mixing than the surface layers. In comparison, the upper layers showed a similar sudden temperature decrease December 19 but it was a full degree drop, ten times higher. There was evidence of warming in deep water already before the final ice formation (Fig.

5). After the formation of ice cover there is a gradual but steady increase in temperature below 50 m. The 75m layer showed, in both years, the highest rate of increase (Fig.5).

3.1.3 Transect profiles

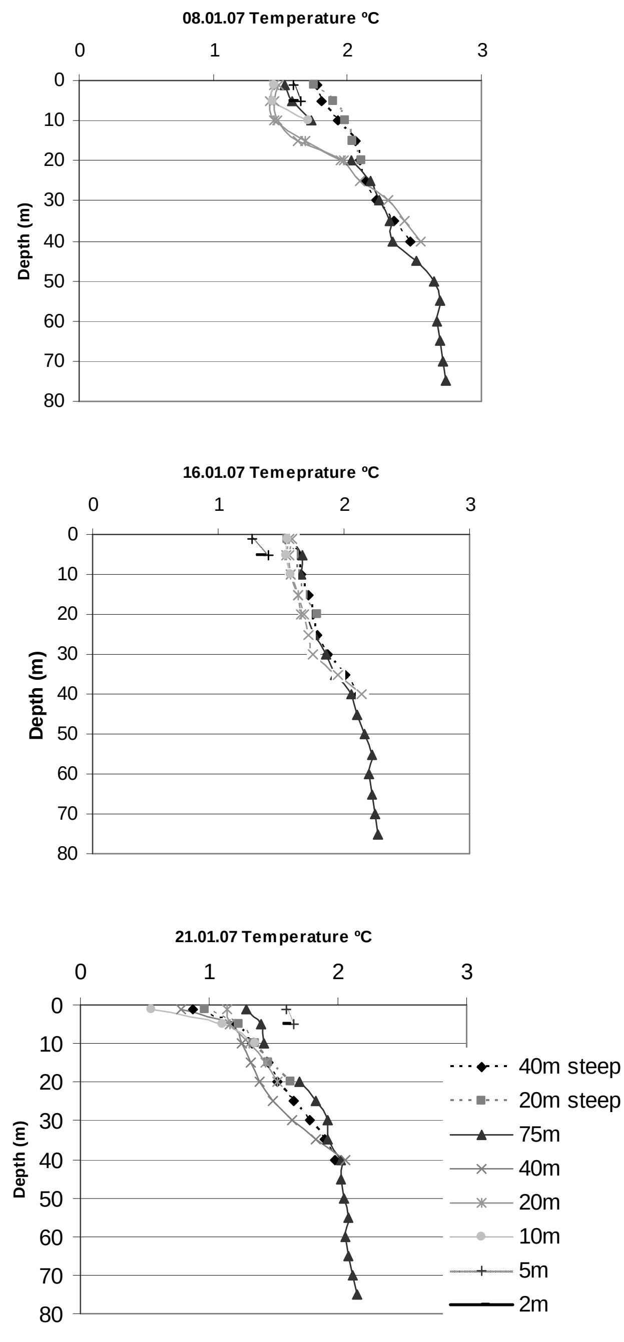
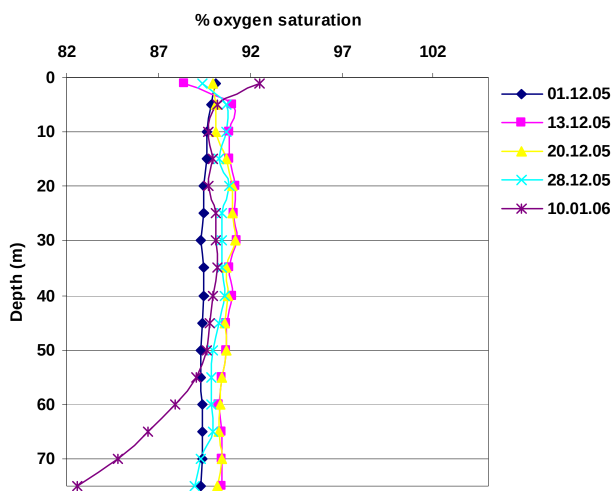


Figure 6. A comparison of the temperature profiles in 2007 along both the steep (jyr) and gentle transects starting on January 8th prior to ice development, then January 16th when marginal ice has formed, then on January 21 when all but the deepest point has ice cover.

Before the final freezing there were cool phases in the near to surface layers which disappears soon after freezing, evidently by spreading horizontally under the ice of the lake margins. On 12-16 December 2005 and 1-4 Jan 2007 clear but temporary inverse stratification formed (Fig 4 & 6).

Prior to the development of marginal ice in 2007, 20 m and 40 m profiles, on the gradual slope, already began to stratify. Then between January 8th and 16th the full lake area had its last complete chance to mix. The temperatures on January 16th show a uniform profile, a near vertical temperature gradient where temperature varies little throughout the water column, for all but the shallowest points on the lake. The 2 m and 5 m points show a decrease in temperature on January 16th, but this is because on this date initial ice formed. These points are the first to be covered by ice, thus this temperature decrease is expected. Surface temperatures show a drop in temperature about the time that ice is formed over that particular location. Once ice was established, the insulating effects were noticed with the increasing profile temperatures. On January 21, when all but the deepest point are frozen over, all points show the characteristic inverse distribution , but at the deepest point a true inverse stratification is observed.

3.2 Dissolved Oxygen



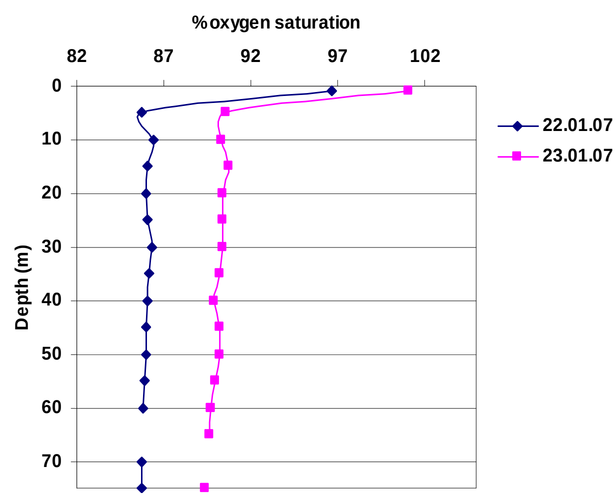


Figure 7. Dissolved oxygen saturation in Lake Pääjärvi during the freezing period. In winter 2007, oxygen concentration was measured using CTD only.

During the early season, December 8th and 9th 2005, both the oxygen and temperature profiles were uniform throughout the water column with temperature <3.5 ºC. It seems that after December 20th, when temperature was periodically inversely stratified, dissolved oxygen in deep water started to decrease (Fig. 7). On December 28th 2005 and January 10th 2006 there showed declining oxygen levels, especially from 50 m to the bottom. Above 20 m there was relatively little change between 2 days prior to freeze and a week afterwards during the 2005/06 season. The 2007 results are less precise since they came only from CTD and not by titration, but still yield good idea of relative vertical distribution of oxygen concentration. Lake Pääjärvi is oligomesotrophic ; it is quite oxygen saturated throughout the lake at all times, with levels not dropping below 10 mg/L during the winter months (saturation concentrations are 14.6 and 13.1 mg/L for 0.0 and 4.0 ºC, respectively). In 2005 oxygen saturation behaved as expected with decreasing oxygen once ice formed. Surprisingly in 2007, oxygen profiles show a 5% increase in oxygen after ice cover is established (Fig. 7).

3.3 Dissolved Inorganic Carbon

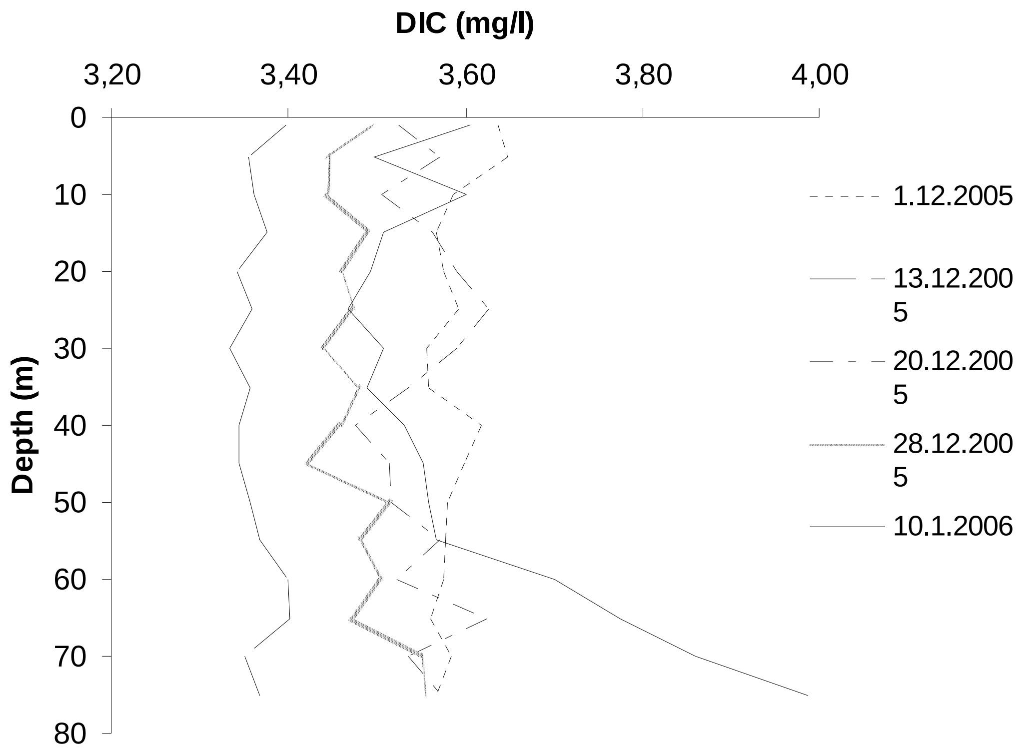


Figure 8. Vertical distributions of dissolved inorganic carbon concentration in Lake Pääjärvi during the freezing period of the year 2006.

The dissolved inorganic carbon is a reciprocal value of oxygen; decrease in oxygen and increase in carbon dioxide reflect respiration rates. The daily averages jump back and forth, which probably reflect fluctuation in calibration. For example December 1 had the highest levels (3.6 mg/L), on the 13th it was the lowest readings with the average at about 3.4 mg/L (Fig 8). Instead, the relative vertical distributions are most important and show, in agreement with oxygen results, uniform concentrations during the freezing period. Only on January 10th below 55 m there was an indisputable exponential increase in DIC.

3.4 Bacterioplankton

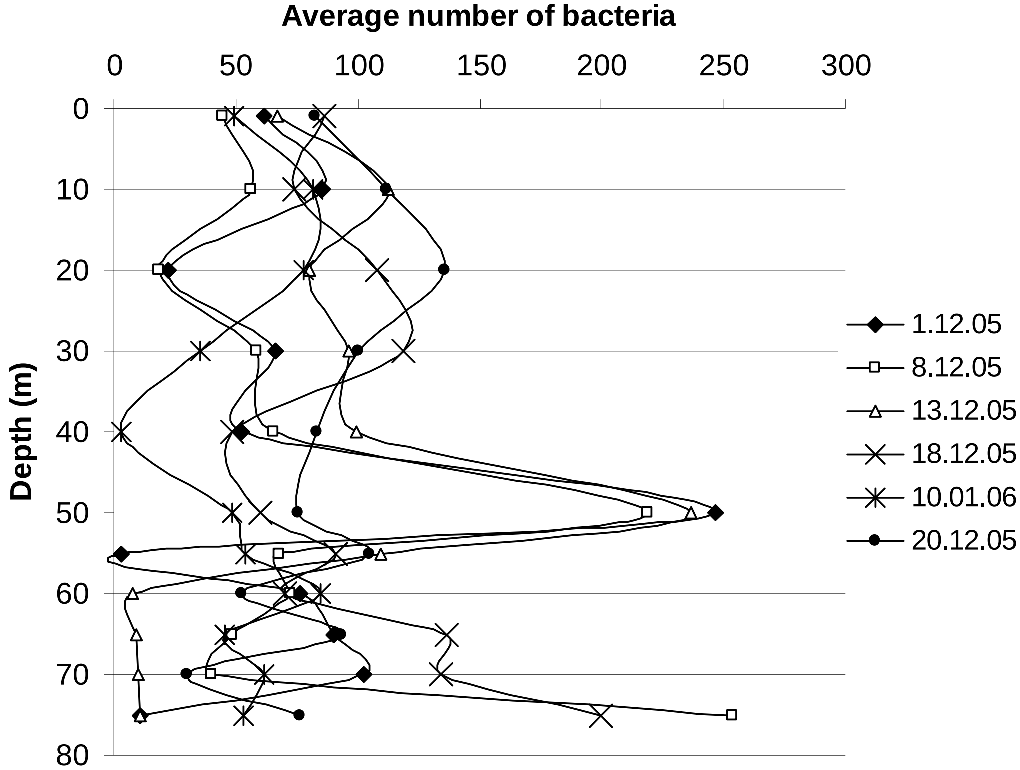


Figure 9. Comparison of relative difference in densities in the vertical bacterial profiles throughout freeze over in Lake Pääjärvi.

In early December 2005, the bacteria densities broadly follow similar trends amongst all dates sampled. There is a small peak at 10 m, a dip at 20 m, and then a huge and very similar peak at 50 m (Fig.9). During the rapid reduction in temperature throughout the lake, we also notice a similar decline in bacteria densities, especially at 50 m. This could be correlated with temperatures below 3 ºC. On the other hand, temperature is not the decisive control of bacterioplankton densities. For instance on December 8th the water temperature is essentially uniform, but it is also the date when bacteria densities show the widest variability throughout the water column. From these bacteria results we can hardly extract any significant features simply due to vast variability. Even the maximum relative density at 50 m may not be accurate although it is successively so three times. Considering the inconsistencies and time restraints, bacterioplankton was not collected in 2007.

4. DISCUSSION

Currently our understanding of under ice circulation and physical dynamics is formed from the investigations of temperature gradients, oxygen consumption rates, and density differences. Only by understanding where and when these mechanisms occur within the lake can we interpret the interplay among these forces, observing how they influence the movement of water under ice. Further how these forces affect the biology, and chemical functioning of lakes in winter becomes important. Ice cover seals off wind induced turbulence and accompanying atmospheric gaseous exchanges and can retard sediment-nutrient exchanges (Agbeti 1995, Bengtsson 1996). Therefore this reduction in vertical mixing sets winter conditions apart from the rest of the ice free period (Holte 2005, Kenney 1996). Sediment heat flow generates convection circulation but is still dependent on the temperature difference between the sediment and water plus the differences found within the water column (Bengtsson 1996)**.** Convective currents induced by heat flow from the sediments lasts throughout winter but are very slow (Bengtsson 1996).

4.1 Temperature

From November to mid December 2005 the water column was completely mixed, temperatures were uniform throughout depth profiles; though in 2007 the water column did not fully have a uniform temperature profile. As the perimeter ice began to form, there was less mixing, more extreme temperatures, and some random variation which contributed to the temperature fluctuations observed through the entire profile between December 10th and until full ice cover establishment on December 22, 2005. The upper layers show the highest daily fluctuations, due to close exposure to ambient air. Higher cooling rates in open water led to lower temperatures during the freezing period in the middle of the lake. According to our temperature logger transects, the shallow areas were only warmer after the establishment of ice cover, otherwise the littoral areas were cooler than the central basin surface water.

As ice formed concentrically towards the centre, the temperature transects showed a drop in surface temperatures just prior to the formation of ice. Both at the observation depths of the 20 m and 40 m on the gentle slope transect, true stratification was observed prior to ice cover. Contrastingly on the steep slope, the 20 m and 40 m logger chains did not show inverse stratification. The short distance between logger points appears to be the key factor; since the horizontal distance was short, the displacement of water masses with different densities had enough time to wipe out stratification before it became visible. Once air temperature was below -5 ºC and with no wind, the remaining lake area froze over. After complete ice cover the thermocline was rapidly disbanded. The continued flow inward of the deep warm water sets up the final temperature gradient seen from ice cover onward. A stabilizing effect was evident at each depth after ice completely formed (Fig 3).

Typically winter lake conditions do not permit inverse thermoclines to develop when the lake cools below 4ºC (Kalff, 2003). However, for a brief period of time (< 3 days) inverse stratification was detected. Because the cooling rate of water at the lake margins exceeded the advection rate of water between the lake centre and margins, ice cover gradually grew from the shoreline towards the lake centre. In this phase, windy and sometimes milder temperature periods periodically eroded or even broke down inverse temperature stratification created during cooler and calmer periods. While the exposed centre water was within fractions of freezing, the warmer ice insulated water moved and sank, causing displacement of the deep cooler waters into the centre basin**.** When all but the central basin was ice covered inverse stratification was initiated; as demonstrated by our results, this stratification can even occur below 4 ºC. However, the resultant truly inverse stratification periods remained short lived. When windy period were over, the cooler and lighter water at the margins soon flowed on the top of the recently mixing water column re-establishing more gradual inverse distribution of temperature.

Changes in air temperatures are not immediately represented throughout the water column. There is a time lag between when the air temperature drops and when the water temperatures show a temperature decrease, mainly due to water’s greater heat capacity as well as the shear volume of water at 75 m depth. Generally the surface water temperatures were near to that of the air, but below 15 meters the temperature increases or decreases would happen a day later. One should keep in mind that these parallel temperature fluctuations are all relative, and dependent on wind effects, for the 10 ºC air temperature change in two days resulted in <0.05 ºC difference in the bottom 40 m. Inverse stratification was coupled with the sharp decline in air temperatures just prior to final freeze up.

4.1.1 Wind effects

Wind effects cause increased mixing, resulting in longer ice formation times, more temperature layers, and heating caused by the more frequent up-wellings. Due to very small temperature specific water density changes near 4 ºC even light winds can disrupt any resistance to mixing. Therefore, according to Kalff (2003) there should be no inverse thermocline. In spite of that, we have observed conditions where inverse stratification appears. However, this is reasonable within the context of gradually reducing area of open water during freezing. Ice cover at the margins of the lake reduces mixing by wind, which again can lead to only partial mixing of the water column and brief, inverse stratification periods in open water.. Wind induced mixing continues to cool the water body until the upper layers reach freezing. Our data suggest that there is a brief inverse stratification only when the lake has ca. 50 % ice cover. Due to wind action and daytime highs the thin central ice was continually decreasing only to reform again during the night thus delaying the freezing time. The area of stacked ice was likely produced by the same mechanisms, as the wind broke up and piled the central ice against the shore. When the lake was mixed lake temperatures more closely followed ambient air temperatures (Figs. 2 & 3). Deeper mixing events and more frequent temporary inverse stratification periods (Fig. 3) in 2007 indicate higher wind effects as compared to 2005**.**

After complete ice cover there was no longer any true temperature stratification but only an inverse temperature gradient. Below 40 m the water temperatures were greater than 2 ºC and increased towards the bottom. Near the ice there was a steep temperature gradient, which indicates minimal mixing between layers. The first day of bottom warming was the day before complete ice cover, December 21, 2005 when the bottom ten meters warmed by 0.015 ºC from the previous day. This supports our hypothesis that warming can be initiated before 100 % ice cover. Evidence of warming at the sediment surface was delayed in 2007 by nearly a week after ice formation, probably due to the differences in duration between complete mixing and formation of ice cover.

4.2 Oxygen

Oligotrophic lakes in theory should have higher oxygen saturation near to 100 % because there is less biota to consume oxygen and therefore these types of lakes have an orthograde vertical profile, as seen in 2007 in Lake Pääjärvi. Initially the 2005 results showed fairly uniform profiles of dissolved oxygen concentrations in the early part of ice cover. Dissolved oxygen is quickly depleted at the sediment water interface by the bacterial assemblages; once oxygen is depleted the bacteria therefore must shift to utilize less energetically favored acceptors, like nitrate (Bradely *et al*., 2007). Temperature has a significant positive effect on oxygen consumption (Stanzel, 2004). Although temperature and oxygen consumption certainly are correlated, in this case the correlation is not only due to activity/temperature relationship, but also due to transport of both consuming bacteria and temperature increase. As supported by our data, there is a rapid decrease of oxygen in the bottom 50 m, where temperatures are above 2 ºC. Advection from the sediment surface has compounded the effect of increased temperature on oxygen consumption (Stanzel, 2004). Carbon utilization rates have varied due to temperature differences proportional to the temperature range; small variance during winter mixing corresponded to a small temperature range (<1 ºC) (Bradely *et al*., 2007). The surface water cools due to the colder nights and is influenced by wind. After fall overturn, the Pääjärvi was nearly 80% saturated with dissolved oxygen, with 10-13 $mgO_2 \cdot L^{-1}$. In in any freshwater lake close to sea level 100% saturation is 13.1-14.6 $mgO_2 \cdot L^{-1}$ at water temperature range of 4-0 ºC. Generally, dissolved oxygen concentration has been seen to stay constant or only increase slightly during the first few weeks after freeze up (Barica and Mathias 1979, Jackson and Lasenby 1982, Trimbee and Prepas 1988). In concert our data also showed that, oxygen concentration increased after freeze up, though we found that dissolved oxygen changed more suddenly. Our observable oxygen increase happened within 6 days of ice cover instead of weeks later, as found in the other studies, most likely a reflection of freezing rates. However, decrease in oxygen became evident clearly later than the rise in temperature.

Especially in 2007, freeze out alone could not have attributed to the observed 5% increase of dissolved oxygen throughout the entire water column. According to calculations the amount of oxygen released from the estimated ice volume could only be a contributing factor to the observed oxygen increase after freeze up. It seems likely that calibration errors in the determinations was the dominate cause for the increase. Bottom dynamics were also more significant; there was a large decrease in dissolved oxygen within the bottom 10 m within only a week following complete ice cover in 2005, but not in 2007. In the initial days following freezing ambient temperature affects the variability in the rate of freeze out (Meding and Jackson 2001). Congruent with other findings, the amount of oxygen decreases with depth after the final freeze, when there was a decrease in oxygen from 60m downward (O'Sullivan 2005, Barica 1979)**.** Before final freezing the oxygen profile is constant from below 20 m during mid December.

Light levels were too low to facilitate photosynthesis; since the snow cover on Lake Pääjärvi was more than 20 cm, which is sufficient to reduce incoming light by 95-99% (Welch and Kalff 1974). With photosynthesis inhibited, the oxygen dynamics become a function of organic matter decay and respiration (Meding and Jackson 2001). The extent to which these influence the entire lake's oxygen balance is determined by climate and morphometry (Mending and Jackson 2001). In deep lakes with low surface area to volume ratio there is a relatively small influence on oxygen production from the water-ice interface (Meding and Jackson 2001). Our data shows that the rate at which oxygen is consumed is different in different water layers, especially seen beneath 50 m depth in the dissolved oxygen and DIC trends.

4.3 Sediment Surface Currents

As the sediment-surface water of Lake Pääjärvi warms in winter its density increases and thus water should descend. Dissolved solutes further help to increase the water density enhancing the warm water to flow along the slopes of the lake bottom. From the sediment there is a net transfer of electrolytes to the surrounding water and there is progressively higher conductivity with depth. Also in this way bacteria might get re-suspended. On December 8, 18, and 20th, 2005, the last measurement at 75 m, saw a spike in bacteria numbers as compared to just five meters higher in the water column. Mortimer's (1941) results also demonstrated that turbulence associated with the horizontal water flow was the main mechanism of heat and chemical exchange. Indirect evidence on the rate of change of temperature and dissolved oxygen demonstrate that there was water movement horizontally towards the deepest basin of Lake Pääjärvi. Therefore a vertical compensation flow, as proposed earlier by Welch & Bergmann (1985), must have been existing in the central basin of Pääjärvi, too.

4.4 Bacterioplankton Patterns

Throughout the fall overturn and mid winter the distribution of bacteria was highly variable, not only among sampling dates but even within 10 m. Methodological constraints/inexperience probably contributed to the high degree of variation shown rather than from true variation within the system. Compounding factors to the profile variability was the quality of the slides. Some samples had precipitate and high background fluorescence which made within sample sets highly variable. Jones (1974) also suggests caution when using fluorescence techniques due to, not only subjectivity, but also the sensitivity of the counting procedure. Some depths samples were entirely uncountable such as those with unexplained precipitates or those with zero fields. It can be seen that before ice cover, bacteria congregate at 50 m, which may be the only indication of a real trend, but this too might be uncertain. In Pearce (2005) bacterioplankton community structure was found to be constant with depth during times of lake mixing. In contrast, even in early December when both chemical and physical properties are constant throughout the water column, the bacteria densities are highly inconsistent. The situation changed so rapidly within shallow depth ranges, that it is difficult to understand the true driving mechanisms of bacteria densities and to explain the large peak at 50 m. Therefore due to the variability of the results, no conclusions can be drawn nor did bacterioplankton sampling continue in 2007.

4.5 Conclusions

Even after knowing about sediment surface interface dynamics and the density currents Kalff (2003) still simply describes the winter arrangements under ice as “stable”. This is only quantitatively true in relation to the other active seasons, but this study has demonstrated there is more to winter lake dynamics than what is generally recognized.

In the early phase of lake freezing, dissolved oxygen significantly reduces below 50 m as we hypothesized. Before final freezing there are no major oxygen depletion events occurring near the lake bottom. However, 2007 results showed an unexpected increase in dissolved oxygen right after final ice cover. Secondly, our study has reconfirmed the sediment surface density current dynamics. The sweeping of water along the sediment surface by density gradients, resulted in increase oxygen consumption in deep water. Unfortunately, similar could not be said for the bacterial densities.

Our results help to understand large scale and dynamic translocations of water masses in early winter. This can help with interpretation and modeling circulations of water and oxygen consumption in deep lake basins in winter.

Further research into the sediment surface current, specifically looking at depth layers where water may not be flowing directly along the bottom, would be important to gain a more complete knowledge of the under ice currents and its effect on the distribution of nutrients and fauna.

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