Reviewed research article

Caldera Lake Öskjuvatn: Unexpected ice loss in winter and multidecadal property changes

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Abstract — The caldera Lake Öskjuvatn, is at 1050 m elevation in Iceland's interior. It is a deep (217 m) dimictic lake formed after an eruption in 1875. Geothermal activity with gas and liquid inflows, down to 84 m depth, maintains a ~0.13 km^2 permanent ice opening in winter. Remote sensing data revealed a progressively disappearing ice cover in the winter 2012. Physical and chemical conditions were explored in April 2012 (ice-free) and April 2013 (ice-cover). Measurements included CTD profiles and continuous temperature records. Meteorological observations from an automatic station show frequent southwesterly winds in the first quarter of 2012. Near-linear temperature increase with depth in April 2012 indicated effective whole lake vertical mixing. In contrast, the lake was weakly stratified in April 2013 with heat stored below 60 m depth. Moored temperature records in the winters of 2013 and 2014, revealed sustained under ice temperature, and hence a density rise in the upper 60 m, which is half the lake volume. The April 2012 concentrations of geochemical temperature indicators gave no indications of enhanced thermal activity. However, the concentrations of dissolved mineral constituents had decreased since 1975. Chloride and lithium decreased by 30‰ but the geothermal indicators, silicate and sulphate, had decreased less, at ~15‰. The inflowing water, from local precipitation, had not changed. The estimated annual lake-air flux of carbon dioxide, 19000 tons in 2012, had substantially decreased. The unexpected winter ice loss in Lake Öskjuvatn in February-March 2012 was driven by a complex interplay of wind stress, the lake's seasonal deep water heat storage and geothermal activity. Inflow of geothermal gas at 84 m depth off the western shore enhances the vertical transport of heat to the lake's upper layer which, together with frequent southwesterly wind stress 2012, eventually induced vertical instability, whole lake turnover and a complete ice melt.

INTRODUCTION

The caldera Lake Öskjuvatn lies in the remote Dyngjufjöll mountains in Iceland's interior. It is unique in Iceland. The lake is at 1050 m elevation, the area is 11 km^2 and the depth is 217 m (Friðriksson, 2014; Rist, 1975). The East-West diameter is 4.5 km and North-South 3.3 km.

The lake developed after an explosive eruption in 1875 which affected large areas in East Iceland (Sæmundsson and Sigmundsson, 2013). The surrounding landscape is relatively flat north and west of the lake where the caldera floor is 20 to 50 meters above the water level. There is no surface outflow. Above the south shore towers the peak Þorvaldstindur, 1516 m. From 1921 to 1923 four small volcanic eruptions caused lava flows into the lake and in 1926 a small island, Askur, emerged in a southern lake eruption. The water in the lake originates from local precipitation that has undergone some evaporation. The lake is cold but with several warm marginal springs and seeps. Furthermore, thermal activity with gas emissions has been observed at 80 m depth in the western region. This activity generally maintains an opening in the winter ice (Figure 1) (J. Ólafsson, 1980). Summer surface water temperature exceeds 4°C. In August 1975 it reached 6°C. The lake is dimictic, it overturns twice a year. On 21st of July 2014 a rockslide fell to the southern part of the lake and generated a tsunami wave and high run-ups around the lake (Helgason *et al.*, 2019).

In February 2012 remote sensing data unexpectedly revealed progressively disappearing ice cover. This event generated scientific and societal questions relating to possible enhanced geothermal activity and signs of eminent volcanism. The ice-free lake was explored in April 2012 and again the following year when it was covered with ice in April, to collect data that could explain this anomaly.

OBSERVATIONS AND METHODS

Records of ice cover on Lake Öskjuvatn come mostly from remote sensing observations, since the site is distant and inaccessible in the winter months. Satellite images in sufficient spatial, spectral and temporal resolution to monitor the lake have been available for over 20 years (Jónsdóttir *et al.*, 2014).

There is no recording weather station at Lake Öskjuvatn. As a proxy for the weather conditions at the lake in winter we use, without adjustments, hourly data from the nearest automatic weather station, Upptyppingar. The station is operated by the Icelandic Meteorological Office and is located 25 km east of the lake at 563 m elevation (Figure 2).

Two expeditions were undertaken, by permission from the Vatnajökull National Park, to study the physical and chemical conditions in the lake. Sampling was conducted on the ice-free lake on 14th and 15th of April 2012 at 24 stations using an inflatable boat equipped with a hand winch and a meter wheel. Weather conditions influenced the station pattern. On 3rd and 4th of April 2013 a snow scooter was used, a sledge and an ice-drill to sample through the ice at 20 stations on two cross sections (Figure 2).

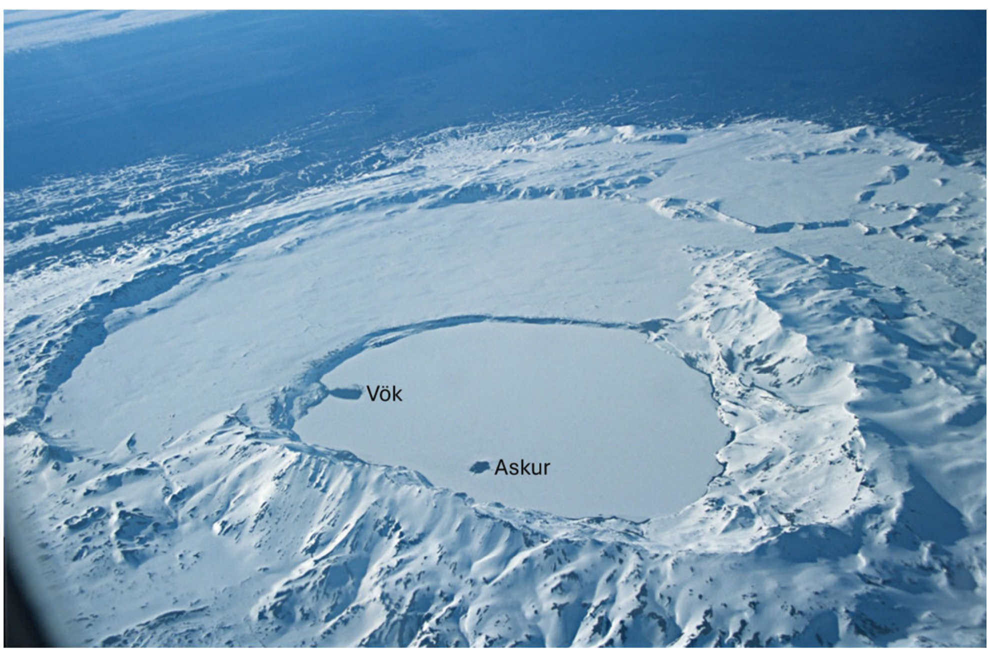

Figure 1: The Askja caldera and ice-covered Lake Öskjuvatn, 23rd of May 2003. The dark area off the west shore is the open water (Icelandic: vök) maintained by lake bottom geothermal emissions. The other dark area is the island, Askur. – *Askja og Öskjuvatn ísi lagt 23. maí 2003. Dökku svæðin tvö eru annars vegar vökin vegna jarðhitavirkni á botni vatnsins og hins vegar eyjan Askur Photo:/Ljósm: Oddur Sigurðsson.*

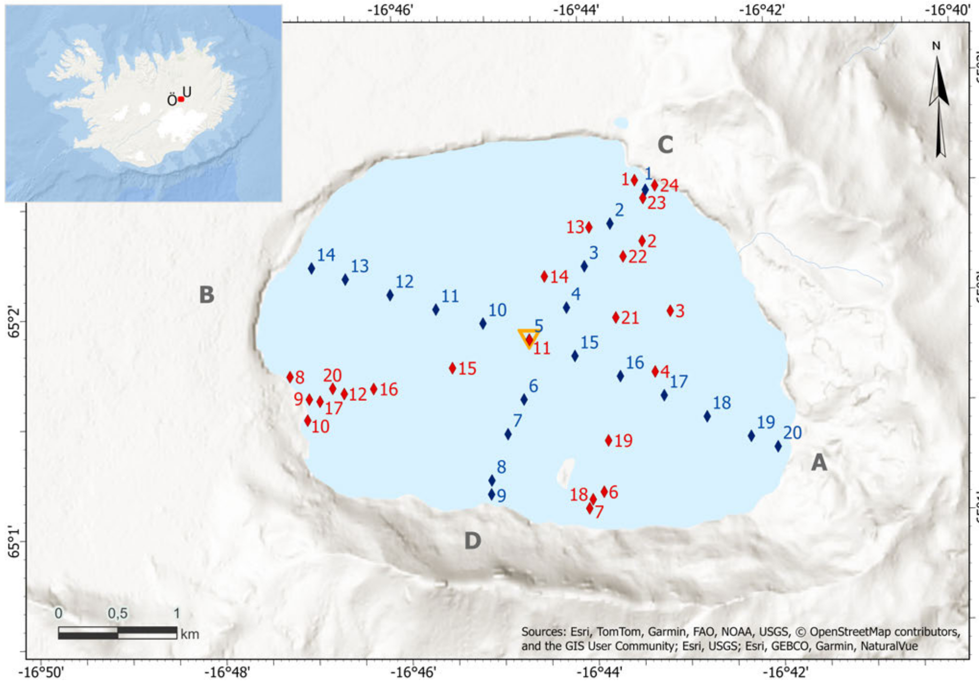

Figure 2. CTD stations on Lake Öskjuvatn in April 2012 (red) and in April 2013 (blue). The yellow triangle marks the mooring location from 2012 to 2014. The insert figure of Iceland illustrates the location of Lake Öskjuvatn and the meteorological station Upptyppingar. The labels A-D indicate the sections in Figures 7 to 10. – *Mælistöðvar í Öskjuvatni í apríl 2012 (rauð tákn) og apríl 2013 (blá tákn). Guli þríhyrningurinn sýnir stað botnföstu lagnarinnar. Innsetta Íslandskortið sýnir staðsetningu Öskjuvatns og veðurstöðina á Upptyppingum. A-D sýna legu sniðanna í myndum 7–10.*

A Sea-Bird Sea Cat CTD (Conductivity Temperature Depth) instrument with temperature precision <0.01°C and salinity (conductivity) ±0.001 was used to collect continuous profiles from surface to bottom. A correction is applied when using the CTD instrument in low salinity fresh water with ionic composition different from sea water (Chen and Millero, 1986). Density is calculated using the equation of state. The temperature of maximum density for salinity S=0.45, typical for Lake Öskjuvatn 2012 and 2013, is 3.88°C. Niskin 3L bottles were used for discrete water sampling. Graphical presentation of the CTD data is by Ocean Data View software (Schlitzer, 2022).

From April 2012 to July 2014, a moored string of Star-Oddi recording temperature sensors, recording at 10-minute intervals, was anchored at a site where the depth is 180 m and 1600 m from the geothermal site with a stream of rising gas bubbles (Figure 2). The sensors have a temperature resolution of 0.032°C and a precision better than ±0.1°C. The rockslide/tsunami event in July 2014 caused the mooring line to break. The surface float was reported adrift the following days. The mooring was recovered at the northern coast 12 days after the event. It included the float, the uppermost 65 meters of string and recorders from 5 depth levels, 5 m to 60 m. The recorded data covers the period from 16th of April 2012 to 21st of July 2014.

Chemistry data was collected in 1975 as described in Ólafsson (1980). In 2012 and 2013 nutrients, dissolved oxygen and carbonate chemistry were analyzed at the Marine Research Institute and major ions with liquid chromatography at the University of Iceland using standard methods. In 2012 and 2013 pCO_2 was measured using a field equilibration equipment comprising a LiCOR 801A infrared pCO_2 analyzer and oxygen samples were collected for Winkler titrations.

Water stable isotope measurements were carried out at the Science Institute, University of Iceland. For the 1975 data only Deuterium isotopes were measured using a modified Nier mass spectrometer (Friedman, 1953). The accuracy of the measurement was ±1‰. The 2012 samples were measured both for oxygen and deuterium isotopes on a continuous Delta V Advantage mass-spectrometer, with a Gas bench device. The accuracy of the measurements is better than 0.05‰ and 1‰ for oxygen and deuterium, respectively.

RESULTS AND DISCUSSIONS

Ice cover loss in 2012 and ice thickness 2013

The onset of ice cover is generally in December, and the ice clears off in late June the following year. Thermal activity with gas rising from the lake floor in the western region sustains a permanent opening in the ice. Ice-free shorelines with thermal springs and seeps also stay open.

Continuous ice cover was remotely observed on the lake on December 3rd, 2011, and the western opening was approximately 0.13 km^2 on February 3rd, 2012. It had expanded to 1.17 km^2 on February 25th, a process which continued until the lake was practically ice free on 27th of March. An accelerated melting occurred between March 9th and March 12th (Figure 3). This coincided with a SW wind event with mean air temperature just under 0°C (Figure 5). The melting rate slowed down after the wind event but stayed nevertheless very high until the lake was completely without ice on April 5th. Lake Öskjuvatn did not refreeze in the spring of 2012.

Lake ice formed again on 14th of December 2012, and no unusual progressive expansion of the opening, vök, was observed that winter. In April 2013, lake properties at 20 stations were recorded by drilling through ice which ranged from 75 cm to 110 cm in thickness. The thinner ice was generally in the offshore parts of the lake (Figure 4). The large range in ice thickness, 35 cm, indicates regional variations in processes affecting the heat flux through the ice (Leppäranta, 2015).

Meteorological conditions

The components most important for evaluating air-water heat flux in the dark winter are air temperature, wind direction and wind strength.

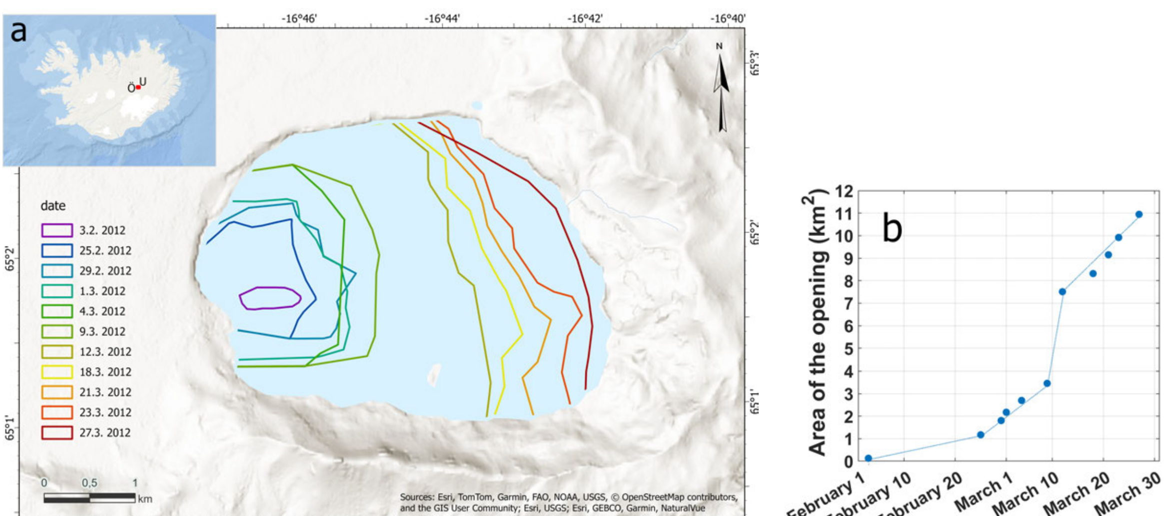

Figure 3. The progression of ice melting in the winter 2012. a) The dated outlines of the opening in the ice from February 3rd to March 27th and b) the area (in km^2) of the opening in the ice as a function of time. – *Ferli ísbráðnunarinnar veturinn 2012. a) Útlínur vakarinnar frá 3. febrúar til 27. mars og b) flatarmál (í km^2) vakarinnar sem fall af tíma.*

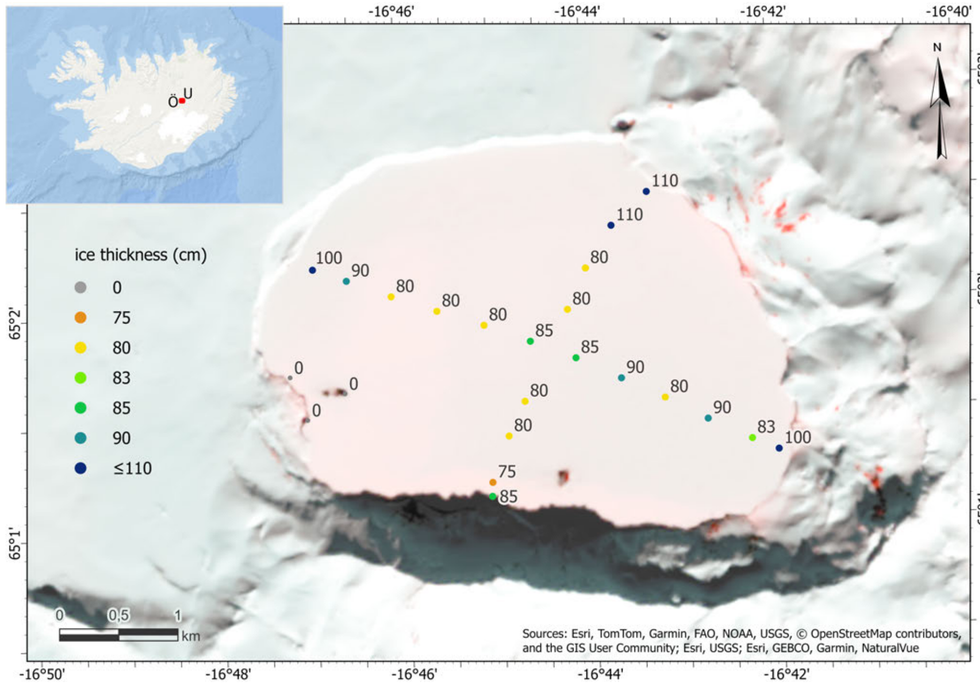

Figure 4. Lake Öskjuvatn ice thickness (cm) measured on 3rd and 4th April 2013. The location of the permanent opening is indicated by 0. – *Ísþykkt (cm) á Öskjuvatni 3. og 4. apríl 2013. Vökin er sýnd með 0.*

As an estimate of the wind effect on the open lake surface we calculate wind stress, τ, which is based on the squared wind speed (Large and Pond, 1981):

$$\tau = \rho C_D W^2 \text{ for } W \geq 4 \text{ ms}^{-1}$$

where ρ= density of air, C_D=the drag coefficient and W=wind speed in ms^{-1}. Examination of the data from Upptyppingar for the months January to April 2011–2015 reveals frequent winds from the south and southwest and strong τ_{SW} episodes in 2012. There were 94 days of τ_{SW} in 2012 but 43 in 2013. Furthermore, there were no northerly wind days with W≥4 ms^{-1} during these months in 2012. Taking into consideration the position of the ice opening in the lake and the surrounding landscape, the focus is here on the temperature and wind stress from the SW quarter.

Daily means of the air temperature and the SW wind stress over the months November to April 2012 and 2013 are presented in Figure 5.

There are important differences in the winter weather of 2011–2012 and 2012–2013 (Figure 5). Both before the onset of ice cover and later when the wind stress worked only on the open water areas. Ice cover developed on the lake on 3rd of December 2011 under calm and cold conditions which followed a period of rather warm November days (Figure 5). The cooling of the lake water from the temperature of maximum density to the freezing point of the surface water under rather low turbulence conditions, may have left the deep water of the lake relatively warm, even >3°C. In 2012, on the contrary, the weather was very cold in November, but the lake froze later, on 14th of December (Figure 5). Still, the observed deep-water temperature in April 2013 approached 3°C at 200 m depth (Figure 6). The wind conditions in January to April 2012 were unusual, with frequent days of SW wind stress and a strong event in March when the ICE melting accelerated to 1.3 km^2d^{-1} (Figures 3 and

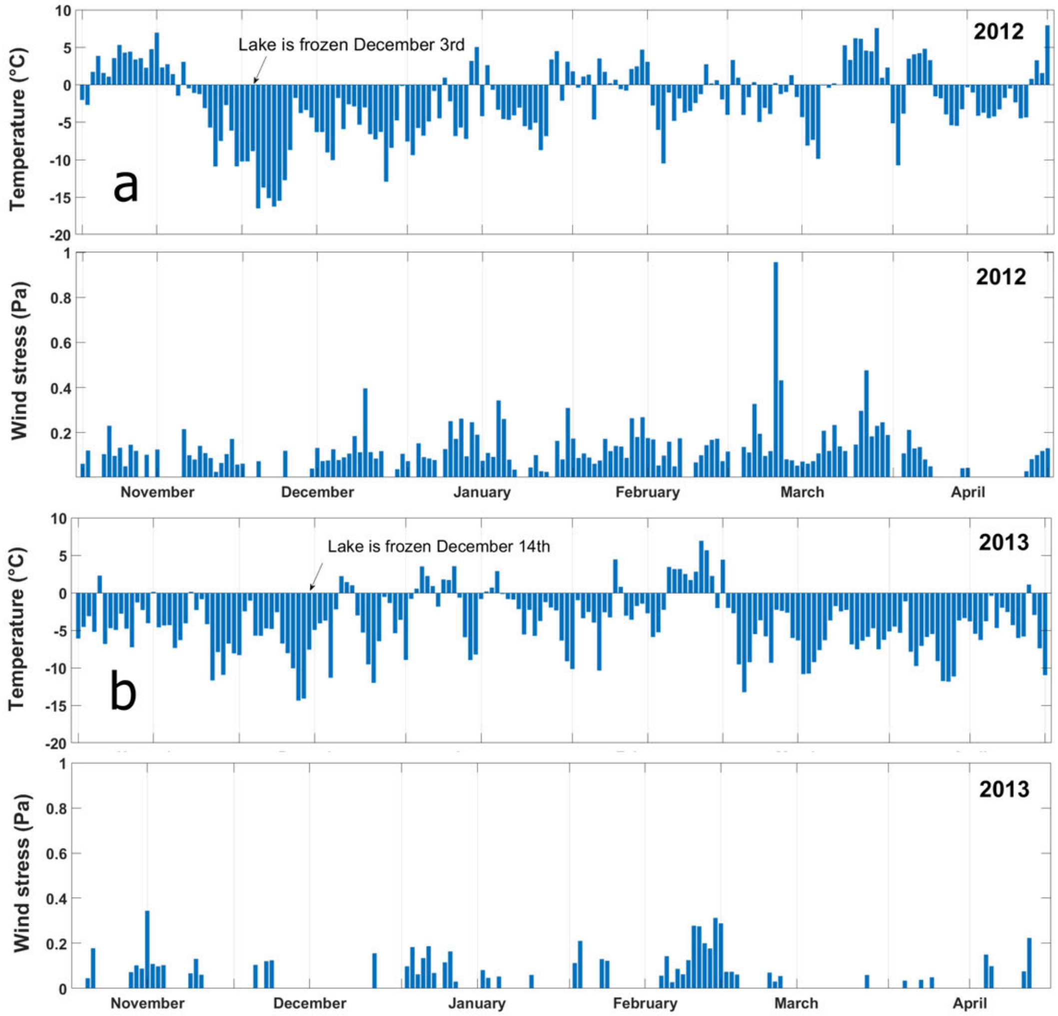

Figure 5. Air temperature (°C) and wind stress (Pa) from the SW quarter for November to April 2012 (top panels) and 2013 (lower panels) from observations at the Upptyppingar weather station. Dates of ice cover are inserted in the temperature panel. – *Lofthiti (°C) og vindspenna (Pa) frá SV fjórðungnum samkvæmt veðurstöðinni á Upptyppingum, frá nóvember til apríl 2012 (efri myndirnar) og 2013 (neðri myndirnar). Tímar ísmyndunar eru skráðir inn á hitamyndirnar.*

5). Southwest wind stress Was much less frequent the same months 2013.

Temperature and density distributions in April 2012 and 2013

The data obtained with the high precision CTD instrument reveals the whole lake differences between the ice-free lake in April 2012 and ice-covered in April 2013 (Figure 6).

The vertical temperature distribution April 2012 shows several stations with increased near bottom temperature. These stations are all in a region with geothermal water and gas emissions. The data also indicates associated slightly lower salinity. A cross section (Figure 7) shows slight horizontal density variations caused by temperature, an indication of recent deep-water upwelling in the western part of the lake.

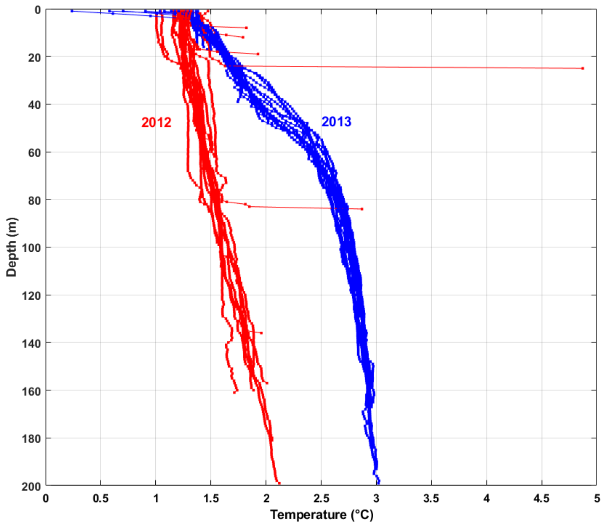

Figure 6. All CTD temperature profiles in 2012 (in red), and in 2013 (in blue). The near bottom temperature increases in 2012 are at stations in the geothermal region off the west coast. – *CTD hitaferlar frá 2012 (rautt) og 2013 (blátt). Hitaaukning næst botni 2012 er á stöðvum á jarðhitasvæðinu út af vesturströndinni.*

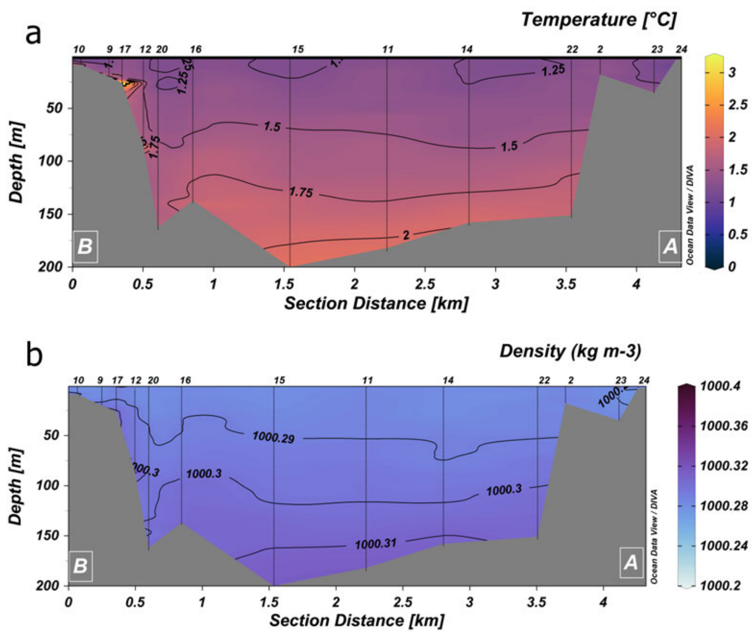

Figure 7. Temperature and density distribution in section B to A in the ice-free Lake Öskjuvatn in April 2012. Effects of the geothermal site off the west shore are both on temperature and density distribution which indicates upwelling. The upper x-axis shows the station numbers in the section. – *Hita- og eðlismassadreifing í íslausu Öskjuvatni í apríl 2012. Áhrif jarðhitasvæðisins út af vesturströnd vatnsins á bæði hita- og eðlismassadreifingu koma fram og benda til uppstreymis. Efri x-ásinn sýnir stöðvanúmerin á sniðinu.*

In 2012 we examined the region of geothermal emanations from a boat whereas this open water was avoided in 2013. Six stations in 2012 show near bottom temperatures anomalies at depths ranging from 8 m to 136 m. They were number 8, 9, 10, 12, 16 and 17 (Figures 2 and 7) where temperature was 4.9°C (Figure 6) at the bottom. The rising gas plume was most intense at station 12 where the 84 m bottom temperature reached 2.8°C. There are no significant near-bottom temperature anomalies recorded in the ice-covered lake in 2013 (Figure 2). The surface to bottom profiles in 2012 all show a near linear temperature increase with depth and the temperature reaches 2.2°C at 200 m (Figure 6). The exceptions are the sites with geothermal activity at the bottom. This suggests effective whole lake vertical mixing such as is generally observed when lakes overturn and mix at ~4°C, the temperature of maximum density.

The lake floor geothermal area in the west region certainly increases the near bottom temperature (Figure 7) and the large volume of geothermal gas emanations from 84 m depth enhances an upward flux of heat and water. This vertical flux maintains an ice-free opening with a variable area of about 0.13 km^2. A second fraction of the heat input escapes from the surface to the atmosphere. The surface temperature there was only 1-1.5 °C in April 2012. A third and largest fraction of the geothermal heat mixes into and remains in the upward mixed water.

The vertical temperature distribution in April 2013 showed the ice-covered lake in two main layers, separated at 60–70 m depth (Figure 6). There were additionally temperature and salinity variations in the uppermost approximately 5 m of the water column.

Comparing the heat content under a 1 m^2 water column at the 200 m deep station in 2012 and in 2013 shows a difference of 750×10^8 J, which is more than twice the heat required to melt 1 m^3 of ice, 300×10^8 J (Figure 6). However, this heat source is mostly below 60 m depth and out of contact with the ice in 2013. The heat stored deep in Lake Öskjuvatn when it froze in December 2011 has evidently been mixed upward and into the surface layers by the whole lake turnover in February-March 2012.

The full depth CTD sections of temperature and density in April 2013 show a deep layer, below 60 m, with gradual temperature and density increases with depth (Figures 6 and 8). Greater temperature and density variability is in the 25 to 60 m depth interval and even greater in the thin water layer below the ice (Figures 9 and 10).

Both in the A-B and C-D surface to 25 m depth sections are variations in temperature and salinity, hence density, showing boluses (eddies) with lower density water due to lower temperature and lower salinity. Warmer water rises towards the ice between the eddies. The observed ranges in temperature, salinity and density are modest but clearly revealed by the CTD in-

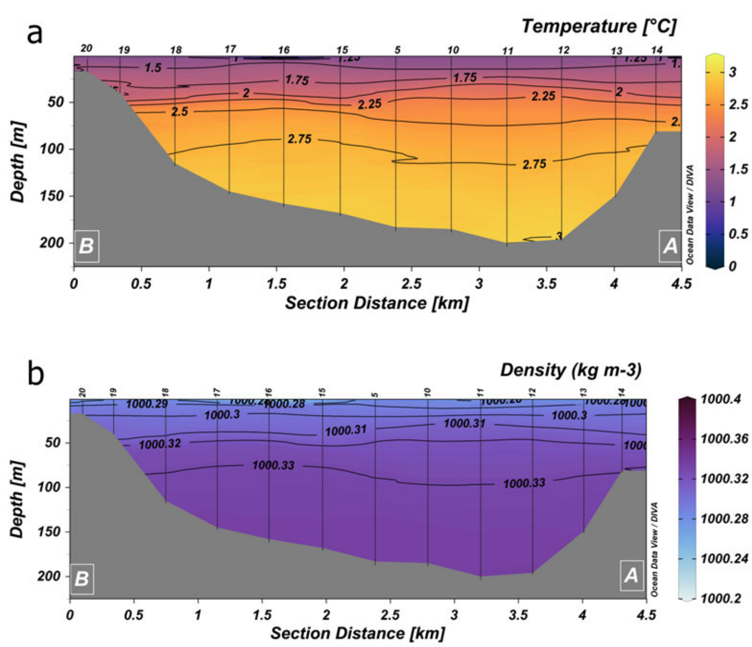

Figure 8. Temperature and density distribution in section B to A in the ice-covered Lake Öskjuvatn in April 2013. The upper x-axis shows the station numbers in the section. – *Hita- og eðlismassadreifing íá A til B sniði í ísilögðu Öskjuvatni í apríl 2013. Efri x-ásinn sýnir stöðvanúmer á sniðinu.*

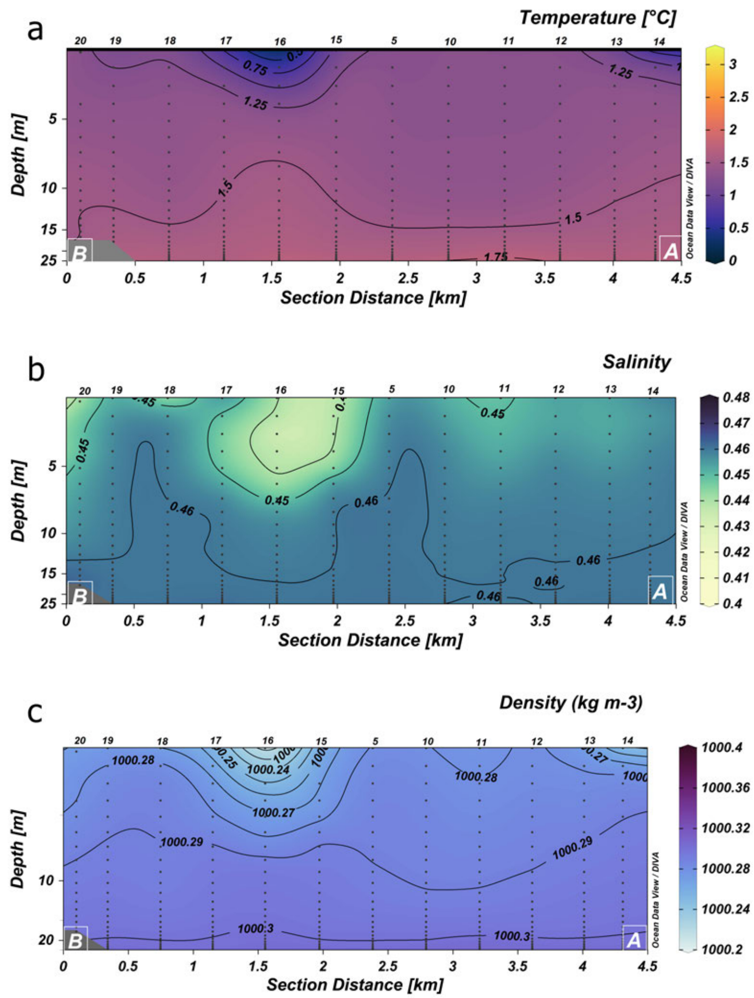

Figure 9. Temperature, salinity and density distribution in the uppermost 25 m of section B-A in April 2013. The depth scale on the Y-axis is logarithmic. The upper x-axis shows the station numbers in the section. – *Hita- seltu- og eðlismassadreifing í efstu 25 metrum vatnssúlunnar á sniði frá B til A í apríl 2013. Dýptarásinn er með lograkvarða. Efri x-ásinn sýnir stöðvanúmer á sniðinu.*

strument. The presence of eddies and the density distribution bear evidence of non-stationary conditions. The eddy at station 16 on the A-B section (Figure 9) is about 500 m in diameter and 5 m deep. On section C-D the large eddy is primarily the result of low salinity (Figure 10). The variations in the depth of the density surfaces, rising or deepening, describe upwelling and downwelling of water. Upwelling brings warmer water upwards, towards the ice and downwelling pumps lower salinity water down. The eddies and Ekman pumping are consequences of winds forcing the open region water under the ice edge. The SW wind stress in the first months of 2012 was much more frequent and intense than in 2013.

Annual temperature variations in the upper part of the lake

The moored temperature records extend over two annual cycles from April 2012 to July 2014 and cover the uppermost 60 meters of the lake. The records demonstrate seasonal changes with both solar and geothermal energy inputs (Figure 11).

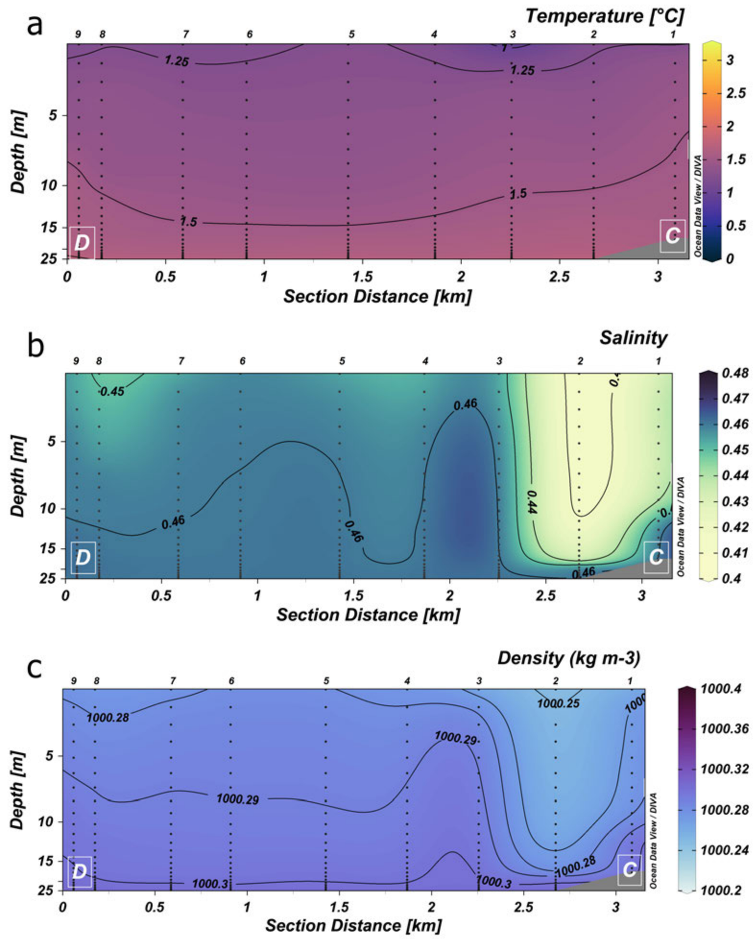

Figure 10. Temperature, salinity and density distribution in the uppermost 25 m of section D-C in April 2013. The depth scale on the Y-axis is logarithmic. The upper x-axis shows the station numbers in the section. – *Hitaseltu- og eðlismassadreifing í efstu 25 metrum vatnssúlunnar á sniði frá D til C í apríl 2013. Dýptarásinn er með lograkvarða. Efri x-ásinn sýnir stöðvanúmer á sniðinu.*

Lake Öskjuvatn did not refreeze in the spring of 2012. Springtime solar radiation reached the ice-free lake and summer heating began in May, approximately a month earlier than in 2013 and 2014 (Figure 11). The spring and summer temperature rising towards 4°C extends uniformly through the observed 60 m water column. A weak stratification develops after 4°C is reached and the maximum summer temperature is in August. In 2012 it was about one degree higher than in 2013 or 5.6 °C vs. 4.7°C. The lake froze on 14th December 2012, which was 63 days after the temperature of maximum density was recorded at the mooring. In 2013 the lake froze on 20th December after an equivalent cooling period of 95 days. The long cooling time 2013 indicates stronger vertical mixing and heat loss to the atmosphere prior to freezing and consequently smaller heat storage in the lake's deep water.

From the time the lake becomes isolated from the atmosphere by the ice cover, the temperature recorders show increases at all mooring depths, 5 m to 60 m (Figure 11). The mean temperature increases in this layer, from 1st of January to 1st of June, was 0.974 °C in 2013, or 0.00645 °C d^{-1}, and 0.810 °C in 2014, or 0.00536 °C d^{-1}. The temperature increase causes a density increase which gradually reduces the stability between this layer and the deep lake water. This phenomenon is evident from the data but since the lower part of the mooring was lost a numerical comparison

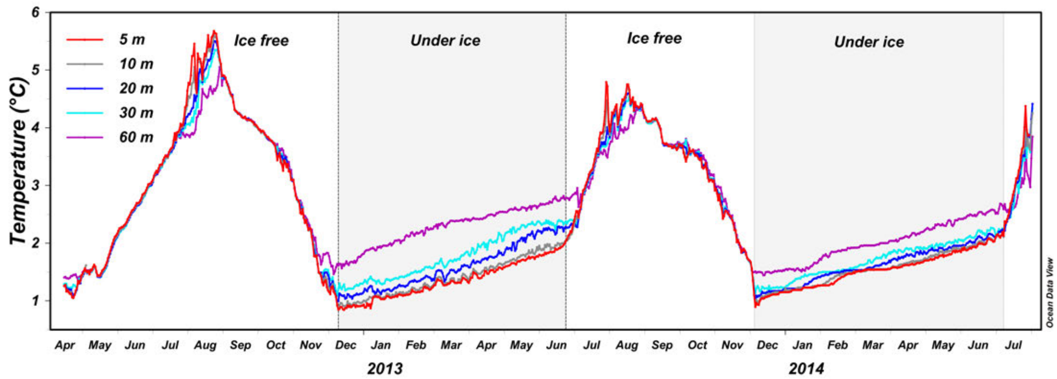

Figure 11. Daily mean temperatures recorded in the upper layer of Lake Öskjuvatn from April 2012 to July 2014 and periods of ice cover. – *Dagsmeðaltöl vatnshita frá efri hluta Öskjuvatns frá apríl 2012 til júlí 2014 og tímabil ísþekju á vatninu.*

is made with the CTD temperature at 100 m depth on station 5 which was 2.74 °C on 4th of April 2013. The mooring temperature from 30 m depth when ice cover formed on 14th December 2012 was 1.25 °C and had risen to 2.38 °C on 1st of June 2013. The temperature differences between these two depths decreased because of warming, from 1.49°C to 0.36°C respectively. The stratification and stability were thus strongly reduced but not sufficiently to induce a turnover.

Both CTD sections from April 2013 show only small horizontal temperature variations in the 5 to 60 m depth range (Figures 9 and 10). This is indicative of a whole lake area temperature increase such as are recorded by the mooring.

The lake hypsographic data (Rist, 1975), show that the volume of the surface to 60 m water layer to be 600 GL or half the lake volume. Hence the total thermal power inputs 1st January to 1st June are 187 mW and 156 MW, in 2013 and 2014 respectively. This large power input may be compared with the Grímsvötn volcanic system with estimated 450 MW during post-eruption conditions (Reynolds *et al.*, 2018).

As the geothermal area on the western lake floor is relatively small calls for attention to a potential source of heat supporting the steady upper layer warming. The volcanic gas rising from 82 m draws continuously water from this source upward. The temperature of the deep water of the lake after ice-cover forms is, however, variable between years as the 60 m temperature records 2013 and 2014 demonstrate.

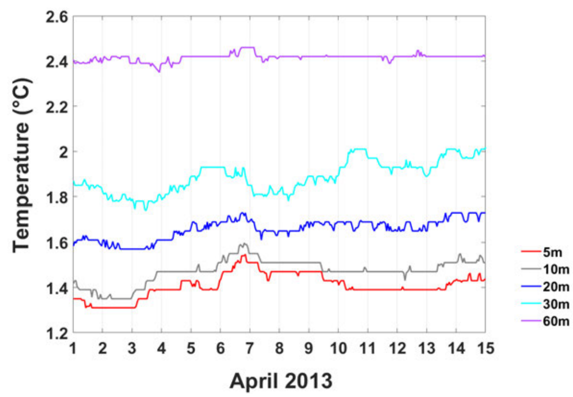

Figure 12. Hourly mean temperatures recorded from 1st to 14th of April 2013. A peak in the 30m temperature on 5th April is recorded the next day at 20 m, 10 m and 5 m depths. Another 30 m temperature peak on 10th April is not transmitted upward. – *Klukkustundarmeðaltöl vatnshita frá 1.–14. apríl 2013. Hækkun hitastigs á 30 m dýpi þann 5. apríl mælist næsta dag á 20 m, 10 m og 5 m dýpi. Annað hámark í hitastigi þann 10. apríl færist ekki ofar.*

Closer examination of the hourly mean temperatures at the mooring in April 2013 shows variations with time of up to 0.2 °C (Figure 12). These temperature, and consequently density, variations may be explained by the movement of small eddies such as were observed in the surface layer sections in 2013 (Figures 9 and 10). The variations at 30 m appear ahead of shallower depths. Eddies are known in large lakes but have not been described under lake ice cover (Ralph, 2002). Mesoscale eddies and Ekman pumping are postulated to be important for the upward flux of heat towards sea ice cover under Antarctic conditions (Auger *et al.*, 2023; Rieck *et al.*, 2025). In Lake Öskjuvatn the small eddies may play a similar role in upward heat flux which maintains the near ice cover temperature of ~ 1°C and the observed 30 cm variations in ice thickness.

Caldera lake chemistry

Dissolved inorganic constituents

The concentrations of dissolved inorganic components in Lake Öskjuvatn are known to be strongly influenced by geothermal activity and higher than in other Icelandic lakes (Jón Ólafsson, 1980).

Dissolved mineral constituents in April 2012 show quite uniform concentrations with depth in agreement with 1975 conditions. However, comparison with the 1975 data reveals a general, but not uniform, concentration decrease for ten constituents (Table 1). This reflects dilution with lower concentration precipitation and inflowing drainage waters. Dissolved chloride and lithium concentrations decreased most over the 37 years, 30%. Geothermal chloride input is low in Iceland and the marine influence in rainwater is also low in interior highlands (Gislason and Eugster, 1987). There are clear signs of geothermal inflows of dissolved silica and sulphate to the lake as these constituents have been least diluted with time, 16% and 14% respectively.

Despite the dilution with time reflected in the chemical composition of Lake Öskjuvatn, no change is observed in the lake water Deuterium isotopic composition (Table 1). This demonstrates that the dilution water, local precipitation, is an unchanged source of inflowing water (Árnason, 1976; Sveinbjörnsdóttir *et al.*, 2015).

The decreased concentrations are an effect of inflowing lower concentration waters and subterranean outflow from the lake. As Lake Öskjuvatn is well mixed by the wind and annual thermal circulation, and taking any long-term volume fluctuations as insignificant, the 1975 and 2012 chloride data can be used to assess the exponential chloride dilution coefficient and describe the time related concentration change by:

$C=C_0 * e^{-0.009484*Yr}$ where Yr is the calendar year.

Assuming also that if the volcanic influence on the lake reached its height during the 1920s eruption episode, the equation indicates that by 2012 the chloride and lithium concentrations had been halved.

Dissolved gases, carbon dioxide and oxygen

Contrary to the uniform distribution of dissolved mineral constituents in Lake Öskjuvatn, the concentrations of the dissolved gases oxygen and carbon dioxide, change with depth (Figure 13a). Dissolved oxygen is 78% saturated in the under-ice water in 2013 and decreases with increasing depth without becoming depleted in the deepest part where the saturation state is 55%. This indicates deep input to the lake of reducing compounds. Carbon dioxide (CO_2) is high in the deep lake and lowest in the surface layer (Figure 13b). The three station profiles show higher oxygen at station 11 than at station 17 in the 50–100 m depth range but for the partial pressure of CO_2 (pCO_2) the relative concentration strengths are in the opposite order. These two components are reactive, and the concentration pattern may reflect their sources and sinks within the lake. The mean under-ice partial pressure of carbon dioxide, pCO_2=2216 ppm, is much higher than in the atmosphere. When open to the atmosphere the lake is thus a site for CO_2 outflux from the lake and oxygen influx from the atmosphere.

Table 1. Mean concentrations of dissolved constituents in Lake Öskjuvatn 1975 and 2012 and their decrease over 37 years. – *Meðalstyrkur uppleystra efna í Öskjuvatni 1975 og 2012 og hlutfallsleg (%) lækkun á 37 árum.*

	TIC ppm	Cl ppm	SO_4 ppm	F ppm	Na ppm	K ppm	Ca ppm	Mg ppm	SiO_4 ppm	Li ppb	δD ‰
1975	33.82	22.3	450	0.90	145	8.60	80.0	23.6	110	38.1	-88.3
2012	14.46	15.7	387	0.66	111	6.35	63.7	17.3	91.6	26.4	-88.5
Concentration decrease %	57	30	14	26	23	26	20	27	16	30	No change

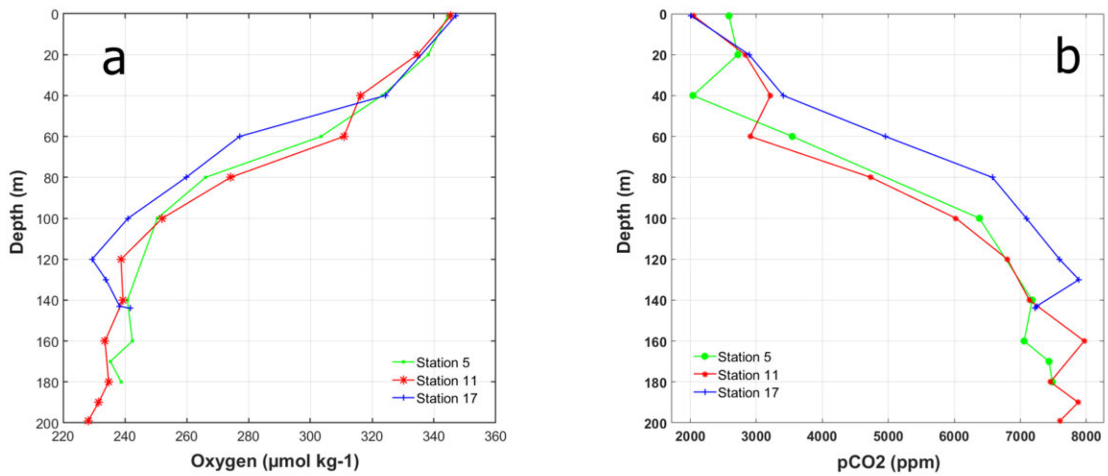

Figure 13. Profiles of dissolved a) oxygen and b) carbon dioxide at three stations in ice-covered Lake Öskjuvatn in April 2013. – *Dýptarferlar af a) súrefni (µmól kg^{-1}) og b) koldíoxíði (ppm) frá þremur stöðvum í ísilögðu Öskjuvatni í apríl 2013.*

The CO_2 outflux from open Lake Öskjuvatn in August 1975 and April 2012 can be estimated. For this we use the difference between lake surface pCO_2 and atmospheric pCO_2 and proxy wind data from the Upptyppingar weather station (Figure 1) (Wanninkhof, 2014). From pH and alkalinity observations in August 1975 we calculate the surface pCO_2 (Pierrot *et al.*, 2006). The 1975 observations of the lake carbonate system showed similar vertical pCO_2 trends but four times higher surface pCO_2 than in 2012.

The estimated annual CO_2 flux from Lake Öskjuvatn to the atmosphere was thus 77000 tons in 1975 and 19000 tons in 2012. This indicates substantially decreased intensity in the CO_2 influx to the lake and to outgassing over the time span of 37 years. The lake water total dissolved inorganic carbon concentrations (TIC) measured in 2012, 14.5 mg kg^{-1}, are similarly lower than was observed 1975, 33.8 mg kg^{-1}. The lake overturning twice a year results in a carbon dioxide outflux to the atmosphere and prevents buildup of dangerously high CO_2 concentrations in the lake.

DISCUSSION

The total loss of ice from Lake Öskjuvatn in midwinter 2012 progressed as a seven-week expansion of a persistent opening (vök) which is generally ~0.13 km^2.

The opening is over a region with geothermal activity on the lake floor observed with variable intensity at 8 stations (Figure 2). The activity extends from near shore and out to 137 m depth. A voluminous stream of volcanic gas rises from 84 m depth and maintains continuous mixing and upward flux of deep water. The base temperature and volume of the inflowing geothermal gas and water is unknown, but it mixes rapidly into the overlying water column.

The April 2012 survey returned two other significant results. Firstly, the lake temperature variations with depth showed an unstratified 1°C–2°C water body indicating a recent lake turnover by which the upper layer of the lake had mixed into the deep. The heat stored in the deep layer had been transferred upward. For this to occur the density of the upper waters must have increased sufficiently through heating to make the whole water column unstable (Figure 14). Secondly, the April 2012 survey gave no signs of recent volcanic influence or enhanced hydrothermal activity on the lake water chemistry. Conversely, there were clear signs of decreased input of geothermal components to the lake from 1975 to 2012. The 2013 survey of the ice-covered and stratified lake showed that the heat stored at >60m depth was more than sufficient to melt 1 m thick ice, but density structure prevented

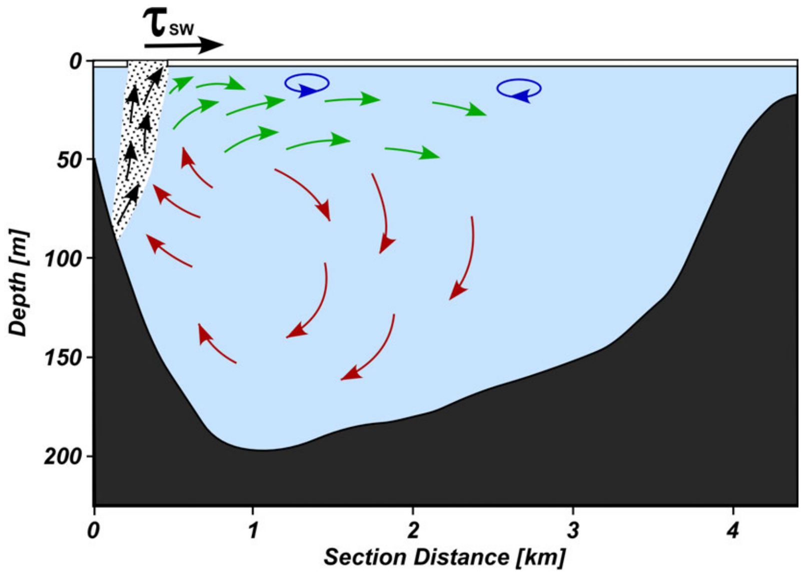

Figure 14. Schematic presentation of Lake Öskjuvatn circulation which leads to overturning and ice melting. Black arrows: Upwelling driven by volcanic gas and geothermal inflow. It maintains an opening in the ice cover. Green arrows: Advection under the ice cover towards lake interior enhanced by SW wind stress, τ_{SW}. Red arrows: Deep water overturning initiated by green layer instability through warming and density increase. Blue circles: A shallow cyclonic eddy with upwelling and an anticyclonic eddy with downwelling through Ekman pumping. – *Skýringarmynd af hringrás vatns í Öskjuvatni sem leiðir til uppblöndunnar og ísbráðnunar. Svartar örvar: uppstreymi sem orsakast af innstreymi jarðhitagass og jarðhita. Það viðheldur vökinni í ísnum. Grænar örvar: Tilflutningur vatns undir íshulunni að miðju vatnsins vegna vindspennu* τ_{SW}. *Rauðar örvar: Ris vatns frá miklu dýpi vegna vegna hlýnunar, aukins eðlismassa og óstöðugleika í efra lagi vatnsins sem sekkur, grænar örvar. Bláir hringir réttsælisstreymi sem leiðir til uppstreymis og rangsælisstreymi sem leiðir til niðurstreymis vegna Ekman tilfærslu.*

contact with the ice. The amount of heat stored at depth in the lake when ice cover forms varies in response to vertical mixing in the cooling period from the temperature of maximum density to surface freezing. In 2011 the lake froze early, on 3rd December, potentially with relatively warm deep water. In 2014 the deep water was colder than in 2013 (Figure 11).

In mid-winter there are other heat sources in Lake Öskjuvatn to consider. Heat from marginal geothermal springs keep some shorelines ice free but the heat is also dissipated into the air and unlikely to flow towards deeper areas.

The observations through ice in April 2013 show variable ice thickness and the presence of small eddies under the lake ice. The under-ice temperature records from a mooring 1600 m away from the "vök" open water site reveal movements of small eddies across the lake. The eddy influence on density indicates vertical transfer of heat to the under-ice surface layer which was ~1°C in April 2013.

Moored temperature recorders at 5 m to 60 m depth show that water is advected from the "vök" open water site towards the lake interior. The onset of the temperature rise is soon after ice covers the lake. The advection is enhanced by wind stress acting on the open water. Wind stress from the southwest was stronger and more persistent in 2012 than in 2013. Nevertheless, the temperatures difference between the upper and lower layers had largely been erased by the end of May 2013.

CONCLUSIONS

Our observation on the environment at Lake Öskjuvatn 2011–2014 do not point to a single process to explain the disappearance of winter ice cover in 2012. We would rather propose a sequence of conditions, interactions and their timing as causes.

⋆The lake froze rather early, i.e. on 3rd December 2011, in a spell of cold and calm weather. This marked the end of a cooling period which started when the water temperature had fallen to the temperature of maximum density. This points to relatively warm deep water, >3°C in early December. 2011

⋆There is continuous upward rise and entrainment of water with geothermal gas emerging from ~84 m depth to the upper water and the surface which remains ice-free. This source lies deep enough to entrain some water from the lake's deep water.

⋆Advection from the open water site, "vök", into the lake's upper layer becomes important after ice cover in early December. This layer is half the lake volume, and its temperature rises steadily with consequent density increases. The advection also generates shallow eddies which migrate under the ice (Figure 14).

⋆There were unusually persistent southwesterly winds in the first months of 2012. The associated wind stress on the open water enhanced the advection and upper layer warming. The density difference between the deep water and the upper water gradually decreased which eventually led to a downward mixing of the upper layer and an upward mixing of the deep water, a lake turnover. This redistribution of heat caused ice melting, the rate of which still accelerated in March during a strong southwesterly wind event. On April 2nd the lake was ice-free.

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ÁGRIP

Öskjuvatn í Dyngjufjöllum, myndaðist eftir eldgos 1875. Það er í 1050 metra h.y.s. og 217 m djúpt. Það blandast allt tvisvar á ári. Að vetrarlagi er um 0.13 km^2 vök yfir jarðhitasvæði í vestanverðu vatninu. Þar berst af botni vatn og gas allt niður á 84 m dýpi. Veturinn 2012 sýndu tunglgögn óvænt að vökin stækkaði og ísþekjan á vatninu hvarf smám saman. Gögn frá sjálfvirkri veðurstöð á Upptyppingum sýna að suðvestan vindar voru tíðir á fyrsta ársfjórðungi 2012. Eðlis- og efnaeiginleikar vatnsins voru rannsakaðir í tveimur leiðöngrum, í apríl 2012 þegar vatnið var opið, og í apríl 2013 þegar vatnið var ísi lagt. Mælt var með tæki sem skráir samfellt seltu, hitastig og dýpi (CTD). Í apríl 2012 var vatnshitinn nær línulega hækkandi niður að 2°C á 200 m dýpi, sem er afleiðing blöndunar vatnsins frá yfirborði til botns. Í apríl 2013 var vatnið lagskipt þar eð hitastigull lækkaði á um það bil 60 m dýpi og á 200 m var vatnið 3°C. Strengur var í vatninu með síritandi hitamælum niður á 180 m dýpi frá apríl 2012 til júlí 2014. Eftir að vatnið lagði veturna 2013 og 2014 tók hitinn í efri hluta vatnsins að hækka, og þar af leiðandi hækkaði eðlismassinn einnig. Hitunin náði niður að 60 m dýpi í það minnsta. Það er helmingur rúmmáls vatnsins. Að jafnaði hækkaði vatnshitinn 0.00645°C d^{-1} fyrri veturinn og 0.00536°C d^{-1} síðari veturinn. Efnamælingar í apríl 2012 bentu ekki til aukins jarðhita. Hins vegar sýndi samanburður við mælingar frá 1975 að styrkur uppleystra steinefna hafði lækkað. Styrkur klóríðs og

liþíns lækkaði um 30% en styrkur kísils og súlfats, sem tengjast jarðhita, lækkaði minna, um 15%. Innflæðið í vatnið, úrkoma og aðrennsli, var óbreytt. Árlegt flæði koldíoxíðs frá vatninu til lofts var áætlað 12000 tonn 2012. Það hafði dregið verulega úr því frá 1975. Óvænt hvarf ísþekjunnar á Öskjuvatni í febrúar-mars 2012 var vegna flókins samspils tíðra suðvestan vinda, varma í djúplögum vatnsins og jarðhita á botni í vatninu vestanverðu. Stöðugt gasuppstreymi á 84 m dýpi í jarðhitasvæðinu eykur lóðréttan flutning varma til efri hluta vatnsins. Tíðar suðvestan áttir 2012 hertu á flæði vatns og varma frá vökinni og undir ísþekjuna. Hækkandi vatnshita fylgir hækkum eðlismassa í efri hluta vatnsins. Það olli að lokum óstöðugleika, uppblöndun og ísbráðnun.

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