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Physical Processes in Natural Waters

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TABLE OF CONTENTS

SESSION 1

1. Observation of a monimolimnetic overturn in the iron-meromictic lake Waldsee

2. Double-diffusive convection in mid-latitude meromictic lakes
   C. von Rohden, J. Ilmberger, B. Boehrer

3. Basic modelling of double diffusive processes in meromictic lakes
   J. Ilmberger and C. von Rohden

4. Physical controls of methane emission
   D.F. McGinnis, S. Sommer, L. Rovelli, P. Linke

5. Gas exchange and deep water renewal in Lake Van (Turkey) estimated by inverse modelling of transient tracers
   H. Kaden, F. Peeters, R. Kipferf, Y. Tomonaga

6. Release and distribution of methane in lakes
   H. Hofmann and F. Peeters

SESSION 2

7. Exchange Flow between Open Water and an Aquatic Canopy
   X. Zhang and H. M. Nepf

8. Simulation of sediment transport in a gap of aquatic vegetation meadow
   G. Ciraolo, C. Costa, G. B. Ferreri, A. Folkard, A. Maltese

9. Hydrodynamics of heterogeneous mussel beds: laboratory flume experiments
   A. Folkard

10. Partial depth exchange flow between canopy and open water
    M. Jamali and S. Marvi

11. Wind and tide induced currents in the Stagnone Lagoon (Sicily)
    G. Ciraolo, M. De Marchis, C. Nasello, E. Napoli

SESSION 3

12. Modeling of the thermal pollution in the lakes-coolers as an example of the Shatura Lakes system (Russia)
    E.I. Debolskaya , E.V. Yakushev, I.S. Kuznetsov

13. The spring thermal bar in a fresh basin
14. The dynamics of internal wave resonance in periodically forced lakes  
   L. Boegman and G.N. Ivey

15. Basin scale internal waves in the bottom boundary layer of an ice-covered lake  
   G. Kirillin, C. Engelhardt, S. Golosov

16. The physical control of the size structure of the phytoplankton community in a Mediterranean reservoir  
   A.B. Hoyer, P.I. León-Díaz, J.M. Blanco, J. Rodríguez, C. Escot, F.J. Rueda

SESSION 4

17. Simulation of the impacts of projected pumped-storage operations on temperature and turbidity in the two affected lakes  
   M. Schmid, D. F. McGinnis, U. Vogel, A. Wüest

18. Past and future lake ice covers of the Berlin-Brandenburg area  
   J. Bernhardt, G. Kirillin, C. Engelhardt, J. Matschullat

19. Fate of groundwater inflows in Lake Þingvallavatn during early spring icebreakup  
   H. Ó. Andradóttir, A. L. Forrest, B. E. Laval

20. Modeling climatological circulation in Lake Michigan  
   D. Beletsky and D. Schwab

21. Summertime Inter-hypolimnetic Thermal Differences in a Small Multi-basin Lake  
   Y. Imam, B. Laval, D. Lim, G. Slater

SESSION 5

22. Turbulence measurements from a Glider  
   Fabian Wolk, Rolf Lueck, Lou St. Laurent

23. In situ measurements of turbulence in fish shoals  
   A. Lorke and W. N. Probst

24. Field observations of breaking high-frequency internal waves  
   M. Preusse, F. Peeters, A. Lorke

25. Hydrodynamics and Salinity of the Future San Francisco-San Joaquin Delta  
   W. E. Fleenor, E. Hanak, J. R. Lund, J. F. Mount

26. Shear-induced bottom boundary layer convection in stratified basins: a modeling study  
   J. Becherer and L. Umlauf

SESSION 6

27. The MAST FV-LMHFE numerical solver of the 2D diffusive shallow waters equations over strongly irregular geomorphologic domain
C. Aricò, C. Nasello, M. Sinagra, T. Tucciarelli

D. J. Schwab, E. J. Anderson, G. A. Lang

29. Temporal evolution and spatial heterogeneity of ecosystem parameters in a subtropical lake
I. Ostrovsky and Y. Z. Yacobi

30. A Comparison of Parameterized, Simulated and Measured Turbulent Mixing in the Gulf of Finland, the Baltic Sea
M. J. Lilover and A. Stips

31. Scenarios of multi-annual simulations of the coupled North Sea – Baltic Sea system
A. Stips, K. Bolding, M. Lilover

POSTER SESSION

32. Flow characteristics in a large amplitude meandering bend
D. Termini

33. Flow velocity and turbulence intensity distribution in a vegetated straight laboratory channel
F. G. Carollo, V. Ferro, D. Termini

34. Use of acoustic-based geophysical methods to detect Posidonia oceanica dead matte
A. Tomasello, F. Luzzu, G. Di Maida, C. Orestano, M. Pirrotta, A. Scannavino, S. Calvo

35. Application of the Princeton Ocean Model to simulate the fate and behaviour of pharmaceuticals in a shallow urban lake
S. Schimmelpfennig, C. Engelhardt, G. Nützmann, G. Kirillin

36. Seagrasses as biological barriers against anthropic input in coastal marine ecosystems
S. Vizzini, C. Tramati, V. Costa, A. Mazzola

37. Optical properties of Sicilian lakes during a Cyanophyceae Planktothrix rubescens algal bloom
V. Pampalone, A. Maltese, G. Ciraolo, G. La Loggia

38. Study of the accuracy of the mean flow from ADCP
M. Gutierrez, J. Planella, E. Roget

39. ADCP velocity profiles analysis in the Castellammare gulf
C. Nasello, G. Ciraolo, G. La Loggia

40. Investigating marine shallow waters dynamics to explore the role of turbidity on ecological responses
S. Di Marca, M. Lo Martire, C. Nasello, G. Ciraolo, G. Sarà

41. Turbidity analysis in Sicilian coastal zones by means of remote sensing images and spectroradiometric measurements
M. Tulone, A. Maltese, G. Ciraolo, G. La Loggia
Fate of groundwater inflow in Lake Thingvallavatn during early spring ice-breakup

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ABSTRACT
Sub-arctic Lake Thingvallavatn is one of Iceland’s largest, deepest and best known lakes. Situated at the rift between the North American and Eurasian tectonic plates, it is part of a world heritage site and a major tourist destination. From a hydrological viewpoint, the lake is unique in that it is predominantly fed by groundwater springs originating from nearby glacier Langjökull. The goal of this study was to establish the near field inflow dynamics of the largest subsurface spring Silfra, contributing approximately 30% of the total inflows to the lake, during early spring ice-breakup. A ten day field study was conducted in February 2009. The groundwater inflows were found to have higher temperature, conductivity, and pH than the receiving lake water. Using temperature as a tracer, the groundwater fate, and mixing regimes were assessed both in open water and under ice, as ice was breaking up and shifting in and out of the study area during the study period. Initial results from moored thermistor chains, CTD profiles, ADV measurements, weather stations and Autonomous Underwater Vehicle (AUV) borne CTD will shed a stronger light on the interaction of river inflows, ice cover and meteorological forcings during winter ice cover and early spring break-up. The use of an AUV platform to collect horizontal CTD profiles characterizes horizontal variability of water properties in open and ice-covered water, something that cannot be obtained using conventional techniques.

KEYWORDS
Groundwater fate; ice-breakup; autonomous underwater vehicle; Thingvallavatn; limnology.

INTRODUCTION
Under-ice mixing dynamics in lakes, and particularly sub-arctic and arctic lakes, are poorly understood. With some notable exceptions (Farmer, 1975; Mironov et al., 2002), this results from a lack of field data being collected during the winter months, especially during the early and late winter when then ice is being initially formed and thawing respectively; times when the water body is experiencing significant mass transport (Petrov et al., 2006) but is logistically difficult to sample. In lake systems that are ice-covered from a portion to the majority of the year, determining these mixing regimes is essential for examining chemical and nutrient transport.

It has long been recognized that different density inflows (e.g. temperature, conductivity or turbidity) will result in varying insertion points into a water body (Wells and Wettlaufer, 2007); however, the influence of ice on such a system has generally not been studied. The largest challenge of studying this problem is the combination of significant horizontal
variability of water properties and thin ice-cover. The horizontal variability cannot be adequately captured by moored instruments and a transect of vertical profiles cannot be safely obtained.

This objective of this study was to examine the fate of the dominant groundwater inflow (negatively buoyant in the winter months) and the ice-edge interactions in the relatively shallow waters using a variety of conventional (moorings and profilers) and non-conventional techniques (UBC-Gavia, an Autonomous Underwater Vehicle). During the course of the study, this system was complicated by intense storm (and associated mixing) events that broke up the ice cover over the 10-day period. This paper will present the initial results during those days with full and partial ice cover and discuss the potential implications for mixing during winter thaw and ice-cover break-up.

METHODS
Site description
Lake Thingvallavatn is one of Iceland’s largest (83 km$^2$) and deepest lakes, with a mean depth of 34 m and maximum depth of 114 m. The lake and its 1000 km$^2$ catchment area are almost entirely situated on the North Atlantic rift zone. From a hydrological standpoint, this lake is unique in that an estimated 90% of its 100 m$^3$/s average discharge originates from underwater springs, composed of surface run-off and glacial melts from nearby Langjökull and Thorisjökull glaciers. This water percolates through basaltic glacial deposits and lavas before entering the northern shore of the lake through a series of underwater cracks (Adalsteinsson et al., 1992; Saemundsson, 1992). The study area in this paper is the 1.5 km$^2$ and 2-10 m deep northwestern bay, into which the largest groundwater spring Silfra, with an estimated 30 m$^3$/s of flow, enters the lake (Vatnaskil, 2000). The temperature of this groundwater is typically 2.8-3.5 °C (Adalsteinsson et al., 1992).

Figure 1. Aerial view of the Silfra groundwater inlet bay (rift approximately delineated by lower box in image) in Lake Thingvallavatn (overview inset) with the overland Oxara river and part of the Silfra inflow (upper box in image) shown at the bay inlet: solid white line - ice edge on Feb. 20, 2009; dashed white line - ice edge Feb. 22, 2009; upper black lines - UBC-Gavia mission tracks on Feb. 20, 2009; lower black lines - UBC-Gavia mission tracks on Feb. 22, 2009; numbered diamonds - temperature moorings; diamond - source monitoring; star - ADV and temperature mooring; and, circle - weather station.
Ice coverage
Ice cover formation over the lake varies from year to year. In the winters between 1951-1990, the lake was ice-covered continuously for 3 months every winter, typically starting in early January and lasting to early April (Rist and Olafsson, 1986). The water temperature during ice formation ranges typically from 0.2 to 1.7 °C, and 2-3°C at ice-breakup (Adalsteinsson et al., 1992). In the past 7 winters, however, the winter ice-cover has been typically intermittent in space and time for 5 weeks (on average), and two years have been completely ice free (Sveinbjornsson, in review).

Field techniques
A comprehensive field monitoring program was undertaken Feb. 18-28, 2009. Air temperature, relative humidity, wind speed and direction were measured by the Icelandic Meteorological office at 10 minute intervals approx. 6 km northeast inland of the study area. For higher precision of local weather wind and solar radiation conditions, an Onset weather station was temporarilily installed at 1.7 m height ~ 10 m from the lake shoreline and within about 600 m leading ice edge on Feb. 20, 2009. Water quality tests were conducted with a handheld Oakton pH-Conductivity-Temperature meter at various locations in groundwater cracks including Silfra, Oxara River and in the lake on Feb. 26-27, 2009.

Water temperatures were continuously monitored at six moored stations along two lateral transects in the bay (see Fig. 1): The first three stations were situated at the ice edge on Feb. 19, 2009 in 4.7-5.1 m deep water. The latter three stations were positioned in a parallel manner in 1.7-2.3 m shallow water. RBR TR-1050 single channel temperature loggers were placed at 0.5-1 m depth intervals from bottom sampling at 1 Hz at each of the six stations. The top loggers were situated approximately at 0.8-1.5 m depth. Vertical conductivity-temperature and depth profiles were taken in open water at various locations in the bay using a Seabird SBE-19plus.

High-resolution CTD measurements were made with a Seabird Electronics SBE-49 mounted on UBC-Gavia, a small Gavia-class AUV owned and operated by the University of British Columbia. As configured for freshwater operations, the vehicle is approximately 2.4 m in length, 0.2 m in diameter, and 55 kg dry weight. For the runs beneath the ice edge, a 3 mm monofilament line (deployed at the vehicle speed of ~ 1.4 m s\(^{-1}\)) was used as a backup AUV retrieval system since the ice was both too thin to safely work on and too thick to break through with the deployment boat. Mission design was for the vehicle to traverse and return on a parallel line (~ 50 m spacing) 300 m underneath the ice edge at a constant depth where a tolerance of 20 cm (i.e. ±10 cm away from the depth set point) was used.

Water speeds were monitored over a 2.5 day period at moored station No. 2 (Fig. 1) at 0.2 m intervals from the bottom using a Nortek Aquadopp ADV. Water speeds were averaged over 10 minutes in order to ensure sufficient signal strength for reliable velocity readings in this extremely clear water. Results from the bottom 3.6 - 4 m are presented in this paper.

RESULTS AND DISCUSSION
Weather and ice coverage
During the first week of February, air temperature dropped below -10 °C accompanied with low winds, at which time the ice cover started to form. In the beginning of the second week of February, the air temperature rose to 0 °C and the average wind rose to 5 m s\(^{-1}\), but in the latter half of the week extremely cold and calm conditions resumed. By Feb. 16, the entire lake was ice covered, with a few small near shore open areas around the Silfra inlet.
From Feb. 13, 2009 throughout the end of the month, air temperatures remained mostly above 0°C and wind speeds fluctuated from 0-15 m s\(^{-1}\) (see Fig. 2). The combination of high winds and warmer air temperatures broke up, pushed and shifted the ice inside the bay during the field study, and by Feb. 25, 2009 the entire lake was ice-free. Thin ice reformed on Feb. 26, 2009 after a short-lived cold spell, but was gone by the next day. A comparison between temporary near lakeshore and long-term inland weather stations show excellent correlation in the meteorological data except for wind speeds that were consistently 2 m s\(^{-1}\) higher at the lake shore, and higher yet when both wind speed data sets are corrected to 10 m elevation.

**Water characteristics**

Near surface water quality sampling clearly demonstrate that groundwater inflows have fundamentally different properties than surface and lake water. As summarized in Table 1, the groundwater is basic with pH exceeding 9.7, whereas surface river water is more neutral with pH of 7.6. The specific conductivity of groundwater was found to be \(\sim 20 \mu\text{S cm}^{-1}\) higher than that of Oxara river. These differences can be explained by the fact that the groundwater interacts with the basaltic and porous volcanic soil on its 50 km long journey from glacier Langjökull to the lake.

In addition, during the cool winter season in which the study was undertaken, groundwater inflow measured around 3.5 °C whereas the surface river water hovered around the freezing point as a result of the soil providing a buffering effect from seasonal meteorological fluctuations. These results conform to the previously published findings of Rist and Olafsson (1986), also summarized by Adalsteinsson et al. (1992).
Table 1. Near-surface water quality results in Lake Thingvallavatn, Feb. 26-27, 2009

<table>
<thead>
<tr>
<th>Locations</th>
<th>pH</th>
<th>Sp. Cond. (µS/cm)</th>
<th>Temperature (°C)</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater cracks</td>
<td>9.8 ± 0.1</td>
<td>89 ± 5</td>
<td>3.5 ± 0.1</td>
<td>5</td>
</tr>
<tr>
<td>River Oxara</td>
<td>7.6 ± 0.1</td>
<td>66 ± 1</td>
<td>0.3 ± 0.2</td>
<td>7</td>
</tr>
<tr>
<td>Lake water</td>
<td>8.7 ± 0.1</td>
<td>80 ± 7</td>
<td>2.0 ± 1.1</td>
<td>6</td>
</tr>
</tbody>
</table>

The water quality sampling provided in Table 1, suggests that specific conductivity and water temperature, may be used as tracers to track the fate of the groundwater inflow in Lake Thingvallavatn. This notion will be explored further in following sections.

**Groundwater plume and mixing at moored stations**

Continuous temperature measurements and vertical CTD profiles at moored stations in the bay shed light onto the fate of the groundwater plume and mixing regimes. The upper panel in Fig. 3 illustrates the near surface and near bottom temperatures measured in the shallow central mooring (No. 5 in Fig. 1). The fact that the two temperatures are almost the same, suggests that the water column is predominantly well mixed in the shallows. But the temperatures across the three shallow stations are not identical suggesting that the groundwater is not equally strong: the highest temperatures are most often measured at the central station (No. 5 in Fig. 1), generally correlated with the North or Northwesterly winds. In Southerly or Northeasterly winds, the warmest temperatures are measured in the western shallow station (No. 4 in Fig. 1; data not shown). This suggests that the wind influences the lateral trajectory of the groundwater plume entering the lake.

![Figure 3](image-url)

**Figure 3.** Vertical and temporal variability in water temperature at central shallow station (No. 5) and central deep station (No. 2). Solid line represents temperatures at 0.5 m distance from bottom, while dashed line near surface temperature (1.2-1.6 m deep).

In contrast, the deeper moored stations in the lake exhibit periods of inverse stratification, followed by periods of fully mixed conditions. As shown on the lower plot on Fig. 3, the bottom water is often 3 °C while the surface water is 1-2 °C. This indicates that in the deeper section of the bay, the groundwater plume at 3°C is heavier than local environment, and hence plunges as it enters the lake. The inverse stratification is particularly strong on days where the majority of the bay is ice covered (see Feb. 19-22, 24, 26 of Fig. 3). Vertical
profiles at the three deep moorings illustrated on Fig. 4 suggest that the groundwater plume is confined within the bottom 0.5-1.7 m of the water column, while the upper 2-3 m are relatively well mixed. Lateral variability is evident between the east, central and west moorings on the windy Feb. 20, 2009.

![Figure 4. Vertical temperature profiles measured at central (solid), east (dashed) and west (dot-dashed) stations on February 20 and 22, 2009.](image)

While the water column at the deeper stations is predominantly stratified, there are 5 distinct periods when the water column becomes vertically mixed. The meteorological conditions during these events (see Figure 2) suggest that the periods of vertical mixing occur: (1) if wind blows at high wind speeds from the North, pushing water and ice out of the bay in cold or cooling air temperatures, indicating that convective mixing may also contribute; or, (2) if wind blows along the greatest fetch (from the South) along the main body of the lake into the bay. Air temperatures are above zero in the latter scenario, suggesting that convective cooling may not have been an important contributor to vertical mixing. This suggests that the mixing regime is not only influenced by ice cover as discussed earlier, but also by meteorological forcings.

**Water Column Velocities**

The acoustic Doppler velocity (ADV) measurements taken at station No. 2 (see Fig. 1) on Feb. 22-24 reveal a multilayer flow. The bottom 1.8 m of the water column moves consistently at 6 cm/s downslope towards Southwest (see Fig. 5). This corresponds to the upper boundary of the 0.5-1.7 m deep groundwater plume observed from temperature measurements (see Fig. 4). The fact that the direction is towards Southwest, as opposed to South where the first crack of Silfra reaches the lake, may suggest that the groundwater inflow is not confined as a localized point source, but rather a continuous line source along the series of cracks located along the entire eastern side of the bay (see Fig. 1). Just above the plunging groundwater inflow at 1.8-2.0 m over the bottom, strong echo was found in the water producing invalidly high flow components along the East-West and vertical axes throughout the entire time period. These unstable readings coincide with the direction of shear turbulence generated by the plunging inflow into the bay, and may be a signal of an interference zone between groundwater inflow and baywater.
As summarized in Table 2, the flow in the mid and upper layers are consistently around 5 cm s\(^{-1}\) moving mostly in the westerly direction. In the upper most layer, the flow is moving in all directions during ice free conditions. In contrast, in the absence of wind during ice cover conditions, the upper layer moving towards northeas t, or in the opposite direction to the bottom groundwater intrusion possibly indicating a return flow.

Table 2. Flow speeds in directions at different depths at moored station No. 2, Feb. 22-24, 2009

| Zone                        | Distance from bottom (m) | Average water speed (cm s\(^{-1}\)) | Prevalent flow direction
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Bottom layer (groundwater)</td>
<td>0.2 – 1.6</td>
<td>6 ± 1</td>
<td>SW</td>
</tr>
<tr>
<td>Interference zone</td>
<td>1.8 – 2.0</td>
<td><strong>Invalid</strong></td>
<td>E (and W)</td>
</tr>
<tr>
<td>Mid layer</td>
<td>2.2 – 2.6</td>
<td>5 ± 1</td>
<td>NW-SW</td>
</tr>
<tr>
<td>Upper layer</td>
<td>2.8 – 3.6</td>
<td>5 ± 1</td>
<td>All</td>
</tr>
</tbody>
</table>

Lastly, it is interesting to consider more closely the time variations in the velocity components along the East and North axes (upper two panels on Fig. 5). Both near bottom (solid line) and upper layer (dashed line) records exhibit oscillations with periods on the order of several hours up to a day during ice free conditions. Once ice covers the mooring on Feb. 24, 2009 these long-term oscillations in the bottom layer appear to be reduced, suggesting that they may be wind driven.
Under ice heterogeneity

During the ice coverage period (Feb. 20 - Feb. 22, 2009), AUV missions were focused on conducting transects under the leading ice edge at a constant depth of 2.0 m in the well-mixed layer (see Fig. 4). As the ice cover was evolving during this time period, these missions were run in different areas (see Fig. 1). On Feb. 20, 2009, two horizontal temperature profiles were collected at the mouth of the bay at the approximate position of the incoming groundwater (upper group of black lines in Fig. 1). Vertical temperature profiles collected in the bay show that the average surface water temperature was approximately 1.5°C when not in the zone of influence of the incoming, warmer groundwater.

![Figure 6. Horizontal temperature profiles at 2 m constant depth (± 10 cm) under the leading ice edge on Feb. 20, 2009 showing transects closer (upper blue) and farther (lower black) from the source water rift (solid and dashed lines represent 50 cm and 10 m horizontal bin average respectively).](image)

As shown in Fig. 6, there are two approximate mixing regimes underneath the ice characterized by relatively constant temperatures from 0 - 50 m (max. deviations of ~ 0.03 °C) and then largely fluctuating temperatures from 50 - 200 m (max. deviations of ~ 0.38 °C). It is proposed that the water is relatively well-mixed in the surface layer above the plunging groundwater plume in the ice-free area as a result of the wind action and that this regime dominates in the near ice edge regime. In the far ice edge regime, the system is subject only to the forcings of the incoming groundwater and not wind. It is conjectured that the observed temperature deviations at 2 m depth under the ice are a localized effect of heterogeneous currents resulting from the groundwater plume flowing along the bottom (at 4-5m) rather than other physical processes such as surface heating. This is because the temperature fluctuations measured here are greater than observed in other ice-covered systems with no groundwater inflows (Forrest et al., 2008). The slight offset between the two transects (~ 0.05 °C in the near ice edge region) is thought to reflect the positioning of the lines to the source water; warmer temperatures representing relative proximity.
This theory is reinforced two days later when further AUV missions were conducted at the ice edge on Feb. 22, 2009. In the interlude, a 20 m s\(^{-1}\) windstorm pushed most of the ice off the bay so the deployments were undertaken much further out into the lake (see lower black lines on Fig. 1). Figure 7 shows a complex mixing regime under the ice which varies laterally in 2D under the ice. Similar to the initial missions of Feb. 20, 2009, the water closest to the ice edge is characterized by low temperature fluctuations. In 50-100 m distance from the ice edge, temperature deviations of about 0.025 °C are observed. Thermal deviations continue to be present until 150-250 m under the ice edge, but with variable strength. The most dominant temperature fluctuations (max. deviations 0.08 °C) are measured in the third transect 200 m under the ice. This is likely the signal of an additional source of groundwater into the lake, because, as seen from Fig. 1, underwater cracks extend into the lake and are therefore likely to have localized effects. In general, however, the thermal deviations are much smaller than previously observed in the shallower inlet region (recall ± 0.38 °C on Feb 20, 2009). This indicates that the water 2 m under ice further into the lake is less heterogeneous. The likely reasons for this difference are related to the geographical positioning of the AUV missions: First, the transects were conducted closer to the main body of the lake, suggesting that water column is more influenced by cold lake water. Second, the water depth was ~ 10 m depth as compared to ~ 4 m at the initial deployment site, such that impacts of bottom flowing groundwater are not as strong near the water surface. Third and last, the AUV missions were conducted further from the source waters on the eastern side, also suggesting less groundwater influence.

**Figure 7.** Horizontal temperature profiles at 2 m constant depth (± 10 cm) under the leading ice edge on Feb. 22, 2009 showing transects closest to the groundwater source (upper blue) successively until furthest from shore (lower red) (solid and dashed lines represent 50 cm and 10 m bins respectively).

Focusing next on temperature trends, Fig. 7 shows that the farther away from the source water located in the eastern part of the bay, the lower the overall temperature became. This is in accordance with the AUV missions conducted on Feb. 20 (Fig. 6). In contrast, the further under the ice that was profiled, the lower the measured temperature. This different trend
could be due to these AUV missions being further into the lake. The surface water in the lake measured a few days later were 1 °C, so the fact that the water measured 200 m under the ice being 1.05-1.10°C is consistent. But this downward temperature trend could also be brought by the large windstorm on the preceding day. As the wind blew from open to ice-covered waters during the windstorm, warmer water (left side on Fig. 7) was likely pushed from shallower section under the leading ice edge, generating a cooler lake water return flow (right side on Fig. 7). Lastly, it is unlikely that the decreasing temperature could be a result from vehicle motion and vertical stratification of the water column, because as Fig. 4 shows that the top 2-2 meters are relatively well mixed. In the worst-case scenario where the vehicle was operating directly along the thermocline, the vertical gradient is only ~ 0.1 °C m⁻¹. In a 20 cm depth tolerance window, the greatest expected variation would be 0.02 °C, which is an order of magnitude less than the overall difference observed from 50 m to 250 m below the ice (e.g. 0.2 °C along the first transect).

CONCLUSIONS
This study collected data in the near-shore region of Lake Thingvallavatn during a dynamic period of late winter ice break-up and explored the fate of the incoming groundwater. Initial datasets (including temperature moorings, vertical profiling, horizontal profiling, and velocity profiling) indicate that the groundwater is a negatively buoyant line source along the underwater cracks situated on the entire eastern side of the bay. This denser groundwater plunges into the lake and travels as a gravity current along the bottom slope. During ice free conditions, the direction of the groundwater plume varies in space and time, depending on local weather conditions. These meandering effects appear to be reduced during ice covered conditions.

The use of UBC-Gavia provides a unique dataset that is unable to be gathered with any other technique. Initial results demonstrate a unique and previously unseen heterogeneity under the ice edge. In the shallow, near delta region, large thermal fluctuations are observed in the horizontal at 2 m below the ice (± 0.38 °C), believed to be an interaction between the groundwater plume and ice cover in the absence of mean wind-shear. In the deeper delta regions, the impacts of cold lake water become more prominent, and lateral heterogeneity is dampened, except at localized spots of groundwater inflows.

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REFERENCES
Adalsteinsson H., Jónasson P.M. & Rist S. (1992), Physical characteristics of Thingvallavatn, Oikos, 64, 121-135.
Rist S. & Ölafsson G. (1986), Ísar Þingvallavats (e. Lake Thingvallavatn ice cover), Náttúrufræðingurinn, 56 (4), 239-258.
Saemundsson, K. (1992), Geology of the Thingvallavatn area, Oikos, 64, 40-68.
Sveinbjornsson E., (in review), Vetrarís á Þingvallavatni – gagnlegur veðurfarsmælir (e. Ice cover on Lake Thingvallavatn – practical weather monitoring), Náttúrufræðingurinn.
Vatnaskil Consulting Engineers (2000), Pingvallavatn. Rennslislíkan. 78 p